RTI INTERNATIONAL | Memorandum

FROM: Carrie Richardson Fry and Jeff Coburn, RTI International

TO: Andrew Bouchard and Brenda Shine, EPA/OAQPS

DATE: July 3, 2012

SUBJECT: Peer Review of "Parameters for Properly Designed and Operated Flares"

This memorandum details the process for the peer review of the report entitled "Parameters for Properly Designed and Operated Flares" prepared by the U.S. Environmental Protection Agency's (EPA's) Office of Air Quality Planning and Standards (OAQPS) dated April 2012. To ensure a comprehensive and balanced peer review, RTI sought to establish a peer review panel consisting of individuals representing a variety of backgrounds and perspectives who could be considered "technical combustion experts." To assist in this process, RTI utilized search engines and reviewed technical literature pertaining to flares and combustion. Experts were identified within four categories: the refinery industry, industrial flare consultants, academia and the environmental arena.

RTI contacted multiple reviewers within each category to assess their availability and interest in participating in the peer review panel, and selected from among the interested parties to form an eight-person panel comprised of two individuals from each category. The eight peer reviewers on the panel are as follows:

- Technical Lead on Flare Combustion Efficiency from a major oil company
- Dr. Murty Kanury, Professor at Oregon State University
- Gary Mueller, Principal Consultant Air Quality, Shell Global Solutions (US) Inc.
- Lucy Randel, Research Director, Industry Professionals for Clean Air, Houston, Texas
- Dr. Ranajit Sahu, Independent Consultant
- Christopher Schaeffer, President and General Manager, Control Instruments Corporation
- Dr. Jim Seebold, Independent Consultant
- Dr. Joseph Smith, Laufer Endowed Chair of Energy, Missouri University of Science and Technology

Each peer review panel member was provided a charge statement with ten charge questions, a copy of the draft report, the corresponding data base, and, if requested, a copy of any references listed in the draft report. The ten charge questions follow:

Section 2: Available Flare Test Data

1. Please comment on the agency's criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have lead to inappropriate exclusions of relevant data points.

Section 3: Steam and Flare Performance

2. Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?

3. Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?

4. Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to $LFL_{VG\text{-}LFL}$) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?

Section 4: Air and Flare Performance

5. Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning? Does the flare data adequately support the EPA's observations?

Section 5: Wind and Flare Performance

6. Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities greater than 22 mph at the flare tip to indicate wake-dominated flame situations. Additionally, also comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance. Comment on the effectiveness of observations identifying

wake-dominated flames. Does the flare data adequately support the EPA's observations?

7. Did the agency adequately examine other operating parameters (different from MFR) for identifying wake-dominated flames? Are there specific other parameters that should be given more or less emphasis?

Section 6: Flare Flame Lift Off

8. Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. Does the flare data adequately support the EPA's observations? Are there specific other parameters or methods/equations that should be given more or less emphasis?

Section 7: Other Flare Type Designs to Consider

9. Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity to non-assisted flares, pressure-assisted flares, and other flare designs.

Section 8: Monitoring Considerations

10. Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters: LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, the ratio of NHV_{CZ} to $NHV_{VG\text{-}LFL}$, C_{CZ}, SR, MFR, and V_{max}. Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.

The panel members performed a thorough review of the draft report and provided answers to each of the questions to the extent possible, based on their technical expertise. Each panel member's response is provided as an attachment to this memo (see Attachments A through H). Each response is provided exactly as submitted, with the exception of modifications to remove identifying information from the submission of the technical expert who wished to remain anonymous.

Attachment A

Technical Lead on Flare Combustion Efficiency from a major oil company

We appreciate the opportunity to participate in the technical peer review of *Parameters for Properly Designed and Operated Flares*. The Panel of technical reviewers was asked to focus on a set of ten charge questions, with invitation to further comment on any aspects of the information in the report or other flare topics. To that end, please find specific responses to the charge questions below followed by a few general comments. Finally, the type of rigorous peer review that would be conducted for the purposes of journal publication seemed beyond the scope of this task. As such, comments for the purpose of technical editing of the paper were not included in this review.

Charge Questions

Section 2: Available Flare Test Data

1. Please comment on the agency's criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have lead to inappropriate exclusions of relevant data points.

Response: Exclusion of data sets B and I seems wholly appropriate. As stated, there was insufficient information regarding conditions (flare vent gas flow rate) in data set B and data set I was on a unique flare design, which resulted in data inconsistent with other types of flares. Table 2-6 identified reasons for removal of data prior to "any final analysis." In general, it is difficult to find fault with the reasoning that lead to data exclusion on these individual accounts; however, one concern with that approach remains. The report reads as though the maximum LFL_{CZ} of 15.3% conclusion has driven the process of data exclusion insofar as the data was more highly scrutinized if inconsistent with that conclusion. It is difficult to infer which other data points would have been excluded under similar criteria had all of the data been similarly scrutinized.

Section 3: Steam and Flare Performance

2. Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?

Response: The primary observations detailed in this report state that LFL_{CZ} is the most appropriate operating parameter toward the identification of oversteaming. The question of appropriateness for any regulatory operating parameter should take into account 1) practical considerations of operating the individual unit with respect to the parameter, 2) ability of the operating parameter to achieve environmental objectives and 3) cost effectiveness. This analysis does not consider the practicality of operating a flare with a new operating parameter nor does it consider the cost effectiveness of implementation. The report addresses part of the second consideration in exploring operating parameters to ensure good combustion efficiency in flares. There is no attempt made to quantify emissions reductions through implementation of such a parameter.

It is difficult to follow how the authors arrived at the conclusion that an LFL_{CZ} of 15.3% is the appropriate limiting value. The authors did an exceptional job of carefully reviewing the data with respect to LFL_{CZ} approach. Monitoring the LFL_{CZ} would require the maximum instrumentation (flow monitoring on waste and assist gas and full speciation of flared gas). Furthermore, a limit of 15.3% would require a large proportion of flares with high combustion efficiency to supplement flare gas with auxiliary gas to no benefit and an unnecessary cost.

The LFL_{CZ} concept relies on the lower flammability limit of a gas or mixture of gases to determine the minimum concentration below which a gas or mixture of gases will not be flammable. Theoretically, below the lower flammability limit (LFL), a gas will simply not burn. One would expect to see essentially a step-function change (high combustion efficiency independent of the dilution until a threshold were reached where combustion efficiency fell to zero) if the combustion efficiency of a particular gas mixture were plotted against the dilution of that gas (i.e. a plot of steam to vent gas ratio vs. combustion efficiency). Practically speaking, the combustion efficiency around the LFL will be greater than zero because the mixture will not be perfectly mixed and there will be pockets of rich material that will combust, resulting in a monotonically decreasing function that rapidly declines to zero near some threshold value of dilution. (It is also important to recall that the accuracy and precision of combustion efficiency measurements themselves decline with degrading combustion efficiency for a variety of reasons.) Individual data sets plotted against steam to vent gas ratio exhibit this type of behavior.

A gas or mixture of gases should be capable of burning irrespective of how high or low the LFL is, provided the gas is present at a concentration between the upper and lower flammability limits in the combustion zone. By concluding that there is an upper bound to the LFL_{CZ} where one expects to see combustion, the authors essentially conclude that gases with a higher LFL_{CZ} are either less likely to be released in adequate volumes to be present in sufficient concentration in the combustion zone relative to their own LFL to combust, or there is inadequate mixing – flare operations specific assumptions. A conclusion that there is a maximum LFL_{CZ} at which gases are less likely to combust is more of a conclusion about what concentrations the authors believe the average flare releases gas to the combustion zone and less of an inherent property of the gas composition. The question remains, in this case, of whether this data set has an adequate representation of flares to arrive at conclusions of average flare operations. The LFL_{CZ} is essentially a semi-empirical parameter that may not be appropriately extended to additional flares outside of this data set, especially future flares or those with differing flare designs.

There was not sufficient information provided to separately comment on the net heating value ratio other than to say that the report concludes it is nearly mathematically identical to the inverse of the LFL_{CZ}, so the comments above likely apply. The report states that the ratio may be “easier for flare owners and operators to understand and implement because it uses a familiar parameter (net heating value).” While the term net heating value, particularly in the context of flare operations, may be more familiar, it is not obvious why the ratio described would be easier to implement. It appears to have the same instrumentation requirements as the LFL_{CZ} methodology given that a net heating value at the lower flammability limit would need to be computed.

3. Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?

Response: It is not clear to which chemical reactions the question refers. The response to question #2 addresses the physical basis for a maximum LFL_{CZ} threshold and the semi-empirical nature of that parameter.

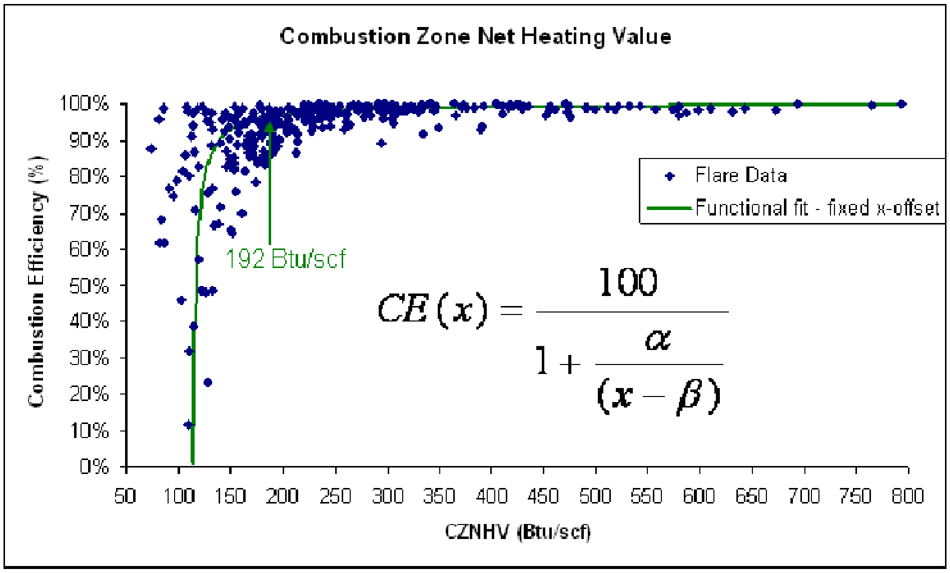
4. Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to LFL_{VG-LFL}) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?

Response: Previous work focused on the latent heat value of the flare gas. That approach should not be discarded. Additional studies in the recent past are reasonably consistent with previous observations, including the work in the 1980s that set the basis for current flare requirements. That work recognized a change in flare combustion efficiency resulting from the addition of assist gas and attempted to address that with different minimum net heating value requirements dependent upon the presence of assist gas (300 Btu/scf for assisted flares as compared to 200 Btu/scf for unassisted flares.) One would expect that the treatment of assisted flares should converge with unassisted flares in the limiting case where there is zero assist gas used. The data suggests that the minimum 200 Btu/scf is likely the appropriate limiting net heating value, but assist gas should be handled by considering its volumetric dilution of the waste gas. That is the approach used in the combustion zone net heating value (CZNHV) concept.

The CZNHV approach, however, appears to be dismissed, out of hand. The report correctly remarks that “using the NHV_{VG} as an indicator of good combustion efficiency ignores any effect of steaming,” and notes that the NHV_{CZ} factors in steam usage. Then the report states that if the data set included here were used “to determine appropriate operating conditions for flares, operators would need to maintain a NHV_{CZ} between approximately 300 and 350 Btu/scf to ensure good combustion.” That conclusion was not further documented or justified. In the identification of an LFL_{CZ} limit, there was a tolerance for some data inconsistency with the limit. A similar philosophy could be applied here.

The data is plotted as CZNHV vs. combustion efficiency below and fit to the inset function. The function essentially interpolates between two lines – one representing good combustion efficiency and one rapidly approaching zero combustion efficiency. The particular fit adjusted the variable β to 114 (to fit the low combustion efficiency data visually) and then used the Microsoft® Excel solver to derive the best fit for α, in this case, 2.85. (One could use a regression technique for both α and β.) Interestingly, the fit crosses 96.5% combustion efficiency right around 200 Btu/scf.

It is true, as noted in the report for a CZNHV parameter (as well as the others examined) that there exist data points of both high and low combustion efficiency on either side of a presumed limiting value, however, one could reasonably anticipate good combustion efficiency were an NHV_{CZ} of 200 Btu/scf maintained. This type of analysis requires only a consideration of dilution at the combustion zone with assist gas above current regulatory requirements. In principle, a revision that simply relocated the point of calculation from the waste gas to the combustion zone would require the addition of engineering calculations or flow monitors (incurring an investment and operating cost) for both the waste and assist gas. CZNHV can be calculated by volumetric dilution of the NHV.



$$CE(x) = \frac{100}{1 + \frac{\alpha}{(x - \beta)}}$$

The report states that “NHV may not be the best operating parameter for determining flare performance because the net heating value of a mixture can vary significantly at certain constant lower flammability limits (and vice versa),” though it is not clear from the report why NHV is assumed to be the inferior parameter of the two. Neither the CZNHV nor the LFL_{CZ} approach described here recognizes the unique combustion chemistry of hydrogen. The NHV, on a volumetric basis, of hydrogen (290 Btu/scf) would lower the calculated CZNHV compared to propane (983 Btu/scf) and the LFL of hydrogen (4%) would raise the calculated LFL_{CZ} compared to propane (2.1%), though data suggests that hydrogen is supportive of combustion.

Perhaps most compelling, however, is that flare combustion practices should be established on a flare-by-flare basis. The challenge in identifying a single parameter and limit that best represents good combustion efficiency for all flares is a testament to the appropriateness of addressing flare combustion on a case-by-case basis. The correlation between a flare operating at the incipient smoke point and good combustion efficiency has been enumerated throughout the literature. For example, a major finding of the referenced 2010 TCEQ/UT study states that “the most efficient flare operation, as measured by DRE and CE, for the flare operating conditions tested, was achieved at or near the incipient smoke point.” One could envision a low cost and perhaps quite effective paradigm where combustion efficiency was more or less monitored visually much in the same way visible emissions are monitored today.

Section 4: Air and Flare Performance

5. Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning? Does the flare data adequately support the EPA's observations?

Response: The stoichiometric air ratio was a concept developed as a result of the recent TCEQ-commissioned study by UT at the John Zink facility. The conclusions of that report appear reasonable only for the limited set of data. Regarding air assisted flares, data were presented on only two flares. The entire data set derived from one of the flares was correctly excluded from this analysis due to fact that the flare had a diameter of 1.5" and it is documented that flares with diameters less than 3" do not scale to industrial flares in the determination of flare combustion efficiency. It is important to note that the complexity of parameterizing steam assisted flares became more apparent as the data set grew. The TCEQ data set is limited to one composition and one flare design. Furthermore, the data near the proposed limiting stoichiometic air ratio is limited to just a few points. Figure 4-4 shows zero data points between a stoichiometic air ratio of 7 and 9, where the single point around 7 shows high combustion efficiency. Given the limited data available on air assisted flares, it is difficult to discern a limiting parameter, particularly with confidence for extrapolation to other flare compositions, designs and sizes.

As described in the response to question 2, the LFL_{CZ} limiting value was established as a semi-empirical parameter describing combustion efficiency observations specific to the steam assisted flares in the present analysis. The authors believe that the LFL_{VG} operating parameter is a natural extension of the conclusions from the steam-assisted flare data; however, a similar conclusion on air-assisted flares is not derived from the present data.

Section 5: Wind and Flare Performance

6. Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities greater than 22 mph at the flare tip to indicate wake-dominated flame situations. Additionally, also comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance. Comment on the effectiveness of observations identifying wake-dominated flames. Does the flare data adequately support the EPA's observations?

Response: There is inadequate data available to understand the effect of wind on an industrial flare. All of the studies targeting the study of wind effects were conducted on small pipe flares, almost all of which were below 3" in diameter. The report notes that these flares are generally not scalable to industrial sized flares. Regarding the analysis of the available test data on industrial size flares, "no test runs were performed in winds any higher than 22 mph." The assumption that observations from small pipe flares should apply in the absence of data on larger flares does not seem appropriate.

The data, as shown in section 5, do support the observation that a low MFR does not necessarily indicate poor flare performance for this data set. There are not data available to comment on the effectiveness of visual inspection of wake-dominated flames.

7. Did the agency adequately examine other operating parameters (different from MFR) for identifying wake-dominated flames? Are there specific other parameters that should be given more or less emphasis?

Response: There are inadequate data to investigate wind effects and correlate operating parameters to those observations.

Section 6: Flare Flame Lift Off

8. Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. Does the flare data adequately support the EPA's observations? Are there specific other parameters or methods/equations that should be given more or less emphasis?

Response: There are no data presented to adequately assess equation 6-1. It is unclear that any conclusions can be drawn from Figure 6-1.

Section 7: Other Flare Type Designs to Consider

9. Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity to non-assisted flares, pressure-assisted flares, and other flare designs.

Response: There are no data to support the application of new parameters to non-assisted flares or other flare types. One can envision that a non-assisted flare is the limiting case of an assisted flare with zero contribution of assist gas. However, it does not seem appropriate to apply the LFL_{CZ} parameter to non-assisted flares given that limiting value was derived from a specific set of steam-assisted flares.

Section 8: Monitoring Considerations

10. Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters: LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, the ratio of NHV_{CZ} to $NHV_{VG\text{-}LFL}$, C_{CZ}, SR, MFR, and V_{max}. Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.

Response: Section 8 of the report details the equipment needed in order to continuously demonstrate, with online analyzers and associated investment and operating cost, compliance with the parameters listed above. Another monitoring scenario worth consideration toward compliance demonstration includes grab samples. A discussion on operating scenarios and conditions where less robust monitoring equipment is indicated belongs in the context of cost effectiveness and the ability for demonstration of a parameter to meet environmental objectives. In that vein, one can readily envision scenarios or conditions in which significantly less robust monitoring equipment / methods or alternate operating parameters would serve to fulfill a flare monitoring function in a vastly more cost effective, yet environmentally protective fashion than the methods and equipment discussed above.

General Comments:

Effort and expense has been invested across the industry between the time of the 1980s promulgation of flare rules and the present time to achieve flare minimization. Some present day flares include equipment such as flare gas recovery units or are in staged flare configurations. As a result, there exist cases with little opportunity to reduce VOC/HAPs emissions as a result of combustion efficiency monitoring. An API study titled *API/NPRA/ACC Steam-Assisted Flare Operations and Control Survey*, investigated the cost-effectiveness of continuous monitoring of a combustion parameter. Conclusions from that study are below:

- Flares that sometimes operate with high steam assist ratios do not necessarily have high VOC emissions.
- Several variables influence the potential benefit from monitoring and controlling steam-assist ratio or CZNHV.
    - VOC content of the flare gas
    - Annual VOC load
    - VOC load during periods of high steam-to-flare gas ratio
    - Duration of high steam-to-flare gas periods
    - Combustion efficiency achieved through current operating practices
- The cost-effectiveness for adding extensive monitoring and control is very poor for flares with a low potential for significant VOC emissions reduction.
- For some flares, opportunities exist to cost-effectively reduce VOC emissions. However, most studied flares have no cost effective potential for significant VOC emission reductions through additional monitoring and controls.
- The degree to which VOC emissions might be reduced depends upon a flare’s specific design, service and operation.
- Potential cost-effective VOC reductions are achieved primarily through control of steam.
- There is little opportunity to reduce VOC emissions from flares with no or minimal flow or VOC load during normal operations (i.e. flares that only handle startup, shutdown (equipment clearing), and malfunction; flares with flare gas recovery; and flares that combust non-VOC gases).
- To assure cost-effective VOC emissions reductions, monitoring and control requirements should be based upon individual flare operations.

Attachment B

Dr. Murty Kanury

Professor at Oregon State University

RTI-EPA FLARE PEER REVIEW PANEL MEMBER REPORT BY
MURTY KANURY
June 4, 2012

A Memorandum, dated May 10, 2012, from RTI for U.S. EPA to the Flare Peer Review Panel members, poses ten "charge questions'' and asks each panel member to present a review of the Report in the form of answers to, and comments on, each question.

This document is a collection of responses of one member of the peer review panel to these ten charge questions. These responses are based primarily on the report titled "Parameters for Properly Designed and Operated Flares," with Appendices, prepared by the U.S. EPA (OAQPS) for Flare Review Panel, dated April 2012. Throughout this review, this report is referred to as the "subject report." Two earlier reports (respectively dated January 2012 and April 2010 by Gogolek, et al., under the sponsorship of the International Flaring Consortium) have also served this reviewer by providing some of the principles underlying the current design and operating parameters of flares.

Prologue: Presented in Appendix A of the subject report are brief descriptions of ten flare test reports and results, published between 1983 and 2011. Their authors come from five (or six) different public and private establishments. The test reports contain flare performance (in terms of carbon combustion efficiency and vent gas destruction efficiency). Among the many factors expected to influence the flare performance are: the flare tip design, configuration and size; composition and feed rate of the flare gas; air or steam addition rate in assisted flares; flare tip exit velocity; cross-wind speed; and the use of pilot flame as a flare flame stabilizer. The vast array of possible combinations of these and other variables (which may now remain unidentified) makes it quite difficult to design, build and conduct a versatile experiment in which repeatable measurements can be made. It also makes much difficult any attempts to compare, contrast, correlate and interprest different sets of experiments and their results obtained by different investigators.

It is hoped that the flare tip designs and implementations are based upon a thorough consideration of combustion fundamentals from principles of flow, heat/mass transfer, chemical kinetics, reaction mechanisms, turbulence, flare gas mixing with air, flow separation, wake formation, flame lift-off and blow-off. A number of references dealing with the fluid mechanical aspects of flow around the flare tip are refernced in Sec. 3 of the 2010 report. It is not clear whether and how these aspects had been incorporated into the designs and builds of the tips engaged in the tests considered in the subject report under review.

Section 2: Available Flare Test Data
QUESTION #1:

Comment on the criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have lead to inappropriate exclusions of relevant data points.

Eleven “criteria for excluding data points” are presented and explained in Table 2-6 of the subject report. These are identified below as criteria (**i**)-(**xi**). As can be seen in the following comments, all the eleven criteria appear to be convincing and reasonable to this reviewer. While some of the criteria are obvious, others need a closer scrutiny and thinking.

(i) The first criterion goes thus; “Test report did not record combustion efficiency (CE) for a specific test run.” And its explanation reads, “It was determined that there was not enough information to be able to use the data point.” No comment is needed.

(**ii**) The second criterion is that the “Test report recorded CE as 0% …” The explanation was that “the flame was completely snuffed out…” Paraphrasing the continued explanation, further review indicated that LFLcz was greater than 15.3%, thus indicating that good combustion was not obtained. This appears quite reasonable and agreeable to this reviewer. The matter of the threshold LFLcz being 15.3% shall be discussed later under Question #3.

(**iii**) The third criterion in Table 2.6 reads, “Test report recorded that the extraction probe … was located in the flame.” The essence of explanation is that the probe gives a good product sample only if it is in the flare plume, not if it is in the flame.

(**iv**) The fourth criterion is stated as “Test report recorded that … probe positioning … was uncertain.” The run was considered invalid because “the …technique may not have obtained a good sample of the flare plume.” The clause “… may not have obtained …” present a troublesome and ambiguous justification.

(**v**) The fifth criterion is “Test report recorded a specific test run time as less than 5 minutes.” This test run was discarded because of too much uncertainty and variability in the reported values. The explanation is continued saying that also discarded were four other tests in Data Set D which had run times longer than 5 minutes. The reason for discarding was stated as “… several of the minutes in the average of the test run … showed zero entries for the PFTIR data. These runs had less than 5 minutes of data that were not zero or not affected by wind.”

This reviewer is convinced that a reliable way of gas sampling with an extraction probe at a precisely known location in the plume is at best very difficult and impossible at worst. There appears to be enough unresolved variation (or fluctuation) even with a well-placed probe, leading one to question the reliability of these composition data.

(**vi**) The sixth criterion is “Test report recorded single test runs and an average of the specific single test runs, the single test runs were removed, but the average was kept.” The explanation was that “The single test runs were considered duplicative because each run was performed at the exact same conditions.”

In the absence of error-bars or scatter-bars, (i.e., departure of the result of one run from that of another), this explanation is not quite convincing.

(**vii**) The seventh criterion reads, “Test report recorded a specific test run as smoking.” The attendant explanation is that “The specific run was considered out of compliance because visible emissions are a violation with the current regulation and such runs should not be used to establish operating parameters for good combustion.”

(**viii**) “…did not record enough information to determine flare vent gas flow rate for a specific run.” It is obvious that there is not enough information to use the data point.

(**ix**) The ninth criterion relates to the flare vent gas flow rate. “… flow rate was less than 10 pounds per hour.” The explanation was that in these extractive tests with low flow, the combustion efficiency values were very different from those in other similar runs but with higher flow rates. “The extractive test method may not have correctly detected the waste gas compositions because the flow rate was too low.” The reviewer cannot complain.

(**x**) The tenth criterion is specific only to 10 runs in Data Set H. In these runs, vent gas involved nitrogen content in excess of 30v%. For these runs, the flare vent gas flow rates are reported to be inaccurate.

(**xi**) The last criterion is specific only to 2 test runs in Data Set C. The combustion efficiency was reported to exceed 99%, yet fraction of combustible in the stream was less than 2%. It is explained that these two test runs are based on extractive test method which may not have correctly detected the waste gas compositions. The reviewer agrees with the statement that “… It is not possible for these two test runs to have achieved greater than 99% combustion efficiency (the combustibility of the stream is too low).”

In closing of this answer to QUESTION #1, it is the reviewer’s opinion that application of the foregoing eleven criteria has led only to appropriate exclusions of data points.

Section 3: Steam and Flare Performance

QUESTION #2*:*

*(**a**) Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ})as an operating parameter for indicating over steaming situations on steam-assisted flares.*

*(**b**) Comment on the agency’s use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}.*

*(**c**) Do the flare data adequately support the EPA’s observations?*

Background: Like the flame at the mouth of a bunsen burner, (with its port of primary air shut off), a flame at the tip of the flare is expected to be a diffusion flame. A diffusion flame is one in which combustion reactions occur infinitely fast compared to the physical convective/diffusive transport (mixing) processes. Due to the larger size of the tip, slower feed of the combustible waste gas and complications resulting from cross wind at the tip of the flare, the flare flame will be much different from the orderly ideal laminar diffusion flame over a bunsen burner in a lab in which the ambient air atmosphere is quiescent.

The flame will be broken up with serious undulations and folds, it will be lifted-off the flare tip, it might even be blown off and reattached in the wake to the flare tube which acts as a flame holder. The flame under these conditions if not entirely a diffusion flame. Combustion chemistry will be of finite rate rather thanof infinite rate. Dilution with steam or someother gas which is presumed to be 'inert' will further reduces the rate of chemical reaction kinetics in the flame. The definition and control of such a complicated beast as this flame is nearly impossible. Here lies the horrendous difficulty, this reviewer believes, in designing and operating flares to effectively and predictably destroy waste gas streams.

With the slowed-down chemistry, the flame ceases to be one controlled solely by physics as it becomes a flame in premixed reactants. Flame propagation in a premixed reactant mixture stream is governed by both physics abd chemistry. The propagation becomes impossible if the mixture is too lean or too rich in 'fuel,' the combustible portion (% 'fuel' by volume or moles) of the waste mixture stream. Thus arise the lower (or lean) flammability limit (LFL) and the upper (or rich) flammability limit (UFL). Below the LFL and above the UFL flame propagation is impossible.

The details belabored in the preceding three paragraphs are important because the LFL is determined definitely by the combustion chemistry (in conjunction with whatever physical processes). This limit flame chemistry, however, may or may not be the same as in the chemistry in a premixed flame away from both the flammability limits. It is definitely not the same as the infinite rate chemistry in an ideal diffusion flame. To produce the highest carbon conversion efficieny and also destruction efficiency, combustion in the hottest possible flame seems to be desirable. The lean limit flame is far from this desirability.

(**a**) With this understood, this reviewer is comfortable to characterize the goodness of flaring with the chemistry of flare flame that is available only through the 'black-box' parameter LFL. Calculation of LFL at the combustion zone by using the mixture rule of LeChatelier and its extensions is reasonable. The description in Secs. 3.1 and 3.1.1 along with Figure 3.3 are sufficiently convincing to arrive at the (LFLcz less than equal to 15.3v% and CI equal to or greater than 96.5%) rule for practical use. The reviewer cannot move to the next item of the question without (presumptuously or, worse, naively) wondering about the significance of the decimal place digits 3 and 5 in these thumb rule figures. It appears debatable if these digits could not be dropped, without harming the hypothesis that supports the correlations, so as to state the thumb rule limits in whole numbers, i.e.,15v% and 96%.

(**b**) As the independent parameter that correlates the measured combustion efficiencies, LFL_{CZ} has been replaced by the ratio of NHV_{CZ} to $NHV_{VG\text{-}LFL}$where the former denotes the net heating value of the combustion zone gas while the later stands for the net heating value of the flare vent gas if diluted to the lower flammability limit. (Contrast Fig 3.10 with Figs. 3.3, et seq.) Analysis showed that this ratio being greater than 6.54 is a signal that the combustion efficiency will be greater than 96.5%. EPA's first observation is fairly well supported by the flare data correlations using this ratio. These correlations appear to be useful in estimating the goodness of flare performance. But, yet an improved understanding of the meaning of the ratio and its relation to the LFLcz criterion will be valuable.

In order to discuss the meaning of this ratio, let us recall that the flare vent gas (VG) mixture includes all waste gas, sweep gas, purge gas, and supplemental gas, but include neither the pilot gas nor the assist media. For a steam-assisted flare, the combustion zone gas (CZ) mixture is formed by mixing the flare vent gas (VG) with various quantities of the steam supplied to the flare. If it is an air-assisted flare, air replaces steam in forming the CZ mixture. It is clear that the CZ mixture contains all the gases injected into the combustion zone of the flare except the pilot gas. It is not stated anywhere in the report but it appears that the CZ mixture does not contain any ambient air induced into the combustion zone. Noting this may be of later use in discussing air-assist flares.

Several comments can now be made. First, in all cases, steam, nitrogen, excess oxygen and such products of combustion as carbon dioxide and carbon monoxide are considered to be inert. This is probably an acceptable assumption because the temperatures involved are sufficiently low enough to neglect dissociation and chemical equilibria. Second, it has been said (somewhere in the flare combustion literature received by this reviewer through RTI) that one of the reasons for injection of steam is to form H and H_2 in the CZ mixture in order to increase the flame reaction rates as well as carbon/soot combustion rates. At a flame temperature near 1,200K, it is doubtful if H_2O decomposition will be measurable, leave alone the dissociation of H_2 to H atoms.

Third, the reference to composition at which the denominator is evaluated at LFL indicates an implicit account for the (especially the chemical) factors that determine LFL in the behavior of flare flame. Is an implicit account sufficient in the important practical application this work is intended to serve? Fourth, even after a careful study of the report as well as the paper of Evans and Roesler, this reviewer did not understand why the denominator of this ratio is $NHV_{VG\text{-}LFL}$ rather than $NHV_{CZ\text{-}LFL.}$ Use of the later appears to be more logical so as to reckon NHV_{CZ} in units of the same at the LFL, i.e., $NHV_{CZ\text{-}LFL}$.

Fifth, the work of Evans and Roesler has prompted the authors of this report to pursue the potential of the net heating value of the vent gas (VG) mixture (or of the CZ mixture which is the VG mixture diluted with steam) as an indicator of the combustion efficiency of the flare. In the second sentence of the first paragraph of Sec. 3.3, it has been remarked that the heating value is "... nearly identical mathematically to the reciprocal of the inverse of the $LFL_{CZ\ ...}$". With apologies for nitpicking, this reviewer points out that it is not "... identical to the inverse," but rather "... inversely proportional to ...". At the 9th line in the second paragraph of the same section, it has been repeated that "... this ratio is mathematically equal to the inverse of the LFLcz ..." Again, it is not "... equal to the inverse ..." but "inversely proportional ..."

Sixth, an inverse relation should not be surprising. Nor its important meaning and potential be under-estimated. When one multiplies the combustible content in the VG mixture (or the CZ mixture which is the quantity on the x-axis of Figure 3.9) by the average heating value of this combustible mixture, one obtains the total chemical energy released in thermal energy form (i.e., heat) upon complete combustion. [Notice that the quantity on the x-axis of Figure 3.12 is the "net" heating value of the VG.] All constituents of the mixture other than the combustible content (with inclusion of nitrogen associated with the burned oxygen plus both N_2 and O_2 of the excess air, if any) have nothing to do with thermal energy release. They are there only to absorb a significant portion of the heat release in order to raise their temperature from the precombustion state to the combustion product stream state. As a result, the "flame temperature" (i.e., the temperature of product mixture resulting from combustion of the CZ mixture) is dramatically reduced; and with it, the flame reaction rates are diminished to a level at which it is susceptible to extinction without or with blow-off by the cross wind.

It is not very difficult to combine the x-axes of Figs. 3.9 and 3.12 (after the basis of one or the other is converted to CZ or VG, to be consistent) and to plot the combustion efficiency as dependent on the product of combustible volume fraction by the average heating value. One need not be surprised if such a correlation turns out to be at least as meaningful as shown in Figs. 3.9 and 3.12, if not better. We will refer to this and the preceding paragraph in answer to Question #4 part (b).

And finally, the seventh comment at this junction relates to the matter of dilution due to adding steam, air or nitrogen to the VG flow at the flare tip. The intended purpose of injecting the assist-steam is three fold: first, to control smoke, hydrocarbon pyrolysis and soot formation; second, to enhance the homogeneous reaction rates by possibly increasing the supply of H_2 from decomposition of H_2O and H atoms from dissociation of H_2; atoms; and third, to reduce the flame temperature due to raising the sensible enthalpy of H_2O in the products of combustion. It may be that the third intended pupose is in conflict with the first two. It is clear why serious head aches arise due to "over-steaming" the stream to be burnt.

Here are a few questions this reviewer would like to pose at this point. Are there any tests done to inject *superheated* steam to keep the flare "flame temperature" from getting lowered too much due to the heat sink effect of the assist-fluid? Is there ever a buoyant flow up the pipe from the VG supply to the flare tip? Would such a buoyant "chimney flow" help obtain a healthy jet flame flame based at the flare tip? What is the pipe height, approximately? What is the temperature of VG at its inlet into the pipe? The answers are certain to be available in the published literature to make estimation possible of buoyancy and its relative importance in controlling the shape and stability of the flare flame at the rim.

(**c**) *Do the flare data adequately support the EPA's observations?* The data do indicate that the lower flammability limit of combustion zone gas (LFL_{CZ}) is the most appropriate operating parameter. Analysis of existing data lead the Agency to conclude that, in order to maintain good combustion efficiency, the LFL_{CZ} must be 15.3 percent by volume or less for a steam-assisted flare.

The data and analysis also suggest, and show, as an alternative to LFL_{CZ}, that the ratio of the net heating value of the combustion zone gas to the net heating value of the flare vent gas if diluted to the lower flammability limit, $(NHV_{CZ})/(NHV_{VG\text{-}LFL})$, must be greater than 6.54 to give combustion with efficiency greater than 96.5%.

QUESTION #3:

*(**a**)Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed?*

*(**b**) Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?*

(**a**) A brief tutorial may be appropriate here. Most of the LFL and UFL data are in textbooks and Handbooks. They were originally measured (in flame-tubes, bunsen burners, flat flame burners, soap bubbles, etc.) in the last 75 years, by combustion scientists at research laboratories, especially at the U.S. Bureau of Mines in Pittsburgh, Pennsylavania. Much theoretical work is available in the combustion literature which includes the Combustion Institute's Proceedings of the the International Symposia, Journals such as Combustion and Flame, Combustion Science and Technology, and others. Most of the theoretical models have the goal of calculating the "fundamental" speed of flame propagation in premixed gaseous reactants (i.e., [pure-fuel-gas + air] mixtures) under the balance of heat conduction and energy release in the reaction. When conduction and convection are excessive, the reaction zone temperature decreases to such an extent that the flame gets "quenched" or "extinguished."

Even if the reaction temperature is high, the reaction rate may be diminished due to a diminishment of the fuel content or oxygen content in the mixture due to their consumption in the progress of the reaction. When either the fuel content or the oxygen content are sufficiently small, the reaction rate will become so small that the flame propagation ceases to occur. This is called "extinction," different from "extinguishment" or "quenching" due to excessive heat losses. The concepts of fuel-lean composition limit (LFL) on one side and (oxygen-lean) or fuel-rich composition limit (UFL) on the other side have thus evolved as measures of limits of composition between which flame can propagate.

The flammability limits are usually tabulated for premixed [pure-fuel-gas + air] mixtures; not for "diffusion flames" in whichthe chemistry is infinitely fast compared to the physical processes such as flow, diffusion, conduction, turbulence and other mixing process rates. Flare flames, like a bunsen flame with the primary air supply port is shut off, are diffusion flames. Yes, near the burner-rim even the a diffusion flame would suffer heat loss by conduction and the flame is quenched near the rim. It is not inconceivable that all flames near extinction are premixed limit flames.

Based on this tutorial, the first half of the question can now be answered. Even in the limit flames, chemical reactions still occur, albeit at a substantially rates smaller than in near-stoichiometric mixtures, by rather complicated reaction mechanisms and interactions. Concerns that these slow chemical interactions may make the $LFL_{CZ} < 15.3$ threshold criterion for efficient combustion inaccurate are most probably unwarranted. A dying flame shall surely die at the flammability limits.

Critique of the LFL_{CZ}: The CZ stream is composed of the VG stream plus the assist-fluid. What is to be burned is the mixture formed by the mixing of the CZ strem and entrained air. It is this mixture which has to be maintained at sufficiently high fuel content in the spirit of the lower flammability limit. This notion seems to be missing in the literature of flare design and operation. If the reviewer is unaware of any published open literature to the contrary, he offers a sincere apology for this critique of the state of the art of flare technology.

(**b**) Assuming that the "data" referred are "flare flame data," this reviewer's answer to the question is "most likely, No." Section 2 and Table 2.6 convince this reviewer that the agency had diligently collected all the available test data and screened them thoroughly for inclusion in the subject report. This reviewer, being a combustion scientist rather than an expert in flare technology, is unable to point out to the agency any data that may have been missed to consider in their work. We will refer to this paragraph below in the answer to Question #4 part (a).

QUESTION #4:

*(**a**) Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to LFL_{VG-LFL}) that could indicate over steaming situations?*

*(**b**) Are there specific other parameters that should be given more or less emphasis?*

(**a**) Answer is "No." Only the work reported in the subject report and its appendices has been reviewed here. In it, other possible flare operating parameters appear not to be considered. The answer to Question #3 part (b) above applies to this question also.

(**b**) As answer to this question, the reader is referred to the reviewer's response to Question #2 part (b), the two paragraphsconstituting the sixth comment.

Section 4: Air and Flare Performance

QUESTION #5:

(***a***) *Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares.*

*(**b**) Additionally, also comment on whether the lower flammability limit of the flare vent gas LFL_{VG} is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning?*

*(**c**) Do the flare data adequately support the EPA's Observations?*

(a) (1/SR) is related to what is known in combustion literature and practice as the "equivalence ratio." If SR = 1, fuel and air are supplied in stoichiometric proportions. SR < 1 represents a "fuel-rich" (or deficient-air) combustion which is of no interest in flare design and operation. SR > 1 stands for "excess-air" (or fuel-lean)) combustion. (SR minus 1) is a measure of the excess air. Whereas SR in most engine combustion processes is set to be only 10 to 30 % greater than unity, a camp fire involves buoyancy-induced air to yield an SR lying in the range 5 to 10. (A peripheral note: SR is numerically the same in both mass units and volume (or molar) units.)

Based on the correlations shown in Figs. 4.1-4 of the subject report, one of the conclusions reached in Sec. 4 was that SR be 7 or less to obtain good combustion in the flare. This is also consistent with the combustion literature in that a higher the SR value leads to a lower flame temperature because the excess air acts as a thermal diluent of the product mixture. The threshold number 7 established in the subject appears to be quite reasonable in magnitude. The quantity (SR minus 1), the excess air fraction, is thus desirable to be 6 or less to produce good combustion in the flare.

A description of how the value of SR is obtained is either absent in the subject report or so meager that it failed to catch the eye of this reviewer. Is all of the air involved in SR calculation introduced at the flare tip to mix with the vent gas to form the CZ mixture, just as steam is introduced in the steam-assist tests?

If the answer to this question is in the affirmative, an interesting dilemma arises. Assuming that the efficacy of the assist-fluid, in doing what it is supposed to do, is roughly independent of the nqature of the assist-fluid, it appears reasonable to expect the same amount of ambient air entrained ("educted," as called by Evans and Roesler), into the flame of both the air and steam assist cases, into the CZ mixing zone to burn the combustible portion of the same vent gas. In the case of air-assisted flare, air has been first provided in a controlled manner as the assist-fluid and then again as the ambient air which is entrained (in an autonomously controlled manner) into the CZ mixture. In the case of steam-assist, however, air is entrained into the CZ mixture only once, i.e., via the second step. Has the resulting drastic difference between these two assist situations been noted, observed or described in any of the test reports? Has this mechanism been discussed and effects accounted for, in any analysis?

[Taking a digression,

Note that in Sec. 3, steam-assisted flare data of combustion efficiency are attempted (Fig. 3.15) to be correlated with steam to vent-gas ratio S/VG by mass as the independent parameter. This ratio is somewhat analogous to SR. The analogy and similarity or dissimilarity between the two parameters appears to deserve some attention.

The conclusion about S/VG analysis was that the combustion efficiency degrades steeply to a value below 90% when S/VG exceeds 0.5. The data contained in Fig. 3.15 are replotted in Fig. 3.16 with units of S/VG ratio changed from "by mass" basis to "by volume" basis to claim, with little explanation, that the trends are "consolidated" by the use of volume basis. Figure 3.17 is similar to Fig 3.16, with S/VG, again by volume, but the vent gas fuel is a well-defined hydrocarbon. The conclusion is that "The figure does seem to show further improvement ..." The reviewer is able to justify neither the "consolidation" nor the "improvement."

Steam is a diluent; it has simultaneously two undesirable effects on the performance of the flare. As a concentration diluent steam reduces the combustible concentration in the mixture entering into the combustion region; this would tend to decrease the reactivity of the mixture with the entrained air. As a thermal diluent with a large heat capacity, steam takes up a significant fraction of the heat released in the combustion process, thus reducing the "flame temperature." The reduction in temperature tends, in its own turn, to lower the reaction rate. These two effects alone are expected to lead to a significantly decreased flare performance. Use of "superheated steam" may curtail some of the the damage.

Not wanting to be a nay-sayer, the reviewer remains reluctant to raise the issues of soot and smoke emissions from a flare the performance of which is negatively influenced by steam's role as a diluent.

End of the digression.]

(b) *B*ecause SR deals only with thermodynamics but not with chemistry, the authors invoke LFL_{CZ}, (which is equal to LFL_{VG} in the air-assisted case), as an indicator of how well a vent gas+air mixture would burn. The conclusion was that along with the criterion of SR equal to 7 or less, an LFL less than 15.3v% will likely result in a combustion efficiency in exceess of 96.5%. "There is simply not enough air-assisted test data" to confirm this conclusion. More air-assist test runs appear to be required to arrive at an upper limit value of LFL_{VG} more reliable than the 15.3v% for efficient combustion of the VG.

(c) Do the flare data adequately support the EPA's observations? The answer is this: "only partially." An explanation is immediately warranted. That SR is one of the appropriate operating parameters is quite correct. It is true that data suggest an SR of 7 or less would give a good combustion efficiency for an air-assisted flare. To declare SR is the "most appropriate" parameter is misleading and incorrect. By itself SR < 7 does not guarantee good combustion in the flare. The vent gas lower flammability limit LFL_{VG} has to be lower than about 15.3v% to make the CZ mixture to result in a vigorous burn with the abundant air supply from the the SR < 7 rule.

For air-assisted flares, the exact value of the maximum allowable LFL_{VG} per centage number is not as firmly established as is the 15.3v% or lower rule for steam-assisted flares. One might argue that the EPA's statement "The LFL_{CZ} should be 15.3% or less to ensure ... adequate burning ..." is a safely conservative rule. But still there is no assurance of the rule for air-assisted flares in the absence of more test data. It has been candidly stated in the subject report, in the last sentence of the penultimate paragraph of Sec. 4 that "... there is simply not enough test data to determine whether a new LFL_{CZ} threshold would be warranted for air-assisted flares (i.e., a LFL_{CZ} threshold different than 15.3 percent)."

Section 5: Wind and Flare Performance
QUESTION #6:

*(**a**) Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities greater than 22 mph at the flare tip to indicate wake-dominated flame situations.*

***(b)** Additionally, also comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance.*

*(**c**) Comment on the effectiveness of observations identifying wake-dominated flames.*

*(**d**) Do the flare data adequately support the EPA's observations?*

(a) MFR is the ratio of the momentum flux of the jet at the flare tip to the momentum flux of the cross wind. A large value of MFR leads to a stable vertical flare flame jet on which the cross wind effects are ignorable and the combustion efficiency is high. A low value of MFR, on the other hand, indicates large cross wind effects which bend the flame over, drive it into the wake of the wind flow (in the lee of the flare tip or stack) and even blow the flame off. The combustion efficiency is rapidly decreased as MFR is decreased to and below 0.1. Unburned fuel is observed to be ejected into the underside of the flame in the wake. The following paragraph of summary notes leaves the reviewer disappointed that there are not enough quantitative test data to fully explore the power of MFR to characterize the degradation of flame performance by cross wind wakes.

Most of the existing large scale test runs are not only incomplete in measurements but also uncoordinated with what measurements are needed in MFR analysis. Not many of larger scale flare tests included measurement of the CG mixture flow velocities at the flare tips. Based on the best possible rough estimates from the limited available tests and their data correlations of combustion efficiency as dependent on MFR are shown in Figures 5.6 and 5.7.

It is found that most of the tests were done at low MFR, mainly due to low flare tip velocities. Most of the tests are with MFR values less than about 0.2. All runs were tested at a MFR less than 7.0. No tests were done at cross wind speeds above 22 mph. Most of the tests were done with $LFL_{CZ} > 15.3$v%. Among those not in this populous group of unacceptable tests, about 25 runs are in the useful group with MFR between 1 and 7, $LFL_{CZ} < 15.3$v%, and CE is above 96.5%. The correlation indicates that for MFR less than 3, wake effects dominate.

***(b)** Comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance.*

When the agency's statement is parsed into the following five separate and smaller remarks, the reviewer finds them logical and meaningful in describing the state of the art of cross wind effects on the flame and the combustion efficiency as mapped on the basis of roughly estimated MFR and its range.

(1) "The data suggest that flare performance is not significantly affected by crosswind velocities upto 22 miles per hour (mph)."

(2) However, a wake-dominated flame in winds greater than 22 mph may affect flare performance.

(3) The data available indicate that the wake-dominated region begins at a momentum flux ratio (MFR) of 3 or greater.

(4) The MFR considers whether there is enough flare vent gas and center steam (if applicable) exit velocity (momentum) to offset crosswind velocity.

(5) Because wake-dominated flames can be identified visually, observations could be conducted to identify wake-dominated flames during crosswind velocities greater than 22 mph at the flare tip.

(c) The reviewer agrees with the agency's statement (remark 5 above) about the ease with which useful visual observations can be made on the flames in the wake. Video is also a visual technique.

(d) Yes.

QUESTION #7:

***(a)** Did the Agency adequately examine other operating parameters (different from MFR) for identifying wake-dominated flames?*

No, not in the subject report. We learn (from the 2010 and 2012 Consortium reports by Gogolek, et al.), that the flare literature contains, in addition to MFR, the definitions and bases of two other nondimensional parameters for characterizing the wake regime, its inception, its capture of the flame and degradation of combustion efficiency. These parameters are the "Buoyant Plume, BP" group and the "Power Factor, PF" group. The BP group is the wind speed V_{wind} divided by the product $(gD_pV_{tip})^{1/3}$ where g is gravitational acceleration, D_p is the effective diameter of the flare pipe and V_{tip} is the actual flare tip velocity, (i.e., VG plus center steam velocity). The combination of $V_{g} = (gD_p)^{1/2}$ denotes a characteristic g-induced velocity. But it is not a velocity representative of buoyancy. V_{tip} represents jet inertia. While increases in either or both of V_g and V_{tip} compete against the V_{wind} to preserve the stability of the flame column, V_g does not really represent the buoyancy. The group $(gD_pV_{tip})^{1/3}$ indeed has units of a velocity and it contain gravity g and tip velocity but it has no rational meaning. The thoughts underlying the invention of the BP group and its use these days are unavailable to me. So I cannot critique it. I can, however, rewrite the BP group into the product of $[V_{wind}/V_{tip}].[V_{tip}/V_g]^{2/3}$ or into $V_{wind}/[V_{tip}^{1/3}.V_g^{2/3}]$ if they make any useful sense. The velocity induced by buoyancy will be discussed in answer (b) below.

The PF group makes no more sense to this reviewer than the BP group. Both of their definitions account for different (and wrong) mechanisms which ignore the meaning given in the field of fluid mechanics to the term "buoyancy-dominated regime" in jet flames, fire and dust plumes or submerged jets. Even if taken for their face value, the merits of BP and PF groups cannot be judged until analyses using them are developed. Their success is likely stunted by the same difficulties as encountered in the application of the notion of Momentum Flux Ratio due to the test engineers having not been given a list of variables and properties that have to be measured or estimated in a series of tests.

(b) *Are there specific other parameters that should be given more or less emphasis?*

An increased value of the ratio [(P of the flare tip flow)/(P of the cross wind flow)] is appropriate in assessing the stability of a vertical flare plume. [Here P is a property which can be: inertia indicated by the flow velocity; mass flux which is a product of density and velocity; momentum flux which is a product of mass flux and velocity; or energy which is velocity squared].

The stability can be made even better if we can generate buoyancy in the stack. This can be done by placing a small auxiliary methane+air flame in the flare pipe a foot or two beneath the flare tip. The tip velocity will be increased due to the buoyancy in the hot auxiliary combustion products. Density differences which are caused by temperature differences produce the buoyancy. Due to buoyancy, he velocity at the flare tip is increased in an order magnitude of $[Xg(T_f-T_a)/T_f]^{1/2}$ where g is gravity constant, T_f and T_a are the absolute temperatures of the auxiliary flame and ambient air respectively and X is the height diffrence beween the auxiliary burner and the tip. A mere 1 ft of this head results in 4 or 5 ft/s of velocity increase at the tip. This is the beauty of buoyancy-driven flows. Is there a new idea here for designing flare tips and flare stacks? Surely, such an invention must have been done by somebody out there before!

Section 6: Flare Flame Lift Off

QUESTION #8:

(a) *Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air.*

This is known as the Shore equation (D. Shore, "Improving flare design: a transition from art-form to engineering science," presented at AFRC-JFRC October 2007 Joint Meeting, Waikoloa, HI) for the maximum allowable flare tip stream velocity V_{max} including (if any) center steam in order to marginally avoid the flame from lifting off the flare rim. Its units, of course, are ft/s. The Shore equation gives V_{max} as dependent on: the unobstructed area of flow at the vent rim A_u ft^2 obtained from the flare tip unobstructed diameter; the LFL_{VGCS} (with the subscript $_{VGCS}$ standing for vent gas plus center steam, if any; and the ratio of the densities of $_{VGCS}$ and ambient air. The equation contains an "empirical" constant 6.85 $sec^{0.2}$. Having no access to a copy of Shore's presentation, this reviewer cannot explain what the empirical constant accounts for where the value comes from. The equation also appeared in Appendix D of the subject report with Eqs. D.42-45 dealing with the calculation.

Let us take a moment here to see an analysis of the test data presented in Sec.6.2 of the subject report. Of the total of 356 steam- or air-assisted test runs, only 108 satisfied the requirements of good flare combustion (i.e., good steam information, LFL_{CZ} < 15.3v%, air-assist runs with SR < 7, and flare diameter not too small). Figure 6.1 is a 2x4 cycle log-log plot to portray the power law of the equation. On the x-axis is the right hand side of the Shore equation and on the y-axis is the left side which contains the maximum allowable flare tip velocity $V_{max.}$ The Shore equation is computed and shown as a straight line with a positive slope.

Also shown on the graph are the flare tip velocities, $V_{VG-S,}$ of the 108 test runs. All but three of the 108 points nicely fell under the predicted V_{max} line implying that their V_{VG-S} is less than the V_{max} allowed by the equation and therefore did not experience a lift off. The three points lying above the prediction are expected to have exprienced a flame lift-off. One of them is known to have not lifted off, probably because the LFL of its vent gas is substantially smaller than the 15.3v%. The reports of the other two tests did not contain any remarks on lift-off. The behavior of each set of tests on this plot are examined and commented on. One conclusion, in Sec. 6 of the subject report caught this reviewer's eye, says that flame lift-off does not necessarily mean poor flare performance. Each of the three tests in which flame was expected to have lifted had combustion efficiency in excess of 96.5%.

*(**b**) Does the flare data adequately support the EPA's observations?*
Yes, quite definitely.

*(**c**) Are there specific other parameters or methods/equations that should be given more or less emphasis?*
This reviewer has no more to say than that the Agency's comments in the Sec. 6.3 are noteworthy.

Section 7: Other Flare Type Designs to Consider

QUESTION #9:

Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity to non- assisted flares, pressure-assisted flares, and other flare designs.

EPA's observations quite accurately summarize the answer to this question. The combustion zone (CZ) mixture is same as the vent gas (VG) mixture for non-assisted flares. Therefore the LFL_{CZ} is simply the same as LFL_{VG}. Because the vent gas is well defined, the LFL_{CZ} is better defined and controlled so as to make application of the "15.3v% or less" rule can be implemented more confidently. The cross wind analysis by the measure of MFR and flame lift off analysis from the Shore V_{max} equation are also directly applicable to non-assist flares; but not to pressure-assisted flares and other flare designs because of the lack of any test data on them to confirm.

Section 8: Monitoring Considerations

QUESTION #10:

*(**a**) Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters:* LFL_{CZ}, LFL_{VG}, *the ratio of* NHV_{CZ} *to* NHV_{VG-LFL}, C_{CZ}, *SR, MFR, and* V_{max}.

*(**b**) Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.*

This reviewer does not feel qualified to comment on these matters of monitoring and measuring. He hopes the rest of the review will make up for the absence of his contribution on this question. Sorry!

Attachment C

Gary Mueller

Principal Consultant Air Quality

Shell Global Solutions (US) Inc.

Review of the ***Parameters for Properly Designed and Operated Flares***

Gary R. Mueller, Shell Global Solutions (US) Inc.

May 21, 2012

Summary

This paper correlates a number of combustion zone composition parameters (LFL_{CZ}, NHV_{CZ}, NHV_{VG}, C_{CZ}, etc.)with observed flare combustion efficiency data. While fundamentally these parameters can be used to estimate when a flame will be extinguished, their ability to correlate when the flare flame transitions from a visible, stable flame to flame extinction is dependent upon far more parameters than these simple composition measures. While these data may be useful in describing this transition for a given set of conditions (flare designs and atmospheric conditions), the ability of the parameters proposed to insure when a flare flame transitions from stable to unstable, is only as representative as the data used to develop the empirical correlation. It is unrealistic to expect these simple parameters to describe all combinations of the factors that can impact flare performance. This observation does not diminish the utility of these parameters to describe the expected trend in combustion efficiency under similar circumstances. This reviewer believes that in developing the empirical expression for these composition parameters, that the authors have put more emphasis on minimizing false positives (poor observed combustion efficiency when the correlation would predict good combustion) at the expense of producing a large number of false negatives (good combustion when the correlation would predict poor combustion). Since it is unrealistic to monitor all the variables necessary to predict every case, this reviewer believes that the in selecting the value of the parameter used to insure good combustion, an attempt should be made to minimize the standard error of all false positives and false negatives. While this reviewer has not done this analysis quantitatively. This would appear to be done at a LFL_{CZ} closer to 20% and a safety factor of 4.8 on NHV_{VG-LFL} versus the values of 15.3% and 6.54 suggested in this paper. While available data do seem to support that MFR can be used to determine flow regime transitions in flares, the data do not support that MFR has any broadly applicable ability to correlate combustion efficiency impacts of crosswinds. This parameter is not scalable to large industrial flares, and no substantive data has been shown that combustion efficiency of industrial flares is impacted by high crosswinds. The data presented for flame lift-off has not been shown to add any value over that provided by the much simpler current V_{max} equation that is a function of vent gas NHV. The case presented is not compelling that this parameter needs to be changed. As the data presented for combustion efficiency are empirical in nature, one should not expect that data developed on different types of flares would necessarily extend to other flares (steam-assisted, air-assisted, unassisted, pressure-assisted). While it is the engineer's hope that there exists a unifying parameter that will describe all situations, this is not likely for the universe of industrial flares. As far as monitoring, the presence of a visible and stable flame is in fact the clearest indication of good combustion. While the composition parameters suggested are indeed useful in correlating operating envelopes that insure a visible and stable flame, they are not the only parameters that can be used. A myriad of parameters can be used to insure that assist gas stays in an acceptable range to produce a visible and stable flame. In an

effort to make this monitoring cost effective, approaches that define the operating envelope that produces a visible and stable flame using existing flare instrumentation should be explored.

Responses to Charge Questions

Section 2: Available Flare Test Data

1. **Please comment on the agency's criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have led to inappropriate exclusions of relevant data points.**

While the criteria for excluding data from the analysis appear justified, what is striking is the high percentage of data excluded (270 of 582 (46%) for steam-assisted data, and 67 of 111 (60%)of the air-assisted data were excluded). This reviewer would find it useful to break the excluded data into a smaller subset of reasons for excluding, such as: insufficient data recorded to calculate necessary parameters (no CE recorded, no flows recorded, etc.), data compromised (extraction probe in flame or uncertain position, flow data compromised by high N2 content, flow rate too low for extractive probe to quantify, etc.), duplicative data (e.g. averages kept, individual runs removed). Of interest to this reviewer is the percentage of data collected that was excluded because data protocols were compromised and tests where insufficient data was recorded to calculate the necessary parameters, as this would seem to indicate inappropriate data protocols or potentially flawed execution of protocols. Further, this reviewer sees no reason to exclude 0% CE data points or data points where smoking occurs. Indeed both of these represent a violation of current regulatory code, but they do serve a purpose in the analysis by defining the current limits of acceptable practice of operation.

Section 3: Steam and Flare Performance

2. **Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?**

This reviewer believes the LFL_{CZ} parameter is a useful parameter in estimating the impacts of combustion zone gas composition on the inherent flammability of a mixture. As calculated it illustrates the impact that various combustibles and non-combustibles will have on the ability to maintain a flame, in particular when a flame cannot be propagated. However, the paper spends virtually no time discussing the factors that contribute to not being able to produce a stable flame when the LFL_{CZ} is greater than 15.3%. In this reviewer's opinion, as long as a combustible mixture can be obtained when mixing air with the combustion zone gas, the ability to produce a stable flame has little to do with what the LFL_{CZ} value is, but in fact is a function of the turbulent mixing conditions present during the test. The LFL_{CZ} parameter is useful in predicting when the flame will be extinguished, but not very useful in predicting the transition from a stable flame to an extinguished flame. In essence, the data attempt to correlate combustion efficiency data over a range of unspecified turbulent mixing conditions against a parameter that measures only the composition of the combustion zone gas. While a relationship is illustrated in these data, it is this reviewer's contention that the relationship depicted between LFL_{CZ} and combustion efficiency is an artifact of the unspecified mixing conditions present during the test runs. The paper spend a significant amount of time explaining the 10 data points which did not achieve a combustion efficiency of 96.5% when the LFL_{CZ} was less than 15.3%, but virtually no time discussing the greater than 50 data points that achieved a combustion efficiency of greater than 96.5% while having a LFL_{CZ} of greater than 15.3%. This would seem to be an indication that the relationship depicted is not a cause and effect relationship, but rather a convenient way to display the data. While it acceptable to attempt such a correlation, it should be acknowledged that such a correlation's ability to predict other combustion conditions is limited to situations that fall within the range of the data presented, and that in fact there is no reason to expect this correlation to be generally applicable.

While the correlation of combustion efficiency versus NHV_{CZ} also suffers from the same pitfall as the LFL_{CZ}, parameter (e.g. correlating parameter is unrelated to factors impacting turbulent mixing), Figures 1 and 2 below would seem to indicate that it suffers from far fewer false negatives than the LFL_{CZ} parameter (e.g. fewer instances when poor combustion is predicted but good combustion is observed) and has a similar number of false positives (e.g. good combustion is predicted but poor combustion is observed), depending upon what Safety Factor is applied to the $NHV_{VG\text{-}LFL}$ value. Safety Factors of 4.8 and 7.2 were selected because they produced average limiting values of NHV_{CZ} of the data set of approximately 200 BTU/SCF and 300 BTU/SCF, respectively. A safety factor of 4.8 increases the number of false positives, but drastically reduces the number of false negatives, as opposed to a safety factor of 7.2. While not technically rigorous, the average limiting NHV_{CZ} for the steam assisted data using a safety factor of 4.8, also reduces to the limit previously determined to insure a stable flame for unassisted flares (e.g. 200 BTU/SCF). One would expect as the steam assist approaches zero, the limiting NHV_{CZ} should approach that of an unassisted flare. Selection of a safety factor should consider minimizing not only the false positives, but also the false negatives . Since the NHV_{CZ} is a function of the LFL_{CZ}, one would expect that this safety factor approach would also apply to the LFL_{CZ} parameter. While the safety factor chosen is obvious within the calculation of the $NHV_{limiting}$ approach, it is less obvious in the somewhat arbitrary selection of the limiting LFL_{CZ} of 15.3%. While there are some false positives with a safety factor of 4.8, the bulk of these observations have combustion efficiencies above 90% and/or are relatively close to the $NHV_{limiting}$ value (e.g. while in error, not grossly in error). No experimental uncertainty was placed upon either the combustion efficiency value or the NHV_{CZ} value, but the bulk of the false positive values at a safety factor of 4.8 are probably close to being within the uncertainty of the experimental data.

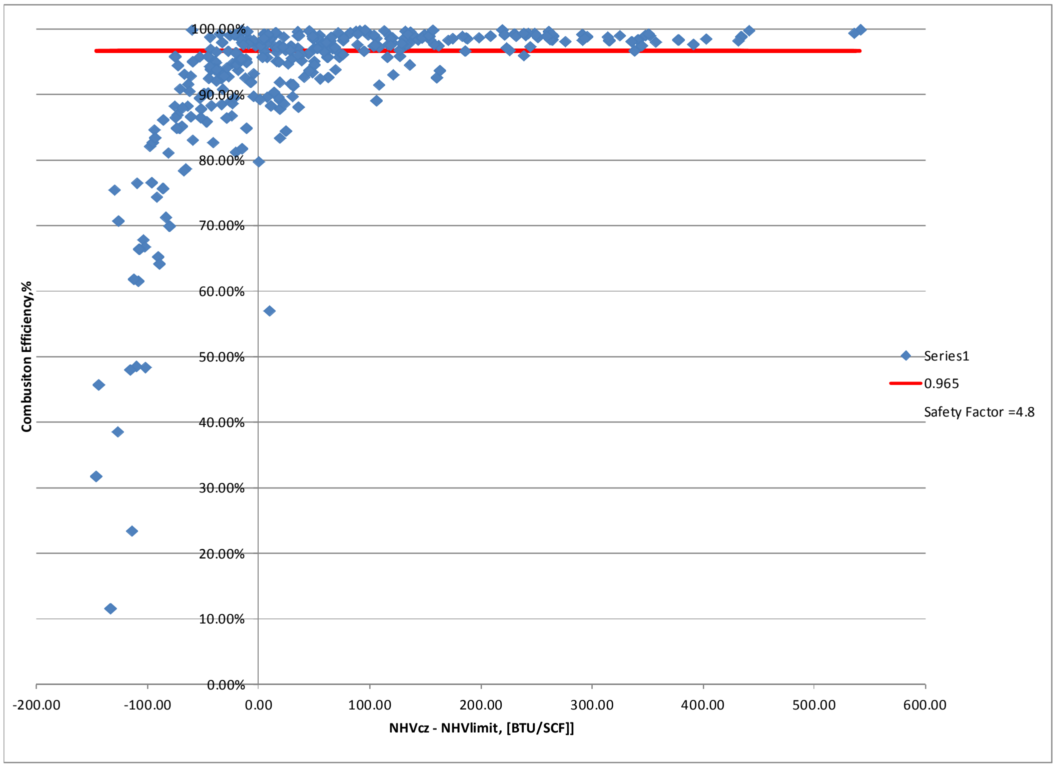


Figure 1. $NHV_{limiting}$ calculated as 4.8 times the NHV_{VG-LFL}

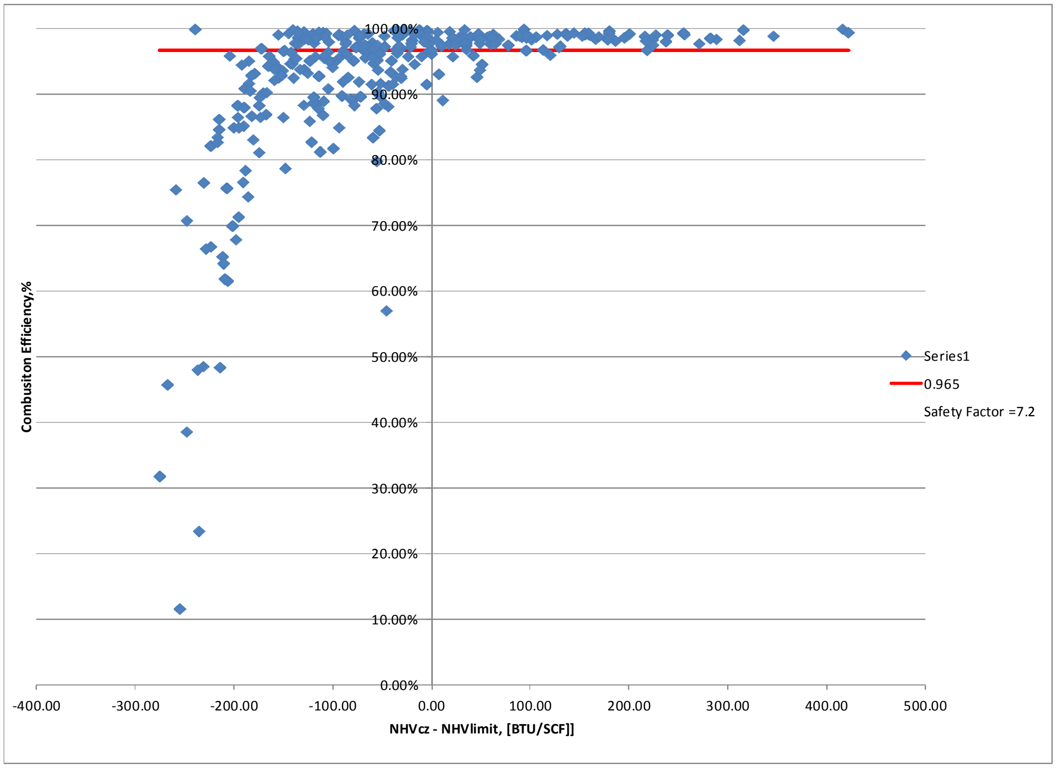


Figure 2. $NHV_{limiting}$ calculated as 7.2 times the NHV_{VG-LFL}

3. **Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?**

As stated in charge question 2 above, while there may be some slight inaccuracies involved with the calculation of the LFL_{CZ}, this reviewer believes this has little bearing on the 15.3% threshold proposed. The LFL_{CZ} can be used to determine when a flame will not be present, it has little value in determining the transition from a stable flame to the extinction of that flame. This would be governed by the turbulent mixing created at the flare tip. To the degree the data set used is representative of all flare tips and all atmospheric conditions encountered at these tips, the 15.3%threshold presented is representative. As stated in charge question 2 above, the selection of the 15.3% threshold would appear to be based upon minimizing the false positives (bad combustion when good combustion is predicted), at the expense of creating many false negatives (good combustion when poor combustion is predicted). This reviewer believes that both false negatives and false positive should be minimized, with the intent of minimizing the magnitude of the error in both false negatives and false positives. While it may be convenient to use these combustion zone composition data to correlate the performance data, there is no fundamental reason these parameters should correlate all the data. The ability to fit the data is only as good as the data used to develop the correlation, and is only representative of all flares to the extent the data set used is representative of all flares and all atmospheric conditions encountered. As such, there will always be exceptions to these empirical correlations, and the regulatory structure should acknowledge that in the absence of a fundamental dependence with the correlating parameter, a procedure to determine alternate compliance metrics should be allowed.

4. **Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to LFL_{VG-LFL}) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?**

The report did not specifically mention the Reduced Steam Volume Fraction (RSVF) introduced by Gogolek (Gogolek, 2010a), but in essence this parameter is but a rearrangement of the LFL_{CZ}. Just like LFL_{CZ}, the RSVF only predicts where a flame will be extinguished, and it too uses an empirical plot of available data in an attempt to predict where a high combustion efficiency will be insured (see Mueller, et al., 2011). What is lacking is a discussion of the impacts that turbulent mixing parameters can have on observed combustion efficiency (Smith, 2009). While use of Large Eddy Simulation (LES) is a developing science in regards to assessing combustion efficiencies for flares, which relies upon computational fluid dynamics that may not be warranted in many situations, some discussion of the variables that impacts the results of these LES analyses is warranted. Some discussion of the parameters that are important in the LES analysis of flare combustion efficiency, and whether the data set used for the correlations presented are felt to be representative of these turbulent mixing variables would go a long way toward addressing if the correlations being proposed are truly representative or merely an artifact of the data sets available.

Section 4: Air and Flare Performance

5. **Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning. Does the flare data adequately support the EPA's observations?**

In theory, if the LFL_{CZ} parameter were a fundamental correlating parameter for combustion efficiency, it should work equally as well with air as the inert (being as air is 80% nitrogen) as with steam as the inert. While this analysis was not conducted for the air-assisted data, the reviewer has attempted to use the TCEQ air assist data and plot it versus a modified RSVF as defined by Mueller (2011). This preliminary (unpublished analysis) indicated that combustion was seen to occur well past and RSVF of 1.0, which should be the theoretical flame extinction point. What this indicates to this reviewer is that the turbulent mixing of the air-assisted flare tested is considerably different than that of the steam assisted flares, with potentially much less penetration of the combustion zone gases by the assist air than is observed with steam in the steam-assisted flare tips. While the combustion efficiency data can be correlated to SR for the data set presented in this paper, there is little data or reason to believe that the small data set presented is necessarily representative of the entire universe of air-assisted flares. In fact, the two data sets presented in the paper are dramatically different (TCEQ and EPA-600/2-85-106).

Clearly, the calculated LFL_{VG} is appropriate for assessing whether the vent gas going to an air-assisted flare is capable of burning. What is not immediately obvious to this reviewer is what that value needs to be in order to insure a high combustion efficiency. This would be a function of the turbulent mixing achieved at the air-assist tip. While the paper correctly states that . . .", there is simply not enough air-assisted test data to determine whether a new LFL_{CZ} threshold would be warranted for air-assisted flares.", there also is not enough data to assess whether there is an appropriate value of LFL_{VG} that needs to be achieved to insure good combustion, as the turbulent mixing behaviors of the steam-assisted tips and the air-assisted tips are clearly different. While LFL_{CZ} or LFL_{VG} can be used to determine a composition that can burn, it is the turbulent mixing of the tip that will determine when the flame becomes unstable. The analysis presented in Section 4 is not technically rigorous, and the conclusions presented are not warranted by the data.

Section 5: Wind and Flare Performance

6. **Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities greater than 22 mph at the flare tip to indicate wake-dominated flame situations. Additionally, also comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance. Comment on the effectiveness of the observations identifying wake-dominated flames. Does the flare data adequately support the EPA's observations.**

While MFR has been shown to be a useful parameter is assessing the transition from one flare flow regime to another (inertia-dominated, buoyancy dominated, and wake-dominated), the ability of this parameter to be predictive of combustion efficiency has been mixed at best. While impacts of crosswinds have been demonstrated on small flares (1”-3”), it has also be demonstrated that the impact on combustion efficiency is less as the flare size gets larger (Gogolek, 2010a & 2010b). Further the data published in Figure 5-5 by Seebold et al. showing a strong correlation with MFR have been further researched by Evans et al. (2011), and virtually all the data points showing diminished combustion efficiency have been traced back to 1” flare studies, which do not necessarily scale to larger flares. In addition, MFR is a hydrodynamic parameter that fails to incorporate the buoyant energy released at the flare tip due to combustion of the gas. Gogolek’s Power Factor makes an attempt to incorporate the impact of this force on the flow regime. Note that for the Power Factor to be valid, combustion has to be occurring at the tip. Gogolek uses an RSVF of less than 0.8 to insure good combustion is occurring. While RSVF was not calculated in the data set presented, most of the full-scale test data points with combustion efficiency below 90% are likely at an RSVF of greater than 0.8 and thus would be excluded from Gogolek’s PF analysis. In summary, MFR has been successfully correlated with flare flow regime, but MFR’s ability to correlate combustion efficiency is size dependent, and has to this reviewer’s knowledge never been shown to correlate to a noticeable decrease in combustion efficiency in any flare larger than 6” in diameter. While full scale flare data have illustrated some instances of diminished combustion efficiency, it remains to be demonstrated that this was due to high crosswinds. As in virtually all the cases were a significant decrease in combustion efficiency was observed, significant combustion zone composition deficiencies were present. The technical case presented for a limiting MFR is not technically robust nor complete, and in this reviewer does not see that sufficient evidence has been presented to warrant establishing a minimum MFR at this time.

7. Did the agency adequately examine the other operating parameters (different from MFR) for identifying wake-dominated flames? Are there specific other parameters that should be given more or less emphasis?

While the Power Factor was examined, the analysis failed to recognize that test points conducted at an RSVF of greater than 0.8 are representative of points where inadequate combustion was occurring for the Power Factor to apply. Since RSVF was not calculated for the data set, it is impossible to say with certainty from the data presented. However, by analogy it is reasonable to assume that the bulk of the data points with combustion efficiencies below 90% were conducted at RSVFs above 0.8. Thus, for the full scale data, the only conclusion that can be drawn is that for the PFs calculated from the test data, no discernible negative impact on combustion efficiency was observed. While the IFC data (Gogolek, 2010b) illustrate the potential for some small combustion efficiency impacts at PFs in excess of 0.05-0.07 (note data in this paper appear to be using the uncorrected PF text, not the January 2012 corrected version of Gogolek, 2010b), the corrected PFs are a factor of 100 lower (e.g. scale in Figure 5-9 should be 0.0005 to 0.0055). None of the full scale tests were conducted at a wind speed where a significant impact on combustion efficiency would be expected. Also, Figure 14 from Gogolek, 2010b (corrected) is produced below. Please not the apparent dependence of flare tip size in these data. While no significant impact of wind was noted until wind speeds exceeded 22 mph, it is uncertain that any impact would be seen on commercial scale flares. Evans and Seebold (2012) have postulated that the negative pressure force that causes wake-stabilized flames is proportional to, v^2/r (velocity squared divided by flare radius), as such, the negative force leading to wake-stabilized conditions diminishes significantly as the size of the flare increases. While it remains to be shown, it plausible that the PF correlation shown in Figure 14 below continues to increase with increasing flare diameter, such that it is quite possible that no noticeable impact of ambient wind will be observed on large commercially available flares. Which is certainly was the current full-scale data have shown (Evans, 2011). The data presented do not demonstrate a compelling case that high ambient winds have any impact on the degradation of observed combustion efficiencies of commercially available steam- or air-assisted flare tips.

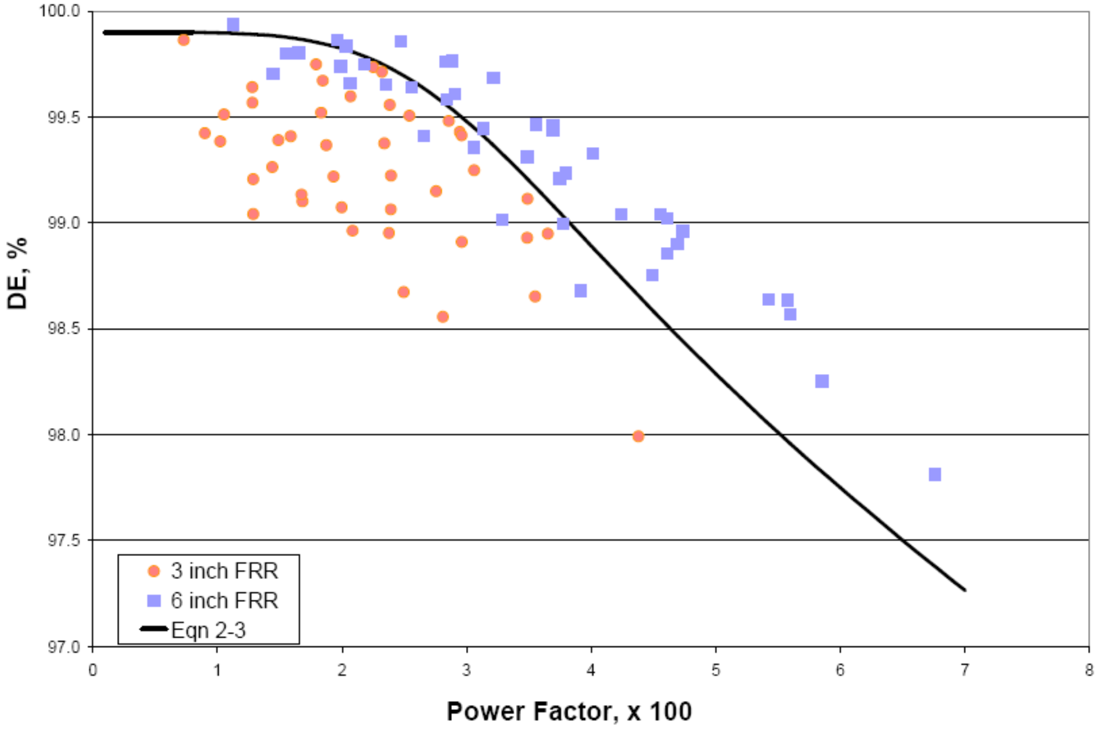


Figure 14 - **Destruction efficiency for 7.6 cm (3") and 15.2 cm (6") pipes fitted with FRR, plotted against the Power Factor. The solid line is the fit to the basic pipes 7.6 cm (3") and larger, equation (2-3).**

Section 6: Flare Flame Lift Off

8. **Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. Does the flare data adequately support the EPA's observations? Are there specific other parameters or methods/equations that should be given more or less emphasis?**

While the data presented in Section 6.0 are intellectually interesting, these data are really of little probative value in assessing whether Eq. 6-1 offers any advantages over the current V_{max} equation (e.g V_{max} as a function of vent gas NHV). It would be worthwhile to plot the 108 data points against the current V_{max} equation. I suspect a similar type of graph would be drawn, with most, if not all, data points below the controlling V_{max} equation. If such proves to be the case, there would seem to be little case for action for changing the existing V_{max} equation.

Section 7: Other Flare Type Designs to Consider

9. **Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity on non-assisted flares, pressure-assisted flares, and other flare designs.**

The LFL_{CZ} parameter clearly is not directly applicable to non-assisted flares, as the expression for LFL_{CZ} approaches LFL_{VG} as the assist gas goes to zero. While not technically rigorous, it would be intellectually pleasing if the limiting LFL_{CZ} or NHV_{CZ} approached that previously determined for non-assisted flares, as the amount of assist gas approached zero. To this reviewer's knowledge no new data on non-assisted flares has been generated, so the minimum NHV_{CZ} determined for zero assist gas should approach 200 BTU/SCF. Note that in charge question 2, this reviewer demonstrated that such is the case when the SF chosen for $NHV_{limiting}$ is selected as ~4.8 (e.g . $NHV_{limiting} = 4.8 * NHV_{VG-LFL}$). Note that this approach also tends to minimize not only false positives, but also false negatives, while minimizing the mean error. Since the current fit of LFL_{CZ} with combustion efficiency is but an empirically fit expression, and the turbulent mixing parameters of pressure-assisted flares are believed to be considerably different from that of steam-assisted and air-assisted flares, this reviewer would agree that it is unlikely that the correlation developed for steam- assisted flares nor air-assisted flares will apply to pressure-assisted flares.

This reviewer sees little value in implementing Eq. 6-1 for steam assisted flares, and therefore it is likely that this equation will not be applicable to non-assisted or pressure-assisted flares.

This reviewer does not see that a credible case has been presented for a minimum MFR to insure the combustion efficiency of commercial steam-assisted industrial flares, and lacking a clear case for flares were data exists, it seems unlikely that MFR is a meaningful parameter to assess the combustion efficiency of non-assisted or pressure-assisted flares either.

Section 8: Monitoring Considerations

10. **Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters: LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, the ratio of NHV_{CZ} to NHV_{VG-LFL}, C_{CZ}, SR, MFR, and V_{max}. Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.**

Clearly, the simplest and most straight forward monitoring to ensure good combustion is the presence of a stable and visible flame. While data on the composition of the vent gas and the combustion zone gas have been correlated to good flare performance in this data set, they speak to only the impact of composition on combustion and not the turbulent mixing that occurs at the flare tip. These impacts are only accounted for to the degree the existing data set is representative of the flares being monitored.

There is the potential to correlate many variables with observed combustion efficiency results. However, this does not mean that combustion efficiency is solely a function of the correlated variable. In that regard, the presence of a stable and visible flame integrates all of these variant factors, and many measured parameters can probably be correlated to the presence of a visible and stable flame, in addition to the parameters mentioned in Section 8.0. Part of assessing what monitoring is appropriate is matching the frequency of changes in key parameters to the frequency of monitoring these parameters. For cases where the vent gas composition does not change (e.g. a loading flare), sampling vent gas composition periodically is probably sufficient. When flow is associated with specific events, then tracking those events may be appropriate to assess flow and composition. In large complex flare systems with the potential for the addition of many streams, flow measurement and more frequent composition measurement may be indicated. The point is that flare performance can be correlated to multiple operational parameters that may be measured and recorded at existing facilities. For a given flare it is impossible to monitor and record all parameters that impact flare performance, but a viable operating envelope that insures a stable and visible flame can be developed using any number of measurable operating parameters. The parameters listed in Section 8.0 are clearly potential parameters, but are by no means inclusive of all parameters that can be used to correlate good flare performance.

References

Evans, S. (2011). Insights from Passive FTIR Flare Performance Testing. *NPRA Environmental Conference.* New Orleans: National Petrochemical and Refiners Association.

Evans, S., & Seebold, J. (2012). Real Industrial Flares in the Field: No Evidence of Wind Induced Combustion Efficiency Degradation. *IFRF 17th International Members Conference Proceedings.* International Flame Research Foundation.

Gogolek, P., A. Caverly, R. Schwartz, J. Seebold, and J. Pohl. (2010a). Emissions from elevated flares – a survey of the literature. Prepared for the International Flaring Consortium, CanmetENERGY (April).

Gogolek, P., A. Caverly, R. Schwartz, J. Seebold, and J. Pohl. (2010b). Flae Test Facility – Results. Prepared for the International Flaring Consortium, CanmetENERGY (October), Amended January 2012.

Mueller, G. (2011). Combustion of mixtures: a modified IFC approach. American Flame Research Committee, Combustion Symposium, Sept. 18-21, 2011, Houston, TX.

Smith, P & Thornock, J. "LES Simulations of Sour Gas Flares in Western Canada" presented at June 1, 2009 American Flame Research Committee Meeting.

Attachment D

Lucy Randel

Research Director

Industry Professionals for Clean Air, Houston, TX

MEMORANDUM

TO: Research Triangle Institute for U.S. Environmental Protection Agency

FROM: Lucy Randel

DATE: May 21, 2012

SUBJECT: Review of the *Parameters for Properly Designed and Operated Flares*

Following are my comments in response to the charge questions for review of ***Parameters for Properly Designed and Operated Flares.*** Overall, the paper is well documented and uses the most current flare test data. For the most part, the conclusions appear well supported. My detailed comments are provided below.

Section 2: Available Flare Test Data

1. Please comment on the agency's criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have lead to inappropriate exclusions of relevant data points.

Response:

For several studies or runs within studies, very limited data were available, making it impossible to determine parameters of interest at all or with any reasonable level of confidence. These were appropriately excluded.

Also, exclusion of data where errors or significant uncertainty were noted in the original report is justified.

An entire run from SDP EPF was removed because of problems with GE panametric flow readings. Flows were adjusted using alternate data and then used in original SDP report. Data excluded appear consistent with conclusions of this report. Their inclusion could provide additional support of the observed data trend, but also subject the conclusions to criticism of data quality. Excluding these data points does not appear to change conclusions reached, however.

Use of average values with statistical range is an appropriate representation of the data. The confidence intervals of the average give an indication of variability within test conditions.

Section 3: Steam and Flare Performance

Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?

Response:

EPA conducted a thorough analysis of multiple data sets and the relevant literature in identifying LFL_{CZ} *as an operating parameter for indicating over steaming situations. While the empirical flare data are used to establish the basic correlations, the parameter can be applied to mixtures of different composition by using published data for the LFL of individual components. This factor can be calculated from vent gas composition and flow rates of vent gas and steam. An advantage of this parameter is that the literature referenced provides equivalencies that can be incorporated for different diluents of nitrogen, steam and carbon dioxide.*

In the data analysis, Figures 3-3 and 3-4 both show a much greater level of certainty of good combustion at an LFL_{CZ} *of 10.0%. EPA had plausible explanations for several of the outlying points between 10.0% and 15.3%* LFL_{CZ}*. Nonetheless, as the complexity of the flare gas mixture increases, the uncertainty in the value of the calculated* LFL_{CZ} *can be expected to increase. In addition, in actual flaring circumstances, vent gas compositions will not be constant and lag times in steam adjustment can occur resulting in variable* LFL_{CZ} *. For these reasons, EPA would need to consider various options for time-averaging of parameters and may want to consider adding a factor of safety to parameters used to define acceptable combustion conditions.*

The flare test data should be correlated to actual operating conditions to see if the more stringent value can be met while still meeting flare manufacturer's operating guidelines. Further the ability to meet this level could be related to the flare design, with more recent designs better able to achieve good combustion with less assist gas. Further, flare operation at low flows and high turn-down ratios, such as for routine venting, is more likely to be operating in the wake-stabilized region and thus more susceptible to wind effects. Under such circumstances a more conservative value for LFL_{CZ} *may be warranted.*

Sine the results are fairly similar, the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) *to the net heating value of the flare vent gas if diluted to the lower flammability limit* (NHV_{LFL}) *appears viable as an alternative to* LFL_{CZ} *if the agency found it to be a much more practical monitoring parameter that would reduce monitoring costs. However, the speciation of the mixture is likely to be one of the larger costs and that would be required in both cases.*

2. Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?

Response:

The report gives examples from Azatayan et al. on potential reactions that could inhibit combustion and describes the differences with the outlier results in the flare data (page 3-19). Based on this discussion, it does not appear the magnitude of any competing reactions is sufficient to invalidate the 15.3% LFL_{CZ} *threshold discussed. One would expect that reactions are occurring which enhance as well as inhibit combustion and that these are both incorporated into the empirical results.*

Zhao (2008) conducted upper and lower flammability limit measurements for binary hydrocarbon mixtures in addition to estimating the flammability limits through CFT-V (calculated flame temperature at constant volume) modeling prediction. Measurements were conducted on mixtures of methane and n-butane, methane and ethylene, ethylene and propylene, and ethylene and acetylene. The model has potential application for flare gas mixtures with components whose LFL values are not available.

3. Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to $LFL_{VG\text{-}LFL}$) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?

Response:

The discussion of other parameters explains their limitations and how their use could require stricter requirements than necessary. On pages 3-33 to 3-34 comparing the similar heats of combustion with the widely different flammability limits of ethylene and ethanol area illustrates well why NHV_{CZ} *would not be a good operating parameter. The* LFL_{CZ} *appears more robust in being applicable to variations in flare design and other parameters such as steam to flare gas ratios between the different studies.*

Section 4: Air and Flare Performance

4. Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning? Does the flare data adequately support the EPA's observations?

Response:

The amount of data available to evaluate air-assisted flares was much less than for steam-assisted flares. However, the 2010 TCEQ data was conducted with multiple analysis techniques and repetition of runs with excellent agreement. The TCEQ 2010 data clearly illustrate that excess air impedes combustion; only nine of 44 runs achieved greater than 96.5% combustion. The TCEQ data also show, that for the very high turn-down ratios studied, a very narrow range exists where an adequate DRE is achieved without exceeding the smoking limitation. (TCEQ, 2011, pg. 92, 94). Also, the data for propylene and propane differed somewhat in that the smoking observed with propylene requiring a higher SR to prevent smoking and thereby limiting the SR that would achieve acceptable combustion to only the runs with SR near 7.

Since all the TCEQ air runs were conducted with the same design and their correspondence to earlier EPA studies was limited, it is not clear if the same value of SR would be appropriate to other flare designs and other gas mixtures.

Because the change from smoking conditions to poor combustion is very narrow, accurate monitoring of low flow air flares becomes critical in minimizing emissions. An alternate monitoring parameter for air flares could be optical monitoring of the flame combined with recording data on air flow rates so that the stoichiometric ratio could be determined and compared to the flame monitoring data.

The detailed discussions of LFL related to steam-assisted flares can be considered in the context of air-assisted flares. Calculation of LFL for the mixture would follow the same principles. The main difference, as discussed by EPA, is that air in the combustion zone is augmented by ambient air making it difficult to get a useful value for LFL in the combustion zone. That said, if the lower flammability limit of the flare vent gas (LFL_{VG}) is such that unassisted vent gas will not burn, addition of air will not make it combustible. Nonetheless, if significant air-assist is required to prevent smoking, as with the TCEQ propylene runs, the LFL_{VG} may not provide much information related to actual flare performance.

Section 5: Wind and Flare Performance

5. Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities greater than 22 mph at the flare tip to indicate wake-dominated

flame situations. Additionally, also comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance. Comment on the effectiveness of observations identifying wake-dominated flames. Does the flare data adequately support the EPA's observations?

Response:

In EPA's analysis of flare test data in this report in section 5.4, the MFR does not appear to be a controlling variable. Efficiencies appear determined by the LFL_{CZ}*. On page 5-15, the report states "it is reasonable to conclude that the momentum flux ratio (MFR) should be 3 or greater in crosswinds that are greater than 22 miles per hour (mph) at the flare tip." This seems to be a reasonable hypothesis, but without data above 22 mph and MFR of 3, it is not a well-supported conclusion.*

While the cumulative data provide evidence that high winds can affect flare performance, the data do not appear sufficient to use MFR as an operating parameter at this time. However, collection of data to calculate MFR coupled with visual observations and other monitoring parameters could provide useful information.

The studies on momentum flux ratios that show a strong correlation between wind speed and combustion efficiency of a flare are referenced from the University of Alberta and the models of Cassimere and Edgar (2006 and 2008)(Johnson and Kostiuk, 2000. They are based on data from 1 inch and 0.5 inch simple pipe flares. Gogolek et al investigated larger diameter pipe flares as well as flares with flare retention rings and found combustion efficiency was not directly correlated with MFR, but more closely related to a power factor.

The amount of data available do not provide any definitive result with respect to crosswind effects because most of the runs were conducted in what was most probably the wake dominated region.

6. Did the agency adequately examine other operating parameters (different from MFR) for identifying wake-dominated flames? Are there specific other parameters that should be given more or less emphasis?

Response:

It may be useful to request monitoring data from facilities that will include calculation of MFR and LFL, combined with visual or optical monitoring of flares that can be used to identify whether it is wake or jet dominated.

EPA notes "there are two main concerns with relying on observations: (1) that some flames may simply be too difficult to see, and (2) it may be difficult to recognize when a flame is wake-dominated."(pg 5-15). Various optical monitors can be used to provide a thermal as well as visual picture of the flame. Examples are discussed under question 10.

Data could be reviewed on a schedule of every few hours, to be increased in winds over 20 mph or in upset conditions when more frequent monitoring could inform operators trying to maintain stable, smokeless flame.

Infrared cameras were used in the 2010 TCEQ study to define the flame and thereby accurately aim the PFTIR detectors and position the sampling probe.

Section 6: Flare Flame Lift Off

7. Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. Does the flare data adequately support the EPA's observations? Are there specific other parameters or methods/equations that should be given more or less emphasis?

Response:

The maximum flare tip velocity equation developed by Shore uses the lower flammability limit parameter, which is reasonably accessible if the mixture composition is known. In Shore's development of this equation, he found a good fit for a variety of vent gas compositions including the presence of hydrogen sulfide, hydrogen and nitrogen. The flare test data presented by EPA in Figure 6-1 also fit this correlation fairly well.

As noted by EPA, "all of the recent flare test data were collected during high turndown rations" and do not validate the equation at higher flare tip velocities.

As discussed in section 6.3, other proposed equations for determining exit velocities would be difficult to apply to complex mixtures in flare gases because the parameters are not easily obtained.

Section 7: Other Flare Type Designs to Consider

8. Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity to non-assisted flares, pressure-assisted flares, and other flare designs.

Response:

It appears that EPA's analysis of non-assisted flares adequately addresses the applicable parameters that affect combustion. The one exception would be for non-assisted, hydrogen-fueled flares with greater than 8% hydrogen content, which currently are subject to different requirements under 40 CFR 60.18 and were not specifically studied in this white paper.

EPA's conclusion that the observations made in this report for non-assisted, steam-assisted and air-assisted flares cannot be directly applied to pressure-assisted or other flare designs, based on currently available data, appears justified. The LFL_{CZ} *addresses the combustibility of the flame, however, which is important in any flare. Since the value of the* LFL_{CZ} *parameter that achieves good combustion may very well be different, additional data specific to those designs would be needed before using this parameter to evaluate ideal operating conditions. Pressure-assisted flares with high exit velocities are more likely to operate in the jetting regime, suggesting wind effects could be expected to have less impact on performance.*

Pressure assisted flares are designed to operate at much higher exit velocities than the flares studied in this report; hence the maximum allowable flare tip velocity equation is unlikely to be applicable.

Enclosed ground flares have very different designs that operate with lower vent gas heating values and isolation from wind effects. The parameters reviewed in this study are not likely to apply.

Section 8: Monitoring Considerations

9. Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters: LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, the ratio of NHV_{CZ} to $NHV_{VG\text{-}LFL}$, C_{CZ}, SR, MFR, and V_{max}. Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.

Response:

Several methods exist for monitoring flare performance with several described in the 2003 presentation, "Flare System Emission Controls" by Zeeco Company presented at the Texas Technology Conference and referenced in the white paper:

"Steam Control Methods
- Flare Gas Measurement and Ratio Control
- Optical Analysis of Flare Flame with Output Steam Controller
- Manual Adjustment of Steam Flow for Smokeless Flame
- Radiant Temperature Measurement for Steam Control

Flare Gas Flow Measurement Options
- Ultrasonic Insertion Type
- Thermal Mass Flow Insertion Type
- Orifice Plate
- V-cone orifice plate
- Annubar Device

- Vortex Meter
- Turbine Meter”

In California, the BAAQMD Regulation 12, Rule 11 requires continuous flow monitoring of vent gas and composition monitoring either continuously or by sampling. The manufacturer SICK is just one company that offers ultrasonic flow meters that meet the BAAQMD requirements:

SICK Volume Flow Monitors FLOWSIC100 Flare Ultrasonic flow meter

https://www.mysick.com/eCat.aspx?go=FinderSearch&Cat=Row&At=Fa&Cult=English&FamilyID=339&Category=Produktfinder&Selections=35223

A product brochure is attached. (accessed May 21, 2012)

Optical flame monitors that monitor flare gas and link into control systems to maintain optimum steam composition are also readily available. Using such monitors eliminates the manual steam adjustment, which so often results in oversteaming in an attempt to eliminate smoking. Effective use of these monitors could potentially greatly reduce emissions from large upset and maintenance flare events. At large flow rates, just reducing efficiency from 99 % to 98% would double the already large emissions. Operators manually adjusting steam are much more likely to err on the side of more steam than less. Two examples that use infrared technology are listed below. (Websites were accessed May 21, 2012):

Powertrol SLX-302 Flare Monitor analyzes the flame with infrared technology and controls steam flow based on a set point.

http://www.powertrol.com/flaremon.htm

Williamson Smokeless Flare Stack also uses infrared technology.

http://www.williamsonir.com/content10646

Hamworthy Combustion Flarscan Automatic Steam - Control System for Smokeless Flaring uses radiant temperature measurement.
http://www.hamworthy-combustion.com/products/flares-thermal-oxidation-gas-cleaning-systems-6/flarscan-automatic-steam-control-system-for-smokeless-flaring-18.aspx

Episodic Emissions

Emergency releases with high LHV content and flow rates were not typical of the flare data referenced in this report, but that does not mean the findings are not relevant to these conditions. These episodic emissions release large quantities of VOCs and

HRVOCs, even under ideal combustion conditions. They also have been correlated with high ozone events in Texas. (Murphy and Allen, 2004) However, current operating practice often includes manual adjustment of steam flow rate to eliminate smoking. Excess steam was clearly shown in this study to reduce DRE. At high flow rates even small reductions in efficiency mean large increases in emissions. Education of operators with respect to best operating practices is important, but improved monitoring and automatic controls such as those described above would be much more reliable and should be required in most circumstances.

Flare Gas Recovery

Scenarios where flare gas recovery systems are used to eliminate routine flows to flares and minimize upset releases may not require continuous flow monitoring. However, provisions for controlling steam other than manually based on visual observations should be employed. Optical flame monitoring would still be important to identify flame properties that cannot be seen visually, especially when steam is used.

Appendix D: Calculations

Errata on page D-11, equation D-14

The equation listed is calculating a mass flow rate, not a molar flow rate. The correct equation, which was used in the spreadsheet calculations, substitutes Qj1 and Qj2 respectively for mj1 and mj2

Where
Qj1 =volumetric flow rate of component 1 (i.e., propylene flow or nitrogen flow)), scf/hr
and
Qj2 =volumetric flow rate of component 2 (i.e., propylene flow or nitrogen flow)), scf/hr

References

Murphy, Cynthia Folsom and David T. Allen. "Event Emissions in the Houston Galveston Area" (HGA), January 14, 2004, p. A-31, http://files.harc.edu/Projects/AirQuality/Projects/H013.2003/H13AppendixA.pdf, accessed June 19 2011.

Zhao, Fuman "Experimental Measurements and Modeling Prediction of Flammability Limits of Binary Hydrocarbon Mixtures" May 2008 http://repository.tamu.edu/bitstream/handle/1969.1/ETD-TAMU-2688/ZHAO-THESIS.pdf, accessed May 16, 2012.

Attachment E

Dr. Ranajit Sahu

Independent Consultant

Comments by Reviewer Dr. Ranajit (Ron) Sahu on EPA's Draft Report entitled "*Parameters for Properly Designed and Operated Flares*"

May 20, 2012

Please see EPA's charge questions in bold followed by my numbered comments in italics. Please note that comments sometime do and sometimes do not explicitly address the charge questions but are considered to be relevant nonetheless, given the context of the discussion. Also, although not specifically requested, comments are provided for Section 1 also.

Comments on Section 1 Introduction

1. The purpose of the report in so far how EPA intends to use it is not discussed clearly. For example, is it EPA's intent that the report will be used as a basis for the ultimate revision of 40 CRF 60.18/40 CFR 63.11(b)? Is it intended to identify data gaps in testing that will help refine the technical analysis further? Is it both? EPA should provide a clear discussion of purpose. Specifically, the report, later in Section 3.4.1, clearly states the shortcomings of using net heating value of the vent gas as a criterion in assuring that destruction efficiencies of flares remain high – directly undercutting the basis of 40 CFR 60.18 etc. While this is technically valid, it begs the question of what EPA intends to do with 40 CFR 60.18 as a result.

2. This section notes that flares are used as "control" devices in many applications. While that may be true in practice, a broader contextual discussion of why that may be inappropriate, without first satisfying the requirements of what a proper VOC or SO2 control device should be, is in order. The fact that elevated stack flares, which are the subject of discussion in the report, cannot guarantee a specified residence time at temperatures necessary for specific hydrocarbon destruction should be noted. How this shortcoming can/may be overcome in design and operation, coupled with monitoring, can then be logically explored.

3. This section notes, without data support, that "industry has significantly reduced the amount of waste gas being routed to flares…." EPA should provide data support for this assertion. Does this cover *both routine and non-routine flaring? Is it true of all industrial flares or just those at refineries? Is it true in all parts of the country? Also, as a follow-up the report should discuss the implications of this statement – in terms of the shift in the operating point (i.e., low turn-down ratio) of flares in routine flaring mode, as compared to design, and how that may affect destruction efficiencies.*

4. EPA should avoid (ideally) or carefully caveat all assumptions made in the report. Specific examples will be discussed later. Words or phrases like "assume", "could", "seems likely" etc. should be carefully considered. Ideally, the report should not stray into assertions that have no data support.

5. In every section, as appropriate, EPA should identify data gaps such as need for additional tests, etc. that can be used to test the various hypotheses that are put forth in this report.

6. As a general matter, before using each of the data sets, such as in Sections 3 and 4, EPA should first conduct a proper data validation/data usability analysis. As it stands, EPA seems to assume that all of the data (except those excluded via Section 2 discussions) are valid. Only after portions of the data set don't seem to confirm to a specific hypothesis, EPA embarks on a discussion of the "anomalous" data and their quality. This is backwards. All validation/usability should be conducted first and decisions on acceptability/flagging/rejection should be made up front. Thereafter, all of the valid and useable data should be used in the analysis. That way, any "anomalies" can be discussed in the context of the hypothesis being tested (i.e., whether or not a particular parameter or metric best predicts combustion efficiency etc.).

Section 2: Available Flare Test Data

Please comment on the agency's criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have lead to inappropriate exclusions of relevant data points.

7. First, a fundamental comment on this section and Table 2-1. EPA notes that this section identifies the data and reports "…that were used to support our investigation…" However, it is clear from Table 2-1 that there are no reports or data sets listed between September 1985 and May 2010 – a period of around 15 years. Is it EPA's position that there are no relevant data sets available, from researchers or from operating flares, in this entire time period? If so, EPA *should explicitly state so and justify. If not, EPA should expand this table and include additional available data sets or provide a discussion of why they could not use such data. Regardless, EPA should broadly discuss its data gathering approach (was data limited to just US or did EPA look globally? for example, etc.) and help the reader understand how it arrived at the list of reports in Table 2-1. As it stands, the selection of the starting data set and reports, without this contextual and supporting discussion, seems arbitrary.*

8. Exclusion of data sets B and I appears to be proper.

9. However, as noted in the general comments above, this exclusion or rejection should be done as part of a broader data validation/data usability exercise for each data point that would consider the data point in detail. As this stage, EPA seems to be excluding data sets/points that have obvious flaws (such as missing parameters, non-representative flare type etc.). The implication is that data not excluded at this stage are all valid and useable. But, in later discussions, EPA states that certain non-excluded data points could still be problematic. For example, in Section 3.1.3.1, EPA notes that certain data runs may be invalid because "…wind came from a certain direction steam may have interfered with the pilot due to a "shaping steam ring failure.." during these runs. In Section 3.1.4.1, EPA speculatively discusses the extent to which steam may have partially mixed or not in certain runs. In Section 3.1.4.2, EPA states that "…there could be issues with the testing of the combustion efficiencies for these runs. Information was not available to judge the accuracy for the FHR test runs. The SDP EPF test report cited the possibility of inaccurately high combustion efficiency measurements during times of unstable combustion conditions. However, the test runs were not identified in the report where this may have occurred." In Section 4.4, EPA rejected all data from EPA-600/2-85-106 and retained only the TCEQ data. All of these examples raise issues with non-excluded data from Section 2. While the deficiencies EPA points out may or may not be true, such "opportunistic" exclusions/aspersions of data, raised later, simply because certain data do not fit certain hypotheses, is properly avoided, by completing a more thorough validation/usability analysis up front in this section. Otherwise, the integrity of the conclusions is questionable.

10. EPA should consider including one or two additional technical appendices describing AFTIR and PFTIR, and additional techniques (DIAL?) that have been used to collect data remote flare *data. Specifically, the actual form of implementation of these techniques that was used, and limitations, should be discussed.*

11. Combustion Efficiency, Destruction Efficiency, and "Good" Performance Level.

Section 2.8 touches on these extremely critical foundational issues, which affect the entire report.

(i) First, the report should clearly define combustion efficiency (CE) and destruction efficiency (DE). In particular, this reviewer does not believe that the definition of destruction efficiency implicitly assumed in the report is correct. This is a fundamental problem that affects ALL subsequent analyses because most of the report assumes a fixed relationship between DE and CE, namely that a CE of 96.5% is enough to assure a DE of 98%.

(ii) The report should note that DE depends on each compound – in other words, DE = 1- (mass out/mass in), and that this is calculated on a per species basis in the flare. Other DE definitions for hydrocarbons are not relevant. For sulfur compounds, the term conversion efficiency, denoting the oxidation of sulfur compounds in the vent gas, to SO2 may be more appropriate.

(iii) The report should discuss the role of products of incomplete combustion (PIC) – i.e., hydrocarbons that are invariable created, even in well controlled combustion conditions, and certainly so in flares, in the definition of DE. Consider an example, of a simple natural gas diffusion flame. It is well known that, in addition to the expected CO2, water vapor, CO, etc., we also measure benzene, formaldehyde, and numerous other PICs in the post-flame region. Even if the CE in such a flame is very high, denoting a high conversion of the carbon molecules to CO2, how does one define destruction efficiency for benzene in this instance? Since no benzene was input into the flame, DE in this case for benzene, is actually negative, denoting benzene creation. Thus, as this simple example illustrates, there cannot be any basis for simply assuming that CE is always lower than DE and that DE is at least 1.5% more than CE.

(iv) This reviewer does not believe that the report does an adequate or even passable job of assuming that "…Baukal's estimation of 1.5% difference is a reasonable assumption…," referring to the difference between combustion and destruction efficiencies. A careful review of Baukal shows that Baukal does not justify the underlying statement that "…a flare operating with a combustion efficiency of 98 percent can achieve a destruction efficiency in excess of 99.5 percent." Baukal does not provide any citations or studies to support this. And, Baukal's definition of DE, neglecting formation of PICs, is

simply inadequate in this instance. Given the criticality of this assumption for all of the conclusions of the report, there needs to be significantly more discussion on this point.

(v) Finally, on an important policy note, the report should refrain from equating 98% DE with "good" performance of a flare, simply because current regulations, that are known to be flawed, assume this.

Section 3: Steam and Flare Performance

Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?

Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?

Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to $LFL_{VG\text{-}LFL}$) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?

12. Please see comments provided under Sections 1 and 2 that address fundamental issues affecting the analysis and conclusions of this section. The analysis of the data presented and the conclusions reached cannot be properly judged without a resolution of the basic issues raised in comments previously provided for Sections 1 and 2.

13. With regards to the used of LFL, there is a fundamental issue that the report does not address. Without stating so, the report seems to assume that LFL (whether in air, or oxygen, and *even more so in the presence of inerts), even for a pure compound, is a fundamental property of the substance. It is not. It is well known that the LFL for a pure compound, say, even methane, in air, is: (i) a function of the underlying test, typically and ASTM (or similar) test involving a specific apparatus such as a specified tube of specified diameter and made of a specified material, etc.; (ii) a function of temperature; and (iii), less importantly, a function of pressure. In fact, it is well known, in safety design, for example, that one cannot simply design for safety by assuming that mixtures below their LFL are safe. Usually significant safety factors, such as assuming that mixtures have to have concentrations one quarter of the LFL or lower etc. are used, precisely because it is understood that LFL values tabulated in standard references cannot be assumed to hold in specific combustion situations that bear little or no resemblance to the standard ASTM (or similar) test conditions under which LFL values are measured.*

Based on the above, the report should first discuss why even a pure component LFL, tabulated elsewhere, should be relevant or how it should be adjusted for typical flare tip conditions. Then, having established that, the further use of the LFL_{CZ} *in the manner used in the report would make more technical sense.*

14. With regard to the question posed, namely whether the data supports the use of LFL_{CZ} *as a proper parameter for denoting good flare combustion conditions, answering this question is premature given data quality and other issues raised previously. Certainly the conclusion that 15.3%* LFL_{CZ} *is a proper value for demarcating good versus not good operation is premature.*

15. Throughput this section, the report discusses steam injection but does not discuss steam tests. This reviewer expects that the incremental enthalpy added via steam made be a fundamental factor affecting combustion conditions in steam-assisted flares. EPA should at least request that stream quality or conditions be properly noted in any future testing.

Section 4: Air and Flare Performance

Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning? Does the flare data adequately support the EPA's observations?

16. Please see comments provided under Sections 1 and 2 that address fundamental issues affecting the analysis and conclusions of this section. The analysis of the data presented and the conclusions reached cannot be properly judged without a resolution of the basic issues raised in comments previously provided for Sections 1 and 2.

17. Please also see comments discussion the fundamental issues with regards to use of LFL.

18. While SR and LFL_{VG} may be proper parameters for use in describing air-assisted flares, the specific technical discussion and the identification of specific demarcation values of SR discussed in this section are premature until issues discussed above are first addressed.

Section 5: Wind and Flare Performance

Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities greater than 22 mph at the flare tip to indicate wake-dominated flame situations. Additionally, also comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance. Comment on the effectiveness of observations identifying wake-dominated flames. Does the flare data adequately support the EPA's observations?

Did the agency adequately examine other operating parameters (different from MFR) for identifying wake-dominated flames? Are there specific other parameters that should be given more or less emphasis?

19. EPA should explicitly stress in this Section (as it does note in later Section 8.5) that all wind speeds have to be measured or estimated at the flare tip.

20. It is unclear how EPA has weighed the findings from Johnston et al (2001). As EPA notes, "…Johnston et al. (2001) provide a sketch of the unburned hydrocarbons detected downwind in a wake-dominated flare with a crosswind velocity of 8 meters/second (m/s) or about 18 mph (Figure 5-3)." EPA should explain how this 18 mph value was factored into its conclusions regarding 22 mph being an appropriate threshold for wind effects.

21. A major uncertainty in this analysis is the issue of scaling (i.e., at what size of test flares – 2", 3", 6", etc. can the results be scaled to actual operating flares that are considerably larger? EPA notes significant uncertainty in this regard. In Section 5.3, EPA notes that "…Gogolek et al. (2010b) states that results of pipes smaller than 3 inch do not scale-up to larger pipes; and it has not been determined whether results for 3 inch to 6 inch pipes can successfully be applied to full-scale industrial flares." This reviewer believes that resolution of this scaling issue is critical before further conclusions can be properly drawn regarding wind-effects. EPA should note this as a critical data gap.

22. Finally, as noted earlier, all conclusions regarding the proper cut-off for MFR for wind effects are premature until fundamental issues relating to combustion and destruction efficiency discussed earlier are resolved.

Section 6: Flare Flame Lift Off

Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. Does the flare data adequately support the EPA's observations? Are there specific other parameters or methods/equations that should be given more or less emphasis?

23. While the analysis is generally sound, EPA's caveat that "…this analysis does not test Equation 6-1 over a very large range of possible flare tip velocities…." is important. It is also noted that the effects of other variables such as cross-wind, etc. on Eq. 6-1 is not clear.

Section 7: Other Flare Type Designs to Consider

Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity to non-assisted flares, pressure-assisted flares, and other flare designs.

24. EPA should not venture into speculation. Having stated that "[W]e are unable to verify whether any of the analyses presented in this technical report could apply to non-assisted flares because there are minimal test data available for non-assisted flares…." EPA has no basis to then suggest that "[I]t seems reasonable to assume that the LFL_{CZ} *analysis in Section 3.0 of this report could apply to a non-assisted flare." Rather EPA should properly identify the underlying lack of data as a data gap.*

Section 8: Monitoring Considerations

Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters: LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, the ratio of NHV_{CZ} to $NHV_{VG\text{-}LFL}$, C_{CZ}, SR, MFR, and V_{max}. Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.

25. Please see prior comments on the use of LFL and therefore how that might affect the calculations of LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, *etc.*

Attachment F

Christopher Schaeffer

President and General Manager

Control Instruments Corporation

Review of *The Parameters for Properly Designed and Operated Flares*

Answers to Charge Questions 2-5 and 10

By Christopher Schaeffer

Section 3: Steam and Flare Performance

Question 2

"Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?"

"To identify over steaming situations that may occur on steam-assisted flares, the data suggest that the lower flammability limit of combustion zone gas (LFL_{CZ}) is the most appropriate operating parameter. Specifically, the data suggest that, in order to maintain good combustion efficiency, the LFL_{CZ} must be 15.3 percent by volume or less for a steam-assisted flare. As an alternative to LFL_{CZ}, the data suggest that the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit ($NHV_{VG\text{-}LFL}$) must be greater than 6.54."

Answer 2

The operating parameter is a threshold value separating good combustion efficiency (CE) from bad. The ideal operating parameter would ensure the desired CE without the unnecessary addition of fuel gas, but the data does not point to an ideal parameter. Each of the operating parameters has some false indications.

The most appropriate operating parameter must minimize false indications, especially "false positives" in which the operating parameter indicates good combustion efficiency (CE) when the actual CE is insufficient to ensure good destruction efficiency (DE).

The most appropriate operating parameter should be readily measureable to an accuracy that allows its effective use.

As a means to evaluate operating parameters, an analysis of the data (Appendix D) can be made that classifies the outcomes as "positive," "negative," "false positive" or "false negative."

Positive	The operating parameter exceeds the threshold and the CE is above the required level. The operating parameter successfully indicates good CE.
Negative	The operating parameter does not exceed the threshold and the CE is below the required level. The operating parameter successfully indicates insufficient CE.

False positive	The operating parameter exceeds the threshold and the CE is below the required level. The operating parameter fails to indicate insufficient CE. This is the outcome to be most avoided.
False negative	The operating parameter does not exceed the threshold and yet the CE is above the required level. The operating parameter fails to indicate good CE. This outcome causes unnecessary use of added fuel.

Comments for some of the operating parameters that were considered:

NHVvg

The net heating value of the vent gases does not account for the effect of added steam on CE. The data shows that for steam-assisted flares it is a poor predictor of CE and should not be used. Even at high thresholds this method produces an unacceptable percentage of false positive outcomes.

Ccz > 0.32

This parameter can be a good predictor of CE, can be measureable, but can require a significant amount of added fuel compared to other parameters. There are very few false positive results, even when the threshold is lowered to Ccz > 0.28 (only two false positive "near misses"), or even Ccz > 0.26 (nine false positives).

NHVcz

The net heating value in the combustion zone accounts for much, but not all, of the effect of added steam on CE. It has the advantage of being readily measured with sufficient accuracy. The quantity of false positive and results false negative results are comparable to the LFLcz parameter.

LFLcz = 15.3 percent by volume and
The ratio NHVcz/NHVvg-lfl = 6.54

These equivalent parameters are good indicators of CE. They most fully account for the effects of different combustible gases and added inert gases, especially steam. But they can be difficult to measure, and depend on flammability values that can have significant variations in published values.

Examination of the false results for NHVcz and LFLcz show they have many in common, and among them are the suspect data, for example the MPC Detroit 4-1, 4-2, 5-1, 5-2, etc.

Given the wide variety of flare designs and operating conditions, it may be useful to determine more than one appropriate operating parameter. There are cases where the otherwise most useful operating parameter cannot be measured effectively or quickly enough to allow proper control.

Question 3

> "Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?"

Answer 3

One concern for any parameter, including LFLcz, is how well operating parameter will apply to other combustible gases and conditions not found in the data.

For example, the combustion properties of ammonia might require special consideration. The narrow flammable range, high LFL in air, and low heating value might produce false results for a threshold value developed for hydrocarbons.

A second concern for the accuracy of the calculated LFLcz is error arising from differences in published values of the Lower Flammable Limit in air. The LFL in air is an experimentally determined value. The LFLcz threshold is directly proportional to the LFL value in air, so an error in the LFL value will carry directly through to an error in the threshold. For the most part, the differences in published LFL values are attributable to test conditions: static or flowing gases, open or closed systems, and "go" versus "no go" criteria. The values themselves are most often determined only to the nearest 0.1 percent by volume. Differences of 0.2 percent by volume or more are not uncommon. If the LFL value is in error by 10%, which is not unheard of, the LFLcz threshold will be in error the same amount. To prevent ambiguity and error, the LFL values used to generate LFLcz should be traceable to flare test data. At a minimum, it should be determined by the same test methods that were used to generate the LFL values in the flare data.

To a lesser extent, it would be worthwhile to investigate the data involving hydrogen, acetylene, and other outliers to see if their outcomes have a different percentage of false results compared to those without. For example, hydrogen has unique combustion properties compared to hydrocarbon: a wide flammable range, low LFL compared to its stoichiometric concentration, and at the same time, a relatively low heat of combustion. It can easily be seen that a threshold value of 300 BTU/SCF NHVvg for hydrogen would not be useful in predicting its combustion efficiency since it would produce a false result even for 95% by volume hydrogen (285 BTU/SCF).

Question 4

> “Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to $LFL_{VG\text{-}LFL}$) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?”

Answer 4

The agency examined the relevant parameters.

The parameter NHVcz should be given more emphasis because in some cases it could perform as well as LFLcz with the virtue of being more readily measurable.

Comments on other parameters:

Burning velocity

The burning velocity of a combustible gas mixture might be expected to indicate conditions for good combustion efficiency, but this parameter is not characterized well enough to be useful. Furthermore, it often true that the maximum burning velocity for many combustible gases is related to flammability, a better characterized parameter.

Oxygen concentration

Oxygen concentration does not appear to provide additional insight for the flare, which burns in open air. Much of the literature for the effect of oxygen concentration on flammability relates to its effect within a homogeneous mixture, would be important to consider in a closed system, but not in a flare.

Temperature and Pressure

Pressure and temperature variations in the open air are not large enough to produce a significant effect.

Stoichiometric concentration (Cst)

For many combustible gas mixtures, the highest burning velocity and lowest ignition energy are found at concentrations just above Cst. Cst also correlates will with flammability. (Appendix C)

Flammable Range

Zabetakis includes the Upper (U25) and Lower (L25) Flammable Limits in air in tables of gas properties. One might predict that the wide flammable range of hydrogen helps promote good combustion efficiency, while the narrow range of flammable of ammonia presents a problem. (Appendix C)

Section 4: Air and Flare Performance

Question 5

> "Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning? Does the flare data adequately support the EPA's observations?"

Answer 5

In the flare study, there is little data, concerning only methane and propylene combustible gases. This may not be representative enough to draw a conclusion from the flare study data alone and apply it to a wide variety of combustible gases.

LFLvg as an operating parameter can be seen as a special case of LFLcz without steam assist. In this limited case, correction for nitrogen equivalence is unnecessary because there is no steam and no added inert beyond what is already present in the vent gases. So the vent gases are effectively the same as the combustion zone gases, and the 15.3% LFL figure should be applicable.

For many combustible gases, the LFLvg threshold of 15.3% by volume at SR = 7 would lead to a concentration near LFL if there was complete mixing of the assist air and the vent gases. In practice, the method of injection of assist air should not produce complete mixing prior to combustion. Since the stoichiometric concentration in air is approximately two times the LFL in air, the mixture of vent gas and air assist gas should pass through the flammable range and present the opportunity of a stable flame envelope burning at the stoichiometric concentration.

In a similar manner LHVvg as an operating parameter should be given consideration because the main difficulty with the use of LHVvg arose from its failure to correct for the added inert water in steam-assisted flares. In air assisted flares this limitation on the use of LHVvg will not be so important, and so the benefit of using LHVcg for air assist flares, namely the ability to monitor effectively with a less robust monitoring system such as a calorimeter.

Section 8: Monitoring Considerations

Question 10

> "Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters: LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, the ratio of NHV_{CZ} to NHV_{VG-LFL}, C_{CZ}, SR, MFR, and V_{max}. Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest."

Answer 10

The monitoring equipment includes an extractive analyzer to measure the desired combustible gas characteristic (volume concentration, net heating value, flammability) of the vent gas, plus a means to measure flow rates.

This answer will look at extractive analyzers that can directly or indirectly measure LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, the ratio of NHV_{CZ} to NHV_{VG-LFL}, C_{CZ}, and SR.

The focus on an extractive analyzer is justified by the well-founded observations of the difficulty in sampling from the combustion zone itself, and on the limits to the use of PFTIR and AFTIR methods as described in the report.

The principal requirements for an extractive combustible gas analyzer are speed and accuracy. In some cases, a gas chromatograph will not be fast enough. So although the GC is most accurate for monitoring LFLcz, a less robust analyzer such as a calorimeter will sometimes be more suitable, even if it measures a less than perfect parameter such as NHVcz.

Accuracy

Response Factors (see Appendix A)

This is not an issue for analyzers such as FTIR and GC that can measure the concentration of each individual species of combustible gas in the sample. For other analyzers that make a total (or combined) measurement of all combustible gases, it is important to know the response factors. These analyzers should have a uniform response factor for the parameter being measured for each species of combustible gas that it must measure. It is common for the response factors of analyzers to be published by the analyzer manufacturer, and in some cases these response factors are verified by a third party. The response factors are typically normalized to a standard reference gas whose factor is 1.0. So when the analyzer is calibrated using the reference gas, the response to another gas can be understood. The indicated reading can be interpreted. A response factor of 1.1 will mean that the indicated gas reading made by the analyzer is 1.1 times the actual concentration.

Other influences on accuracy are usually less significant and can be adequately addressed by installation, operation and maintenance of the equipment according to industry norms.

Sample Handling and Conditioning

The sample of vent gases should be conveyed to the analyzer without adulteration. It is preferable to make a measurement on a wet basis, with all parts of the sampling system that come in contact with the sample heated to at least (and preferably 10 degree C above) the temperature of the vent gases being measured. Otherwise, condensation of water vapor will cause false readings unless the measurement is corrected for loss of the water volume.

Filtration of particulate matter is routine and necessary to protect the analyzer from clogging.

If the sample is passed through a pump before it reaches the analyzer the pump should not raise the pressure of the sample to a point where it could condense out water vapor. Notably, vent gases saturated with water vapor at the measuring point temperature and pressure will not readily tolerate an increase in pressure or a reduction in temperature without condensation. This would require correction of the measurement to account for the lost water's volume.

Speed

Response Time

If the analyzer is to be used to control the flare it must respond quickly enough to allow stable control, preferably more quickly than the vent gases can change. For example, consider waste gases from different chemical batches being vented to a flare. Each batch may require (only) 30 to 60 minutes to be vented, which would present a challenge to a slow analyzer, such as a gas chromatograph having a ten minute response (cycle) time.

If the analyzer is to be used solely to monitor and not for control, a longer delay can be tolerated, and in some cases the interval between measurements can be extended, provided the interval does not produce a significant error.

The total response of the analyzer's measurements includes the "sample transport time" to convey the sample from the measuring point to the analyzer's inlet plus the "T90" time for the analyzer to reach a final stable reading. The analyzer should be located as close as possible to the point of measurement. Particulate filters should be small, tubing diameters small, and flow rates high enough to transport the sample quickly from the measuring point to the analyzer.

The delay in sample transport for a filter having a dead volume V and a sample flow rate Q is approximately V/Q. The delay in sample transport for standard¼ inch OD tubing at a flow rate of 1 liters per minute is approximately one second per meter.

Comments on analyzer types:

Gas Chromatograph

The sample is separated and each constituent is individually determined to a high degree of accuracy. The response for each combustible gas is optimized. The separation and analysis steps require a significant amount of time, for example, ten minutes. It may require sample conditioning to remove gases that interfere with its normal operation.

Flame Ionization Analyzer

A small continuous sample flow is burned in a small hydrogen flame (40 cc/min) in the presence of an electric field, which results in an ion current that is proportional to the "total hydrocarbon" in the sample. It response correlates best to the density of C-H (carbon hydrogen bonds) and can be characterized as PPM Cv (parts-per-million carbon by volume). It has a weakened response to oxygen-bearing hydrocarbon, and no response at all to hydrogen or carbon monoxide. It is most commonly used for very low concentration (up to 300 PPM), and also for measurements in the flammable range (1 to 3 percent by volume) but can saturate at high concentration. It has a fast response time – a few seconds.

Flame Temperature

This analyzer uses a small sensing flame to measure total flammability in the range from 0 to 100% LFL (Lower Flammable Limit <u>in Air</u>). A sample of the gas to be measured enters the sensing flame by diffusion and produces a temperature rise proportional to the "total flammability." It has a fast response time – a few seconds. It is relatively unaffected by corrosive gases and can make measurements on a wet basis. To measure vent gases, the limitation on range would have to be overcome by an accurate dilution of the sample gas of 10x or more in a sample conditioning system.

Combustion-type Calorimeter

There are many types designed to measure the heating value of gases across a wide range. One type presently used for flares burns a small continuous sample flow premixed with hydrogen to produce a temperature rise proportional to the net heating value of the sample. It has a uniform response to many different combustible gases in terms of the net heating value, including hydrogen and carbon monoxide. ." It has a fast response time – less than ten seconds. It is relatively unaffected by corrosive gases and can make measurements on a wet basis.

Non-dispersive Infrared Sensor

Relatively simple and inexpensive, it quickly measures the "total absorbance" of infrared energy. It has a wide range of response factors to different combustible gases, which usually limits or even prohibits its use for mixtures.

Sensors: Electrochemical / Catalytic bead / Semiconductor (tin-oxide)

These detectors are intended for leak detection in air and so in the great majority of cases do not have the range and specificity for use with flares.

Conditions where “less robust” monitoring equipment (combustible gas analyzer) could be used:

> Note: For this answer “less robust” is not meant to not imply reliability (such as the availability of the measurement, or MTBF). This answer addresses the analyzer used to measure the combustible gas characteristics. In general here, the less robust system is one which is not able to identify the concentration of each individual combustible gas in the vent gases.
>
> There is an acceptable margin of error
> The operating parameter is defined as a threshold beyond which the CE and thus DE is sufficient. This is an important feature affecting the required accuracy. An accurate monitoring system can be controlled at the threshold. A less accurate monitoring system can operate equally successfully if controlled at a safe margin beyond the threshold, in such a way that the inaccuracy of the less robust monitoring system does not defeat (exceed) the safe margin.
>
> This may allow successful operation in cases where the measurement accuracy is difficult to achieve with existing monitoring equipment. For example, monitoring equipment that is accurate to within +/-5% could be employed to control LFLcz below 15.3% by volume by operating with an indicated measurement not greater than 14.5%. This provides a balance between cost and complexity of the monitoring system and the cost of added fuel to reach the threshold (if needed) without a compromise in CE.
>
> A single combustible gas is present
> If just one species of combustible gas is present, then any analyzer that measures a proportionally related characteristic of the gas over the range of interest may be used in combination with a conversion factor between the characteristic being measured and the operating parameter that is needed. For example, is propylene alone is being flared, then a BTU/SCF measurement of propylene could be made with a calorimeter and it could be converted to volume fraction or flammability as needed.
>
> One combustible gas dominates a mixture
> If a single species of combustible gas dominates a mixture such that the other combustible gases in the mixture can be considered trace gases, then a measurement of the dominant gas alone can be used as long as the resulting error is within an acceptable margin of error (see above). For example, if a trace amount of hydrogen is present, and it could be ignored (not measured) without compromising CE (the actual CE would be better than the indicated CE made by excluding hydrogen from measurement), then an analyzer able to measure the dominant combustible gas would be acceptable.
>
> The analyzer’s response factors are uniform
> If all response factors for all combustible gases that can be present in the vent gases are within an acceptable margin of error, then the less robust system can be used. The standard mixing rule for response factors is to use the weighted average on a volume basis. For a worst case analysis, this simplifies to a consideration of only the lowest and highest response factors.

The analyzer is calibrated for the combustible gas having the weakest response

If the analyzer is calibrated to read “true” for the combustible gas to which it is least sensitive, then all indicated readings will be at or above the actual gas concentration such that all operation will meet or exceed the threshold.

Appendix A – Response Factors

Response factors show how a sensor that is calibrated for one particular gas, usually a "reference" gas, will read when exposed to other gases. If two gases both have the same response factor, they respond equally, unless the sensor is non-linear (infrared), in which case linearization of the signal can introduce more error, or less, depending on the individual characteristics of the sensor for each gas.

The degree of error that results from attempting to measure two different gases that have different response factors can be understood by taking the ratio of the two factors. Thus an attempt to measure two gases, one with a response factor to 0.5, and another with a response factor of 1.5, could yield a reading one third (0.5/1.5) or three times (1.5/0.5) the actual concentration.

The industry standard accuracy requirement for a flammable gas sensor is +/-10%. Response factors are therefore one of the most significant influences on accuracy. They easily introduce large errors.

Response factors are obtained by testing. The response factors should be obtained from the manufacturer of the sensor. In addition, the manufacturer's response factors can have independent verification as part of the third-party approval process(FM, CSA, ATEX, CENELEC).

The response factors given here are from various sources, including several manufacturers. The factors were all put into the same format (calibration readings in some cases were converted into response factors). This information is for illustrative purposes only. The calibration of actual sensors should be performed only according to the manufacturer's instructions.

For many process monitoring applications, the sensor must be calibrated so that all gases to be detected read the actual concentration or higher, but do not under-report the actual concentration. Therefore, the sensor is calibrated for the gas with the lowest response factor.

The flame temperature type sensor is said to have a "universal calibration" for common solvent vapors, because the response factors for common solvent vapors are in the range from 0.9 to 1.1. By contrast, response factors for FID and Catalytic sensors are usually in the range from 0.5 to 1.5 (a three-to-one ratio), and factors for infrared sensors can easily reach 0.25 to 2.0 (an eight-to-one ratio).

The response factors for catalytic sensors are subject to drift as the sensor ages. The sensor loses its response to hydrocarbons, which are harder for the sensor to detect, while maintaining its response to more easily catalyzed gases like hydrogen. The sensor eventually reads only hydrogen and not hydrocarbon.

Table of response factors

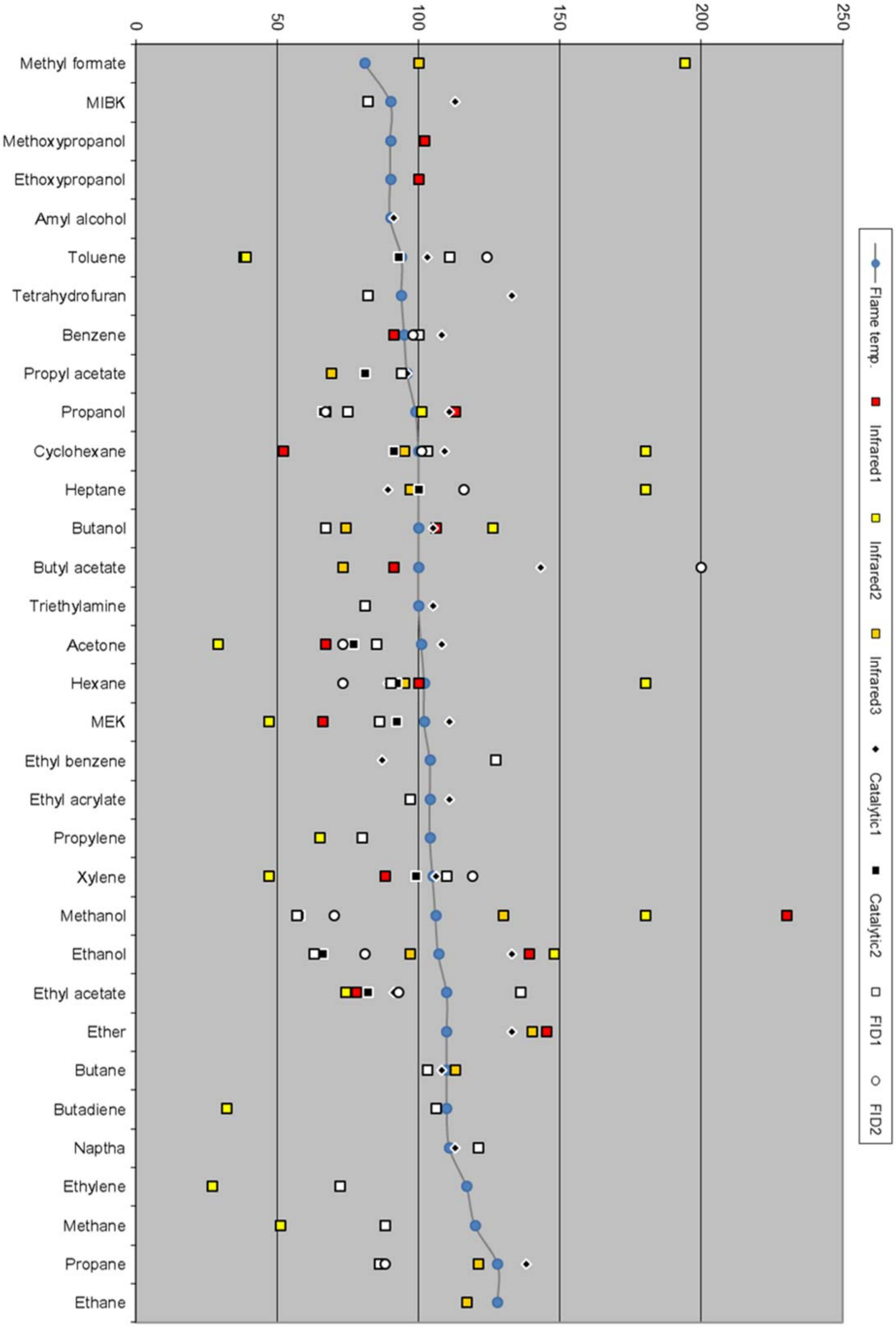
Response factors for several sensor and analyzer types measuring %LFL in air

Relative to standard test gas = 100, equivalent to factor of 1.0

Gas	**FTA**	**Infrared 1**	**Infrared 2**	**Infrared 3**	**Catalytic 1**	**Catalytic 2**	**FID1**	**FID2**
Methyl formate	81		194	100				
MIBK	90				113		82	
Methoxypropanol	90	102						
Ethoxypropanol	90	100						
Amyl alcohol	90				91			
Toluene	94	38	39		103	93	111	124
Tetrahydrofuran	94				133		82	
Benzene	95	91			108		100	98
Propyl acetate	96			69	96	81	94	
Propanol	99	113	101	67	111	66	75	67
Cyclohexane	100	52	180	95	109	91	103	101
Heptane	100	97	180	97	89	100		116
Butanol	100	106	126	74	105		67	
Butyl acetate	100	91		73	143			200
Triethylamine	100				105		81	
Acetone	101	67	29		108	77	85	73
Hexane	102	100	180	95	89	92	90	73
MEK	102	66	47		111	92	86	
Ethyl benzene	104				87		127	
Ethyl acrylate	104				111		97	
Propylene	104		65				80	
Xylene	105	88	47		106	99	110	119
Methanol	106	230	180	130		58	57	70
Ethanol	107	139	148	97	133	66	63	81
Ethyl acetate	110	78	74		91	82	136	93
Ether	110	145		140	133			
Butane	110			113	108		103	
Butadiene	110		32				106	
Naptha	111				113		121	
Ethylene	117		27				72	
Methane	120		51				88	
Propane	128			121	138		86	88
Ethane	128			117				

The table above illustrates how analyzers and sensors of different types and manufacture have differing response to combustible gases. Because these types of "less robust" analyzers make readings of the total gas mixture, not individual components, variations in the relative proportions of each combustible gas in the mixture will cause error in readings.

In the accompanying chart (below) the distribution of response factors can be seen. A perfect response to all gases would be represented as a flat line with all values equal to 100 (i.e. 1.0).


0
50
100
150
200
250
Methyl formate
MIBK
Methoxypropanol
Ethoxypropanol
Amyl alcohol
Toluene
Tetrahydrofuran
Benzene
Propyl acetate
Propanol
Cyclohexane
Heptane
Butanol
Butyl acetate
Triethylamine
Acetone
Hexane
MEK
Ethyl benzene
Ethyl acrylate
Propylene
Xylene
Methanol
Ethanol
Ethyl acetate
Ether
Butane
Butadiene
Naptha
Ethylene
Methane
Propane
Ethane
Flame temp.
Infrared1
Infrared2
Infrared3
Catalytic1
Catalytic2
FID1
FID2

Response Factors – Conversion of Factors

The chart below gives response factors for a FTA (Flame temperature) analyzer for measurement of flammability and also for measurement of heating value. The analyzer's principle of operation yields a uniform response to a variety of combustible gases in terms of flammability. For the combustible gases listed ("solvents"), the standard deviation of response factors is 5%.

To illustrate the conversion of response factors, the chart includes a heating value (BTU) response factor for the same combustible gases. The response factors converted from flammability to heating value have a much greater standard deviation, 22%. This is expected, since the relationship between flammability and heating value is not perfectly correlated.

Even so, this shows how response factors can be converted.

Solvent	**LFL**	**MW**	**Liquid Density** ***Pounds per Gallon***	**Heat of Combustion** ***BTU per pound***	**Heat of Combustion** ***BTU per gallon***	**LFL Definition:** ***Cubic Feet of Air per Gallon of Solvent at 100% LFL***	**Pounds per cubic foot at LFL**	**BTU per Cubic Foot of Solvent @LFL**	**BTU "Factor" normalized to Toluene = 1**	**LFL for flame temperature response factor**	**Flame temperature LFL response factor**	**Flame temperature BTU relative response factor**
Acetone			6.7	12,250	82,075	1,780		46	0.97	2.50	1.01	0.95
Butyl acrylate	1.4%	128.2		13,860			0.003923	54	1.15	1.70	1.00	1.11
Cellosolve			7.8	13,000	101,400	1,210		84	1.77	1.70	1.02	1.75
Cyclohexane			6.5	18,684	121,446	2,320		52	1.11	1.33	1.00	1.07
Cyclohexanone			7.9	15,430	121,897	2,640		46	0.98	1.10	0.84	0.80
Dimethyl Formamide			7.8	11,280	87,984	1,780		49	1.04	2.20	0.95	0.96
Ethyl Acetate			7.5	10,110	75,825	1,630		47	0.98	2.00	1.00	0.95
Ethyl Alcohol			6.6	11,570	76,362	1,630		47	0.99	3.30	1.08	1.04
Heptane			5.6	19,170	107,352	2,210		49	1.03	1.00	1.02	1.02
Hexane	1.2%	86.2		19,246			0.002261	44	0.92	1.10	1.00	0.89
Hexane			5.5	19,246	105,853	2,330		45	0.96	1.10	1.00	0.93
i-Propyl Alcohol			6.6	12,960	85,536	2,070		41	0.87	2.20	0.99	0.84
Methanol			6.5	8,419	54,724	1,264		43	0.91	6.00	1.06	0.94
Methyl Ethyl Ketone			6.7	13,480	90,316	2,540		36	0.75	1.80	1.01	0.74
n-Butyl Acetate			7.3	13,130	95,849	1,450		66	1.40	1.70	1.00	1.36
n-Butyl Alcohol			6.7	14,230	95,341	2,410		40	0.84	1.70	1.00	0.81
n-Propyl Alcohol			6.7	13,130	87,971	1,920		46	0.97		0.99	0.93
o-Xylene			7.3	17,558	128,173	2,670		48	1.01	1.10	1.04	1.02
sec-Butyl Alcohol			6.7	15,500	103,850	1,980		52	1.11		1.00	1.08
Toluene			7.2	17,430	125,496	2,650		47	1.00	1.20	1.03	1.00
Turpentine	0.8%	136.2		19,000			0.002383	45	0.96	0.80	1.00	0.93
acetic acid	4.0%	60.1		5,645			0.005251	30	0.63	0.80	0.80	0.49
formic acid	18.0%	46.0		2,045			0.018114	37	0.78	0.90	0.90	0.68
										mean	1.00	1.01
1. Liquid density from NFPA-86 (1990)										stdev	0.05	0.22
2. Heat of combustion from Noyes Solvent Safety Handbook												
3. LFL Definition from NFPA-86 (1990)												
4. BTU per cubic feet from Solvent = Heat of combustion / LFL definition												
Gases that are used during calibration - for reference only												
Propane	*1.7%*	*44.09*		*19,782*			*0.00164*	*32*	*0.67*	*1.70*	*0.97*	*0.65*
Propane	*2.0%*	*44.09*		*19,782*			*0.00193*	*38*	*0.79*	*1.14*	*0.97*	*0.76*
Methane	*4.4%*	*16.04*		*21,517*			*0.00154*	*33*	*0.68*	*4.40*	*1.20*	*0.82*
Ethylene	*2.3%*	*28.05*		*20,290*			*0.00141*	*29*	*0.59*	*2.70*	*1.17*	*0.69*
Methane	*5.0%*	*16.04*		*21,517*			*0.00175*	*38*	*0.78*	*5.00*	*1.40*	*1.09*
Ethylene	*2.7%*	*28.05*		*20,290*			*0.00166*	*34*	*0.69*	*2.70*	*1.17*	*0.81*
Propane	*2.1%*	*44.09*		*19,782*			*0.00202*	*40*	*0.82*	*1.14*	*0.97*	*0.80*

Appendix B- LFL Values from Various Authorities

Substance	IEC 79-20 1996	NFPA 325M 1991	NFPA 325M 1969	Bureau of Mines Bulletin 627	CCOHC (Canada)	Redeker / Schoen 1990 (Germany)	Nabert / Schoen 1991 (Germany)
acetaldehyde	4.0	4.0		4.0		4.0	4.0
acetone	2.5	2.5	2.6	2.6	2.6		
acetone						2.5	2.5
benzene	1.3	1.2	1.3	1.3			1.2
butadiene 1,3-	1.4	2.0		2.0	2.0	1.4	1.1
butyl acetate	1.4	1.7		1.4	1.7	1.2	1.2
cyclohexane	1.2	1.3		1.3	1.3		1.2
cyclohexanone	1.0	1.1			1.1	1.0	1.3
dichloromethane	13.0	13.0			12.0		13.0
dimethyl ether	2.7	3.4		3.4		2.7	2.0
dimethyl sulfide		2.2		2.2			2.2
dioxane 1,4-	1.9	2.0		2.0			1.9
ethane	2.5	3.0		3.0	3.0	2.7	3.0
ethanol	3.3	3.3		3.3	3.3		3.5
ethyl acetate	2.2	2.0	2.2	2.2	2.0		
ethylene	2.5	2.7		2.7	3.1	2.3	2.7
ethylene glycol		3.2		3.4			3.2
heptane	1.1	1.1		1.1	1.1		1.1
hexane	1.0	1.1		1.2	1.1	1.0	1.2
isobutane		1.8					1.8
isobutyl alcohol		1.7					1.7
isobutylene		1.8		1.8			1.6
isopropyl alcohol		2.0		2.2	2.5		2.0
methane	4.4	5.0		5.0	5.0		5.0
methanol	5.5	6.0	6.7		7.3		
methanol				6.7		5.5	5.5
methyl acrylate	2.4	2.8			2.8	2.4	2.8
methyl chloride, chloromethane		8.1		7.0			7.1
methyl ethyl ketone		1.4	1.8	1.9	2.0		1.8
methylene chloride		13.0			12.0		13.0
N,N-dimethylformamide	1.8	2.2		1.8	2.2		2.2
n-butane	1.4	1.9		1.8	1.8	1.4	1.5
n-butyl alcohol		1.4					1.4
o- xylene	1.0	0.9	1.0	1.1	1.0		1.0
p-, m- xylene		1.1			1.1		1.1
propane	2.0	2.1	2.2	2.1	2.2	1.7	2.1
propanol	2.2	2.2	2.1	2.2	2.2	2.1	2.1
styrene		0.9		1.1			
t-butyl methyl ether		1.5				1.6	
tert-butyl alcohol		1.4		1.9	2.4		2.3
toluene	1.2	1.1	1.2	1.2	1.3	1.2	1.2

Appendix C – Cst, with U25 and L25 ratios

In tables of gas properties, Zabetakis includes the stoichiometric concentration air (Cst), and also the ratio "L25/Cst," which is the ratio of the Lower Flammable Limit of the combustible gas in air to the stoichiometric concentration of the combustible gas in air. For many combustible gases, the Lower Flammable Limit in air is within 10% of the value 0.54*Cst. The exceptions to this general rule L25 = 0.54*Cst are themselves interesting, for example hydrogen and ammonia.

Cst may be of interest as a parameter interesting because it can be calculated, and so it is less ambiguous than the Lower Flammable Limit in air.

Substance	*L25/Cst*	*U25/L25*	*U25/Cst*	*Cst*
1,3-Butadiene	*0.52*	*6.00*	*3.13*	*3.8%*
1-Butene	*0.50*	*5.29*	*2.67*	*3.4%*
Acetylene	***0.32***	***40.00***	***12.93***	***7.7%***
Benzene	*0.44*	*6.50*	*2.87*	*2.7%*
Carbon Monoxide	*0.42*	*5.92*	*2.51*	*29.5%*
Cis-2-Butene	*0.50*	*5.29*	*2.67*	*3.4%*
Ethylene	*0.41*	*13.33*	*5.51*	*6.5%*
Hydrogen Sulfide	***0.33***	***11.00***	***3.59***	***12.3%***
Hydrogen	***0.14***	***18.75***	***2.54***	***29.5%***
Iso-Butane	*0.58*	*4.67*	*2.69*	*3.1%*
Iso-Butylene	*0.53*	*5.33*	*2.85*	*3.4%*
Methane	*0.53*	*3.00*	*1.58*	*9.5%*
Methyl Acetylene	*0.34*	*6.88*	*2.35*	*5.0%*
n-Butane	*0.45*	*6.07*	*2.72*	*3.1%*
Pentane	*0.59*	*5.20*	*3.06*	*2.6%*
Propane	*0.52*	*4.52*	*2.36*	*4.0%*
Propylene	*0.54*	*4.63*	*2.50*	*4.4%*
Toluene	*0.53*	*5.92*	*3.12*	*2.3%*
Trans-2-Butene	*0.53*	*5.39*	*2.87*	*3.4%*
Ammonia	***0.69***	***1.87***	***1.28***	***21.8%***
Butadiene 1,2-	*0.50*	*6.00*	*2.98*	*4.0%*
Cyclopropane	*0.54*	*4.33*	*2.34*	*4.4%*
Ethane	*0.53*	*4.17*	*2.21*	*5.6%*
Ethyl Benzene	*0.41*	*8.38*	*3.42*	*2.0%*
Heptane	*0.54*	*6.70*	*3.58*	*1.9%*
Hexane	*0.51*	*6.82*	*3.48*	*2.2%*
Propadiene	*0.50*	*6.80*	*3.42*	*5.0%*
Xylene	*0.55*	*6.36*	*3.50*	*2.0%*

Appendix D – Analysis of Operating Parameters

For each operating parameter, the “steam data used all analysis” is categorized as “positive,” “negative,” “false positive” or “false negative.” This allows for a comparison of operating parameters and an understanding of the type of outcome the use of the parameter will have. The effect of changes to the threshold or to the CE limit can be readily seen.

The data is more readily viewed in the Excel spreadsheet, but the first page of each of several representative views is included in the following pages.

Nbr	Flare Vent Gas Net Heating Value (NHVVG) [Btu/scf]	Reported Combustion Efficiency (CE) [%]	NHVvg Threshold **300**				NHVvg Threshold **500**				NHVvg Threshold **700**			
			CE Threshold **96.5%**				CE Threshold **96.5%**				CE Threshold **96.5%**			
			Sums of outcomes				Sums of outcomes				Sums of outcomes			
			160 True Positive	1 True Negative	147 False positive	4 False negative	139 True Positive	51 True Negative	97 False positive	25 False negative	118 True Positive	71 True Negative	77 False positive	46 False negative
1	2183	100.0%	1	0	0	0	1	0	0	0	1	0	0	0
2	2183	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
3	2183	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
4	2183	99.5%	1	0	0	0	1	0	0	0	1	0	0	0
5	309	98.7%	1	0	0	0	0	0	0	1	0	0	0	1
6	2183	99.7%	1	0	0	0	1	0	0	0	1	0	0	0
7	294	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
8	298	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
9	2183	82.2%	0	0	1	0	0	0	1	0	0	0	1	0
10	305	99.5%	1	0	0	0	0	0	0	1	0	0	0	1
11	342	99.9%	1	0	0	0	0	0	0	1	0	0	0	1
12	364	99.8%	1	0	0	0	0	0	0	1	0	0	0	1
13	339	99.7%	1	0	0	0	0	0	0	1	0	0	0	1
14	405	99.8%	1	0	0	0	0	0	0	1	0	0	0	1
15	192	95.1%	0	1	0	0	0	1	0	0	0	1	0	0
16	232	99.3%	0	0	0	1	0	0	0	1	0	0	0	1
17	275	99.4%	0	0	0	1	0	0	0	1	0	0	0	1
18	329	97.9%	1	0	0	0	0	0	0	1	0	0	0	1
19	425	99.7%	1	0	0	0	0	0	0	1	0	0	0	1
20	425	99.6%	1	0	0	0	0	0	0	1	0	0	0	1
21	732	99.5%	1	0	0	0	1	0	0	0	1	0	0	0
22	732	99.5%	1	0	0	0	1	0	0	0	1	0	0	0
23	732	97.5%	1	0	0	0	1	0	0	0	1	0	0	0
24	748	96.3%	0	0	1	0	0	0	1	0	0	0	1	0
25	732	94.8%	0	0	1	0	0	0	1	0	0	0	1	0
26	753	89.7%	0	0	1	0	0	0	1	0	0	0	1	0
27	705	92.6%	0	0	1	0	0	0	1	0	0	0	1	0
28	732	85.9%	0	0	1	0	0	0	1	0	0	0	1	0
29	826	82.8%	0	0	1	0	0	0	1	0	0	0	1	0
30	901	98.4%	1	0	0	0	1	0	0	0	1	0	0	0
31	932	99.0%	1	0	0	0	1	0	0	0	1	0	0	0
32	908	97.7%	1	0	0	0	1	0	0	0	1	0	0	0
33	940	97.4%	1	0	0	0	1	0	0	0	1	0	0	0
34	932	92.7%	0	0	1	0	0	0	1	0	0	0	1	0
35	926	93.9%	0	0	1	0	0	0	1	0	0	0	1	0
36	873	97.1%	1	0	0	0	1	0	0	0	1	0	0	0
37	876	89.2%	0	0	1	0	0	0	1	0	0	0	1	0
38	777	99.1%	1	0	0	0	1	0	0	0	1	0	0	0

The net heating value in the vent gases for various threshold values 300, 500 and 700 BTU/SCF shows a large percentage of false outcomes.

Nbr	Net Heating Value of Combustion Zone Gas (NHVCZ) [BTU/scf]	Reported Combustion Efficiency (CE) [%]	NHVcz Threshold **250**				NHVcz Threshold **275**				NHVcz Threshold **300**			
			CE Threshold **96.5%**				CE Threshold **96.5%**				CE Threshold **96.5%**			
			Sums of outcomes				Sums of outcomes				Sums of outcomes			
			110	135	13	54	101	138	10	63	84	141	7	80
			True Positive	True Negativ	False positive	False negativ	True Positive	True Negativ	False positive	False negativ	True Positive	True Negativ	False positive	False negativ
1	793	100.0%	1	0	0	0	1	0	0	0	1	0	0	0
2	471	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
3	693	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
4	267	99.5%	1	0	0	0	0	0	0	1	0	0	0	1
5	242	98.7%	0	0	0	1	0	0	0	1	0	0	0	1
6	241	99.7%	0	0	0	1	0	0	0	1	0	0	0	1
7	236	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
8	298	99.9%	1	0	0	0	1	0	0	0	0	0	0	1
9	153	82.2%	0	1	0	0	0	1	0	0	0	1	0	0
10	305	99.5%	1	0	0	0	1	0	0	0	1	0	0	0
11	342	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
12	364	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
13	339	99.7%	1	0	0	0	1	0	0	0	1	0	0	0
14	405	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
15	192	95.1%	0	1	0	0	0	1	0	0	0	1	0	0
16	232	99.3%	0	0	0	1	0	0	0	1	0	0	0	1
17	220	99.4%	0	0	0	1	0	0	0	1	0	0	0	1
18	295	97.9%	1	0	0	0	1	0	0	0	0	0	0	1
19	333	99.7%	1	0	0	0	1	0	0	0	1	0	0	0
20	373	99.6%	1	0	0	0	1	0	0	0	1	0	0	0
21	235	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
22	224	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
23	172	97.5%	0	0	0	1	0	0	0	1	0	0	0	1
24	204	96.3%	0	1	0	0	0	1	0	0	0	1	0	0
25	129	94.8%	0	1	0	0	0	1	0	0	0	1	0	0
26	166	89.7%	0	1	0	0	0	1	0	0	0	1	0	0
27	133	92.6%	0	1	0	0	0	1	0	0	0	1	0	0
28	106	85.9%	0	1	0	0	0	1	0	0	0	1	0	0
29	120	82.8%	0	1	0	0	0	1	0	0	0	1	0	0
30	461	98.4%	1	0	0	0	1	0	0	0	1	0	0	0
31	456	99.0%	1	0	0	0	1	0	0	0	1	0	0	0
32	313	97.7%	1	0	0	0	1	0	0	0	1	0	0	0
33	305	97.4%	1	0	0	0	1	0	0	0	1	0	0	0
34	259	92.7%	0	0	1	0	0	1	0	0	0	1	0	0
35	266	93.9%	0	0	1	0	0	1	0	0	0	1	0	0
36	261	97.1%	1	0	0	0	0	0	0	1	0	0	0	1
37	215	89.2%	0	1	0	0	0	1	0	0	0	1	0	0
38	411	99.1%	1	0	0	0	1	0	0	0	1	0	0	0
39	435	99.0%	1	0	0	0	1	0	0	0	1	0	0	0

The net heating value in the combustion zone gas accounts for much of the effect of added steam and so produces relatively low percentages of false outcomes, similar to LFLcz. Many of the false positive results are suspect data points.

Nbr	Lower Flammability Limit of Combustion Zone Gas Adjusted for Nitrogen Equivalency (LFLCZ) [vol frac]	Reported Combustion Efficiency (CE) [%]	LFLcz-adj Threshold **13.8%** CE Threshold **96.5%** Sums of outcomes				LFLcz-adj Threshold **15.3%** CE Threshold **96.5%** Sums of outcomes				LFLcz-adj Threshold **16.8%** CE Threshold **96.5%** Sums of outcomes			
			82 True Positive	142 True Negative	6 False positive	82 False negative	98 True Positive	138 True Negative	10 False positive	66 False negative	106 True Positive	135 True Negative	13 False positive	58 False negative
1	6.7%	100.0%	1	0	0	0	1	0	0	0	1	0	0	0
2	11.5%	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
3	7.7%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
4	20.9%	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
5	22.0%	98.7%	0	0	0	1	0	0	0	1	0	0	0	1
6	23.4%	99.7%	0	0	0	1	0	0	0	1	0	0	0	1
7	22.5%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
8	25.1%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
9	38.5%	82.2%	0	1	0	0	0	1	0	0	0	1	0	0
10	19.8%	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
11	15.3%	99.9%	0	0	0	1	0	0	0	1	1	0	0	0
12	14.4%	99.8%	0	0	0	1	1	0	0	0	1	0	0	0
13	15.5%	99.7%	0	0	0	1	0	0	0	1	1	0	0	0
14	14.1%	99.8%	0	0	0	1	1	0	0	0	1	0	0	0
15	27.3%	95.1%	0	1	0	0	0	1	0	0	0	1	0	0
16	22.6%	99.3%	0	0	0	1	0	0	0	1	0	0	0	1
17	22.9%	99.4%	0	0	0	1	0	0	0	1	0	0	0	1
18	16.9%	97.9%	0	0	0	1	0	0	0	1	0	0	0	1
19	15.0%	99.7%	0	0	0	1	1	0	0	0	1	0	0	0
20	13.3%	99.6%	1	0	0	0	1	0	0	0	1	0	0	0
21	14.3%	99.5%	0	0	0	1	1	0	0	0	1	0	0	0
22	15.1%	99.5%	0	0	0	1	1	0	0	0	1	0	0	0
23	20.3%	97.5%	0	0	0	1	0	0	0	1	0	0	0	1
24	17.6%	96.3%	0	1	0	0	0	1	0	0	0	1	0	0
25	28.0%	94.8%	0	1	0	0	0	1	0	0	0	1	0	0
26	22.1%	89.7%	0	1	0	0	0	1	0	0	0	1	0	0
27	25.3%	92.6%	0	1	0	0	0	1	0	0	0	1	0	0
28	35.6%	85.9%	0	1	0	0	0	1	0	0	0	1	0	0
29	32.6%	82.8%	0	1	0	0	0	1	0	0	0	1	0	0
30	9.2%	98.4%	1	0	0	0	1	0	0	0	1	0	0	0
31	9.3%	99.0%	1	0	0	0	1	0	0	0	1	0	0	0
32	14.0%	97.7%	0	0	0	1	1	0	0	0	1	0	0	0
33	14.4%	97.4%	0	0	0	1	1	0	0	0	1	0	0	0
34	17.3%	92.7%	0	1	0	0	0	1	0	0	0	1	0	0
35	16.9%	93.9%	0	1	0	0	0	1	0	0	0	1	0	0
36	17.0%	97.1%	0	0	0	1	0	0	0	1	0	0	0	1
37	21.4%	89.2%	0	1	0	0	0	1	0	0	0	1	0	0

The LFLcz-adj accounts best for the effect of added steam and so produces relatively low percentages of false outcomes. Many of the false positive results are suspect data points.

Nbr	Unadjusted Lower Flammability Limit of Combustion Zone Gas (LFLCZ) [vol frac]	Reported Combustion Efficiency (CE) [%]	LFLcz Threshold **14.5%** CE Threshold **96.5%** Sums of outcomes				LFLcz Threshold **15.3%** CE Threshold **96.5%** Sums of outcomes				LFLcz Threshold **16.0%** CE Threshold **95.5%** Sums of outcomes			
			96 True Positive	137 True Negative	11 False positive	68 False negative	103 True Positive	136 True Negative	12 False positive	61 False negative	116 True Positive	118 True Negative	10 False positive	68 False negative
1	6.6%	100.0%	1	0	0	0	1	0	0	0	1	0	0	0
2	11.1%	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
3	7.6%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
4	19.6%	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
5	21.6%	98.7%	0	0	0	1	0	0	0	1	0	0	0	1
6	21.7%	99.7%	0	0	0	1	0	0	0	1	0	0	0	1
7	22.2%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
8	25.1%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
9	34.1%	82.2%	0	1	0	0	0	1	0	0	0	1	0	0
10	19.8%	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
11	15.3%	99.9%	0	0	0	1	0	0	0	1	1	0	0	0
12	14.4%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
13	15.5%	99.7%	0	0	0	1	0	0	0	1	1	0	0	0
14	14.1%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
15	27.3%	95.1%	0	1	0	0	0	1	0	0	0	1	0	0
16	22.6%	99.3%	0	0	0	1	0	0	0	1	0	0	0	1
17	22.4%	99.4%	0	0	0	1	0	0	0	1	0	0	0	1
18	16.7%	97.9%	0	0	0	1	0	0	0	1	0	0	0	1
19	14.8%	99.7%	0	0	0	1	1	0	0	0	1	0	0	0
20	13.2%	99.6%	1	0	0	0	1	0	0	0	1	0	0	0
21	13.5%	99.5%	1	0	0	0	1	0	0	0	1	0	0	0
22	14.2%	99.5%	1	0	0	0	1	0	0	0	1	0	0	0
23	18.6%	97.5%	0	0	0	1	0	0	0	1	0	0	0	1
24	16.3%	96.3%	0	1	0	0	0	1	0	0	0	0	0	1
25	24.6%	94.8%	0	1	0	0	0	1	0	0	0	1	0	0
26	19.9%	89.7%	0	1	0	0	0	1	0	0	0	1	0	0
27	22.8%	92.6%	0	1	0	0	0	1	0	0	0	1	0	0
28	30.1%	85.9%	0	1	0	0	0	1	0	0	0	1	0	0
29	28.0%	82.8%	0	1	0	0	0	1	0	0	0	1	0	0
30	8.9%	98.4%	1	0	0	0	1	0	0	0	1	0	0	0
31	9.0%	99.0%	1	0	0	0	1	0	0	0	1	0	0	0
32	13.1%	97.7%	1	0	0	0	1	0	0	0	1	0	0	0
33	13.4%	97.4%	1	0	0	0	1	0	0	0	1	0	0	0
34	15.8%	92.7%	0	1	0	0	0	1	0	0	0	0	1	0
35	15.4%	93.9%	0	1	0	0	0	1	0	0	0	0	1	0
36	15.5%	97.1%	0	0	0	1	0	0	0	1	1	0	0	0

The LFLcz also produces relatively low percentages of false outcomes. Many of the false positive results are suspect data points.

Nbr	Combustible Components in the Combustion Zone (CCZ) [vol frac]	Reported Combustion Efficiency (CE) [%]	Ccz Threshold **26%** CE Threshold **96.5%** Sums of outcomes				Ccz Threshold **28%** CE Threshold **96.5%** Sums of outcomes				Ccz Threshold **32%** CE Threshold **96.5%** Sums of outcomes			
			88 True Positive	139 True Negative	9 False positive	76 False negative	75 True Positive	146 True Negative	2 False positive	89 False negative	55 True Positive	147 True Negative	1 False positive	109 False negative
1	36.3%	100.0%	1	0	0	0	1	0	0	0	1	0	0	0
2	21.6%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
3	31.7%	99.8%	1	0	0	0	1	0	0	0	0	0	0	1
4	12.2%	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
5	11.1%	98.7%	0	0	0	1	0	0	0	1	0	0	0	1
6	11.0%	99.7%	0	0	0	1	0	0	0	1	0	0	0	1
7	10.8%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
8	9.6%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
9	7.0%	82.2%	0	1	0	0	0	1	0	0	0	1	0	0
10	12.1%	99.5%	0	0	0	1	0	0	0	1	0	0	0	1
11	15.7%	99.9%	0	0	0	1	0	0	0	1	0	0	0	1
12	16.7%	99.8%	0	0	0	1	0	0	0	1	0	0	0	1
13	15.5%	99.7%	0	0	0	1	0	0	0	1	0	0	0	1
14	17.1%	99.8%	0	0	0	1	0	0	0	1	0	0	0	1
15	8.8%	95.1%	0	1	0	0	0	1	0	0	0	1	0	0
16	10.6%	99.3%	0	0	0	1	0	0	0	1	0	0	0	1
17	9.4%	99.4%	0	0	0	1	0	0	0	1	0	0	0	1
18	12.5%	97.9%	0	0	0	1	0	0	0	1	0	0	0	1
19	14.2%	99.7%	0	0	0	1	0	0	0	1	0	0	0	1
20	15.9%	99.6%	0	0	0	1	0	0	0	1	0	0	0	1
21	27.3%	99.5%	1	0	0	0	0	0	0	1	0	0	0	1
22	26.1%	99.5%	1	0	0	0	0	0	0	1	0	0	0	1
23	19.9%	97.5%	0	0	0	1	0	0	0	1	0	0	0	1
24	23.2%	96.3%	0	1	0	0	0	1	0	0	0	1	0	0
25	15.0%	94.8%	0	1	0	0	0	1	0	0	0	1	0	0
26	19.2%	89.7%	0	1	0	0	0	1	0	0	0	1	0	0
27	15.5%	92.6%	0	1	0	0	0	1	0	0	0	1	0	0
28	12.3%	85.9%	0	1	0	0	0	1	0	0	0	1	0	0
29	12.3%	82.8%	0	1	0	0	0	1	0	0	0	1	0	0
30	48.1%	98.4%	1	0	0	0	1	0	0	0	1	0	0	0
31	45.9%	99.0%	1	0	0	0	1	0	0	0	1	0	0	0
32	32.4%	97.7%	1	0	0	0	1	0	0	0	1	0	0	0
33	30.5%	97.4%	1	0	0	0	1	0	0	0	0	0	0	1
34	26.1%	92.7%	0	0	1	0	0	1	0	0	0	1	0	0
35	26.9%	93.9%	0	0	1	0	0	1	0	0	0	1	0	0
36	28.2%	97.1%	1	0	0	0	1	0	0	0	0	0	0	1
37	23.0%	89.2%	0	1	0	0	0	1	0	0	0	1	0	0
38	49.3%	99.1%	1	0	0	0	1	0	0	0	1	0	0	0

The Ccz parameter would be very useful in cases where the flare normally handles a high concentration of combustible gas.

				STOICHcz Threshold	200.0%			STOICHcz Threshold	237.5%			STOICHcz Threshold	300.0%	
				CE Threshold	96.5%			CE Threshold	96.5%			CE Threshold	96.6%	
				Sums of outcomes				Sums of outcomes				Sums of outcomes		
			150	84	64	14	134	115	33	30	100	139	11	62
Nbr	Stoichiometric concentration in combustion zone gas	Reported Combustion Efficiency (CE) [%]	True Positive	True Negative	False positive	False negative	True Positive	True Negative	False positive	False negative	True Positive	True Negative	False positive	False negative
1	816.7%	100.0%	1	0	0	0	1	0	0	0	1	0	0	0
2	484.6%	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
3	713.3%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
4	275.1%	99.5%	1	0	0	0	1	0	0	0	0	0	0	1
5	249.2%	98.7%	1	0	0	0	1	0	0	0	0	0	0	1
6	248.1%	99.7%	1	0	0	0	1	0	0	0	0	0	0	1
7	243.3%	99.9%	1	0	0	0	1	0	0	0	0	0	0	1
8	215.4%	99.9%	1	0	0	0	0	0	0	1	0	0	0	1
9	158.0%	82.2%	0	1	0	0	0	1	0	0	0	1	0	0
10	272.6%	99.5%	1	0	0	0	1	0	0	0	0	0	0	1
11	352.4%	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
12	375.3%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
13	348.9%	99.7%	1	0	0	0	1	0	0	0	1	0	0	0
14	383.7%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
15	197.8%	95.1%	0	1	0	0	0	1	0	0	0	1	0	0
16	239.0%	99.3%	1	0	0	0	1	0	0	0	0	0	0	1
17	232.9%	99.4%	1	0	0	0	0	0	0	1	0	0	0	1
18	311.9%	97.9%	1	0	0	0	1	0	0	0	1	0	0	0
19	353.0%	99.7%	1	0	0	0	1	0	0	0	1	0	0	0
20	395.1%	99.6%	1	0	0	0	1	0	0	0	1	0	0	0
21	274.2%	99.5%	1	0	0	0	1	0	0	0	0	0	0	1
22	261.4%	99.5%	1	0	0	0	1	0	0	0	0	0	0	1
23	199.9%	97.5%	0	0	0	1	0	0	0	1	0	0	0	1
24	234.5%	96.3%	0	0	1	0	0	1	0	0	0	1	0	0
25	150.7%	94.8%	0	1	0	0	0	1	0	0	0	1	0	0

The “stoichiometric concentration in the combustion zone gas” is an invented parameter. It is the sum of the volume fractions of each combustible gas in the combustion zone divided by that gas’s stoichiometric concentration in air (eg Cst from Zabetakis). It is interesting to see if it compares favorably with LFLcz.

				STOICHcz Threshold	250.0%			STOICHcz Threshold	300.0%			STOICHcz Threshold	350.0%	
				CE Threshold	96.5%			CE Threshold	96.5%			CE Threshold	96.5%	
				Sums of outcomes				Sums of outcomes				Sums of outcomes		
			125	121	27	39	100	137	11	64	82	142	6	82
Nbr	Stoichiometric concentration in combustion zone gas	Reported Combustion Efficiency (CE) [%]	True Positive	True Negative	False positive	False negative	True Positive	True Negative	False positive	False negative	True Positive	True Negative	False positive	False negative
1	816.7%	100.0%	1	0	0	0	1	0	0	0	1	0	0	0
2	484.6%	99.9%	1	0	0	0	1	0	0	0	1	0	0	0
3	713.3%	99.8%	1	0	0	0	1	0	0	0	1	0	0	0
4	275.1%	99.5%	1	0	0	0	0	0	0	1	0	0	0	1
5	249.2%	98.7%	0	0	0	1	0	0	0	1	0	0	0	1
6	248.1%	99.7%	0	0	0	1	0	0	0	1	0	0	0	1

Attachment G

Dr. Jim Seebold

Independent Consultant

— *Good Try* —

Peer review of a report by

U.S. EPA's Office of Air Quality Planning and Standards (OAQPS)

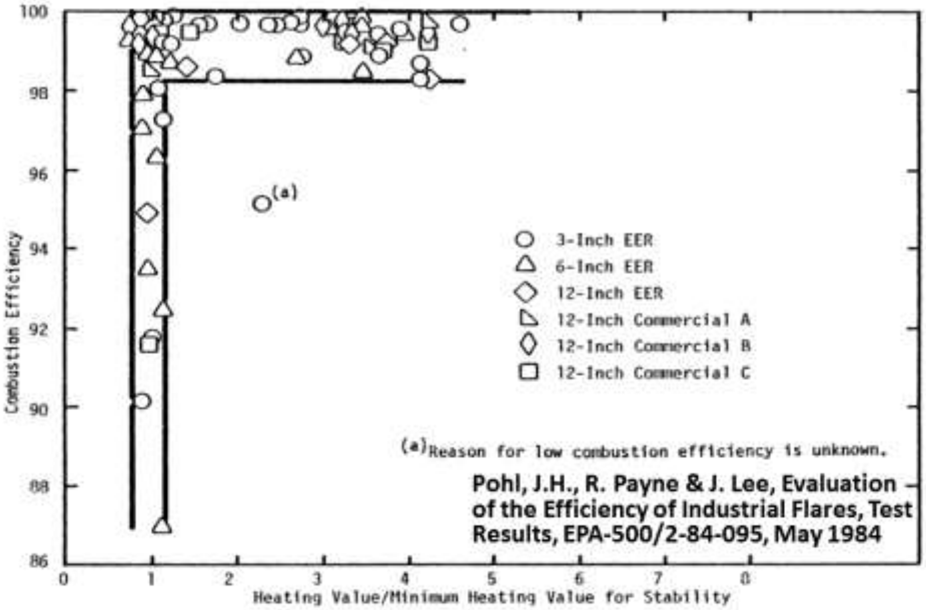
"Parameters for Properly Designed and Operated Flares"

submitted by
James G. Seebold, Chevron (Retired)
Independent Consultant
May 21, 2012

In the United States, alleged wind-induced combustion efficiency ("CE") degradation in the operation of real industrial flares in the field has become a big issue amongst environmental activists in consequence of which the United States Environmental Protection Agency is considering regulations related to wind effects. While it is true that wind effects have been reported in model-scale *(typically ≤3"D and often «3"D, soda-straw like)* tests in wind tunnels, there is no evidence whatsoever in recent and extensive *in situ* full-scale *(typically »18"D)* remote-sensing field testing of any significant wind-induced CE-degradation.

Nothing has changed

The regrettable absence of systematic variation in combustion efficiency found in past and present flare studies leads inevitably to the idea of "stochasticness" and great difficulties for regulatory interpretation.



Pohl, J.H., R. Payne & J. Lee, Evaluation of the Efficiency of Industrial Flares, Test Results, EPA-500/2-84-095, May 1984

Figure 2-4. Combustion efficiency near the lower limits of flame stability.(b)

(b) Based on flares burning propane/nitrogen mixtures with no pilot flame.

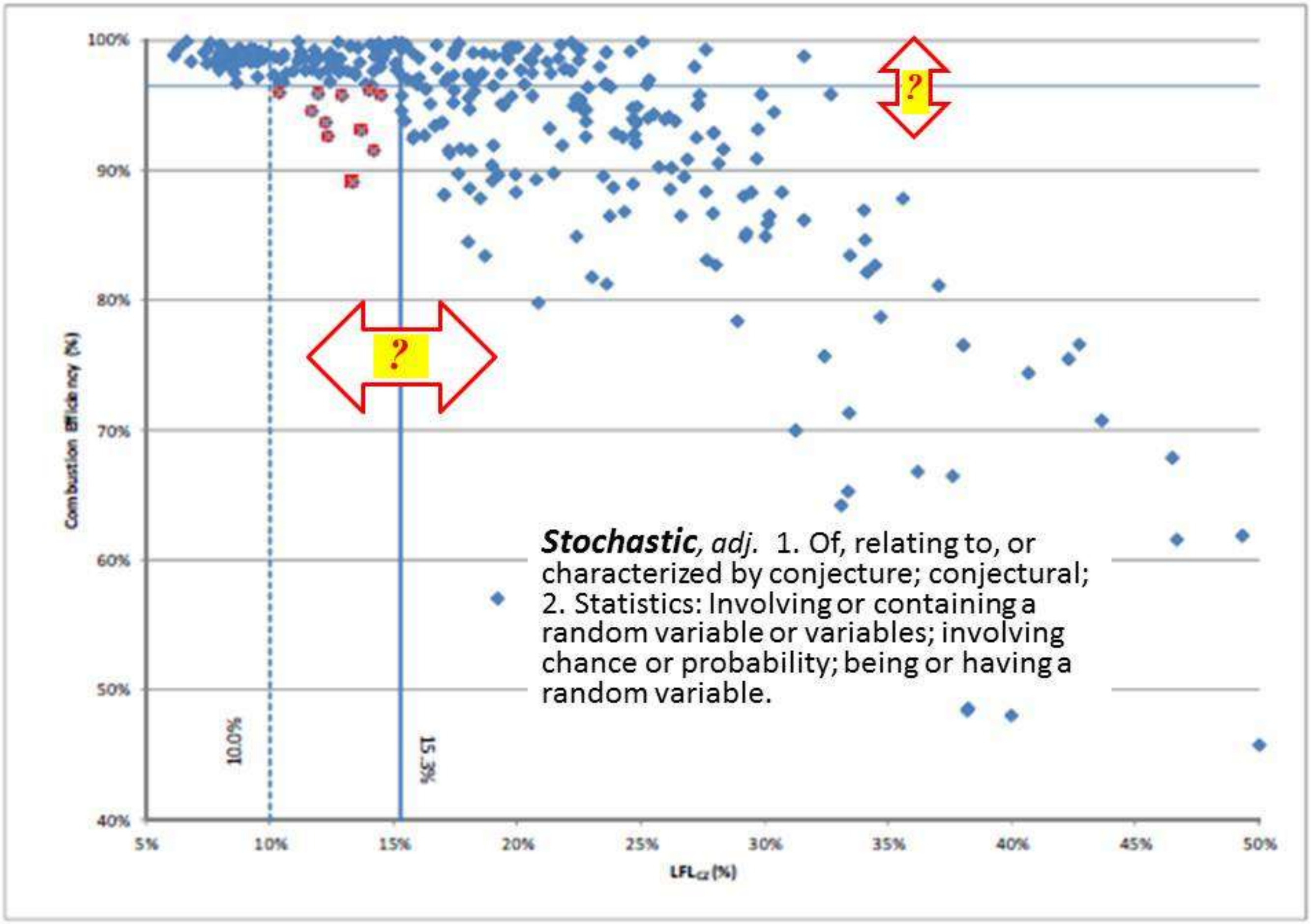
This fact is illustrated not only in recent USDOJ/USEPA consent-decree-imposed *in situ* PFTIR testing of real industrial flares in the field that is the subject of the USEPA OAQPS report now in peer review but over and over again in the decades since Siegel's monumental work[1] in competently executed studies from the mid-1980s USEPA-sponsored "Evaluation of the Efficiency of Industrial Flares" *(illustrated above)* on which the current failed federal law *(40CFR60.18)* was based to the most recent USDOJ/USEPA consent-decree-imposed field studies.

A summing up of the valiant PFTIR-based *in situ* field investigations carried out by eminently qualified practitioners, the USEPA OAQPS report, ***"Parameters for Properly Designed and Operated Flares,"***

---

[1] Siegel, K. D., "Degree of Conversion of Flare Gas in Refinery Elevated Flares," PhD Thesis in Engineering Science, Feb, 1980, Chemical Engineering Department, University of Karlsruhe, Germany

appears merely to be an elaborately perseverated defense of the blatantly conjectural nature *(illustrated in "Figure 3-3" below)* of the so-called "conclusions" in a report that does not come any closer than previous efforts to producing the long sought but to date elusive flare researchers' *"Holy Grail;" viz.,* the omniscient, universal, all-encompassing, incontestable correlating parameter for flare combustion efficiency.



Stochastic*, adj.* 1. Of, relating to, or characterized by conjecture; conjectural; 2. Statistics: Involving or containing a random variable or variables; involving chance or probability; being or having a random variable.

Figure 3-3. Combustion Efficiency vs. LFL$_{CZ}$

"... suggests ..." or *"... most appropriate ..."* hardly implies data quality good enough for rule making or policy making

"To identify over steaming situations that may occur on steam-assisted flares, the data suggest that the lower flammability limit of combustion zone gas (LFL$_{CZ}$) is the most appropriate operating parameter. Specifically, the data suggest that, in order to maintain good combustion efficiency, the LFL$_{CZ}$ must be 15.3 percent by volume or less for a steam-assisted flare."[2]

Are you kidding me? No better than the OAQPS long ago jumped-to "conclusions" on which today's failed federal law *(40CFR60.18)* is based.

---

[2] Quote highlighted in the Research Triangle Institute for U.S. Environmental Protection Agency instructions to Peer Reviewers that are appended to this review.

Furthermore, "15.***3***" implies far more accuracy and reliability in LFL_{cz} or any variant thereof than is actually there in the USEPA OAQPS adduced data.

Similarly with the combustion efficiency demarcation arbitrarily set at "96.***5***."

Those lines could be put pretty much any place else depending upon what one seeks to "prove."

The fatal error lies in USEPA OAQPS's compulsion to extract a bullet-proof activist-indemnifying regulation-justifying argument from stochastically flawed data just as was done so many years ago in the formulation of today's failed federal law *(40CFR60.18)*.

MFR nonsense

There is no evidence whatsoever in the test report data to support the pseudo-scientific speculations ***quoted below*** that are highlighted in the Research Triangle Institute for U.S. Environmental Protection Agency instructions to Peer Reviewers that are appended to this review.

"The data suggest that flare performance is not significantly affected by crosswind velocities up to 22 miles per hour (mph)."

No, the USEPA OAQPS adduced data ***demonstrates*** ***conclusively*** that in the extensive USDOJ/USEPA consent-decree-imposed testing of real industrial flares in the field there is ***no*** ***evidence*** ***whatsoever*** of wind-induced combustion efficiency (CE) degradation!

"There are limited data for flares in winds greater than 22 mph."

Actually, as far as I am aware, there are ***no*** data for real industrial flares in winds greater than 22 mph! Perhaps USEPA OAQPS might like to sponsor a study similar to Siegel's in which the blower is cranked-up above 6 m/s?

Or perhaps not ...

"However, a wake-dominated flame in winds greater than 22 mph may affect flare performance."

And pigs might fly. Show me the data for *real industrial flares in the field!*

"The data available indicate that the wake-dominated region begins at a momentum flux ratio (MFR) of 3 or greater."

No, not the USEPA OAQPS adduced data in the report currently under peer review to which "peers" should restrict their attention and to which USEPA OAQPS should restrict their attention in attempting to formulate regulations; and certainly not the USEPA OAQPS adduced data on *real industrial flares in the field*.

This is pure pseudo-scientific speculation which, in my opinion, is ill-advisedly at best applied to *reacting* jets as explained below.

"The MFR considers whether there is enough flare vent gas and center steam (if applicable) exit velocity (momentum) to offset crosswind velocity."

No, it doesn't; the USEPA OAQPS MFR concept is severely flawed in that it completely neglects the physical and chemical realities of ***reacting*** jets!

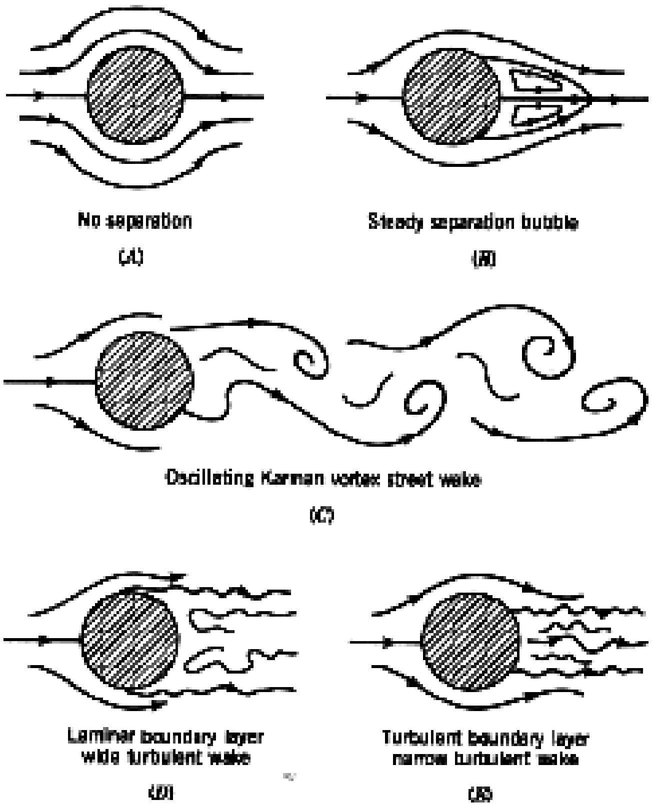
To say that this is poorly understood today would be a gross understatement.

But what is clear is that while it seemed appealing a few years ago, the manifest uselessness of the momentum flux ratio (MFR) in “correlating” combustion efficiency or anything else for that matter related to real industrial *flare* performance has by now become pretty well recognized.

MFR may very well have some utility in describing the flow out industrial stacks or other *unfired* vents in windy conditions which is, in and of itself, a seriously complicated downwash, vortex street interactive fluid mechanics phenomenon.[3]

But MFR is *not* useful in the case of flares which are required by existing federal law to be lit. The reacting jet, even if it would not appropriately be described as a “jet” on its own compared with the crosswind velocity, gains a lot of upward and rapidly-building momentum the instant the reaction starts to heat it up.

In short, the reactants get a sharp upward buoyancy-rise velocity jolt upon ignition. It may be that this marked upward momentum impulse partially accounts for the marked absence of downwash-induced wake-stabilized combustion efficiency degradation via partially reacted or unreacted eddy stripping in *real full-scale industrial flares in the field*.



Flow patterns for flow over a cylinder:
(A) Reynolds number 0.2; (B) 12;
(C) 120; (D) 30,000; (E) 500,000

Additionally, the USEPA OAQPS report overlooks the fact that there are a number of different wake regimes that establish themselves at various stages in the development of the vortex street, each of which has different pull-down and wake-formation propensities.

There exist Reynolds Number regimes in which the vortex street is more coherent than others and presumably, therefore, exerts a stronger pull-down to wake-stabilization and also, presumably, a greater propensity toward stripping partially-reacted eddies out of the trailing wake-stabilized combustion zone.

We don’t know. It hasn’t been studied. Not on *real industrial flares in the field*. Too bad, so sad, but it remains poorly understood. Perhaps we are in that critical Reynolds Number regime for toy flares in a wind tunnel but not for the conditions in which real industrial flares have thus far been tested in the field.

What we do know is that there is a great deal of data both recent and historical on real industrial flares reliably tested *in situ* in the field on which ***no CE-degrading wind effects whatsoever have been seen*.**

---

[3] See for example: http://library.usask.ca/theses/available/etd-04212008-124717/unrestricted/MAdaramola.pdf

And *quite* *literally* not "seen" – no trailing wake-stabilized plume and, therefore, no partially reacted eddy stripping combustion efficiency degradation.

Toy flares vs. real industrial flares in the field

Studies alleging a significant MFR influence on combustion efficiency are based on data from small diameter model-scale flares. How do these data scale up to real industrial flares? The key scaling concept can be found in any basic textbook on aerodynamics.

In brief, assuming a smooth vertical cylindrical stack, the relative vacuum in the low pressure region in the wake behind the flare stack is proportional to the square of the wind velocity and inversely proportional to the stack diameter; *i.e.,* $\propto V_{wind}^2/D_{stack}$. This means that for a given vent gas flow rate, *larger diameter stacks are inherently more resistant to wind effects than smaller diameter stacks.*

In short, everything else being equal, the larger the stack diameter, the less "suck" there is in the wake of the stack. Therefore, at a given wind speed, larger diameter flares are more resistant to the formation of the stationary "suck-down" vortex and hence more resistant to crosswind-induced combustion efficiency degradation.

Thus, on large flare stacks, one would not expect to see wake dominated flow except perhaps under hurricane conditions nor any so-called "MFR"-related combustion efficiency degradation as, indeed, we do not.

Both historical and recent *in situ* tests of *real industrial flares in the field* show ***no evidence whatsoever of wind related combustion efficiency degradation nor any evidence of wake stabilized behavior*.**

What about real stacks terminated at the top?

Then there is the question of the fluid mechanics at the top of a *finite* circular cylinder and that *local* influence on pull-down. It turns out that the strongest pressure deficit is not downwind 180-degrees from the upwind face of the cylinder but on the sides at 90-degrees and 270-degrees from the front, a perhaps inconvenient truth.

What does that mean with respect to alleged but increasingly discredited crosswind-induced combustion efficiency degradation on *real industrial flares in the field*?

We don't know. Nobody has studied it. But it probably matters ...

"Because wake-dominated flames can be identified visually ..."

Maybe.

Maybe not.

What is certain is that in the USDOJ/USEPA consent-decree-imposed testing of *real industrial flares in the field*, ***NO*** ***(no)*** so-called "wake-dominated behavior" whatsoever was observed as far as I am aware!

Regulating the wind

There exists a veritable plethora of authoritative articles on the aerodynamics of flow across infinite cylinders and finite cylinders terminated at the top.[4]

While I do not recommend it, in the event that USEPA OAQPS are determined to regulate or engineer the wind, perhaps the many and varied erudite dissertations that have appeared over the years in the ***Journal of Wind Engineering and Industrial Aerodynamics***[5] might be found useful.

But I doubt it ...

Flame liftoff hardly implies degraded combustion efficiency

"To avoid flame lift off, the data suggest that the actual flare tip velocity (i.e., actual flare vent gas velocity plus center steam velocity, if applicable) should be less than an established maximum allowable flare tip velocity calculated using an equation that is dependent on combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air."[6]

Hardly! Sonic flares are characterized by flames that are lifted to a perfectly stable *calculable* position some distance *above* the tip. Just because today's failed federal law *(40CFR6018)* doesn't recognize sonic flares doesn't mean we can't go there perfectly safely and with combustion efficiencies »98%!

MFR disconnect

Momentum Flux Ratio (MFR) is appropriately defined for unfired stacks as the momentum of the stack gas divided by the momentum of the wind. It is true that for MFR defined that way for relatively cold vents, an MFR < 1 generally indicates that the wind momentum predominates and the plume begins to deflect from the vertical as the plume trajectory develops.

However, for *hot* plume dispersion, depending upon just *how* hot, of course, ***buoyancy rise invariably greatly exceeds velocity rise.*** The USEPA OAQPS MFR calculation considers only the ambient process temperature of the vented flare gases.

Accordingly, by overlooking buoyancy rise for fired "stacks" such as flares, ***USEPA OAQPS are not even looking at the*** **dominant** ***plume rise mechanism!***

---

[4] See for example:
Free end effects on the near wake flow structure behind a finite circular cylinder (http://www.postech.ac.kr/lab/me/efml/html/publication/pdf/64.pdf);
Flow Around a Circular Cylinder with a Free End (http://library.usask.ca/theses/available/etd-07252011-090143/unrestricted/Heseltine_Johnathan_Lucas_sec_2003.pdf):
Tubes: cross-flow over (http://www.thermopedia.com/content/1216/?tid=104&sn=1410)

[5] http://www.sciencedirect.com/science/journal/01676105

[6] Quote highlighted in the Research Triangle Institute for U.S. Environmental Protection Agency instructions to Peer Reviewers that are appended to this review.

Upcoming papers/presentations

The foregoing issues and others will be amply illustrated and explained and in two upcoming papers, one to be presented at the International Flame Research Foundation's triennial Members Conference, Chateau Maffliers, France, June 11-13, 2012 *(Link:http://www.ngcom.it/17thMC/)*; and the other to be presented at the American Flame Research Committee's Annual Meeting, University of Utah, Salt Lake City, Utah, September 5-7, 2012 *(Link:http://www.afrc.net/assets/fordownload/pdfs/afrc_2012_call_for_papers.pdf)*.

I should like to take this opportunity once again to suggest that the latter meeting would be an excellent opportunity to promote agency/industry cooperation around flare innovation. I have extended to USEPA several cordial invitations to participate in any manner USEPA chooses, thus far without any affirmative commitment at the USEPA end, and I am more than pleased to extend the invitation again here.

AFRC would be happy to host the USEPA representatives. Supposing that USEPA are interested, at the AFRC end I can get it done in whatever form and format the agency would actually be interested in doing it.

At last year's AFRC-sponsored Industrial Flare Colloquium in Houston in which USEPA and TCEQ participated, the industrial participation was great. I expect this year, especially after the recent USEPA announcements, the interest and attendance will be even stronger at the AFRC 2012 gathering. I am sure that, just as last year, there will be a lot of AFRC industrial delegates who are interested in "EPA's Vision," *whatever* that means, *vis-à-vis* industrial cooperation on flare issues going forward and how their companies might cooperate and fit in.

In the event that USEPA would be interested in taking advantage of what seems to me to be a marvelous opportunity to promote such agency/industry cooperation on flare innovation, I would be more than pleased to make all the arrangements.

Is there a better way?

Perhaps. One of the worst that mistakes "we" – regulators, activists and industrialists alike – ever made was to allow ***emergency*** flares to become "emission control devices," thus compromising the emergency flare's legitimate and overarching safety functionality.

Far better to have a fire in plain sight safely up there in the nighttime sky than a devastating explosion back there in the plant. Nobody would disagree with that.

Perhaps that historic mistake has been viewed, in some quarters as least, as a good thing, particularly today. Over the decades since the commission of that mistake it has, after all, provided gainful employment to generations of regulators, process engineers and activist lawyers seeking injunctive relief.

But rather than perseverating in trying to specify what have proven over the last three decades to be an increasing number of to date stochastically uncorrelatable independent governing parameters, a few of which doubtless have even yet to be discovered, why not consider returning to the use of flares strictly as ***emergency*** devices, not emissions control devices?

If a plant has "too many" emergencies, fine them. When the CEO takes notice, the plant operators and process engineers will figure out how better to run and design. They always have. And there are lots of other ways to deal with the frequent but typically piddly releases that require environmental control.

It just might be a better way to a better end. I commend it to your consideration.

Appendix

MEMORANDUM

TO: James G. Seebold, Independent Consultant

FROM: Research Triangle Institute for U.S. Environmental Protection Agency

DATE: April 5, 2012

SUBJECT: Review of the *Parameters for Properly Designed and Operated Flares*

This memorandum provides background information and specific charge questions to the Flare Review Panel in its review of a report on parameters for properly designed and operated flares prepared by U.S. EPA's Office of Air Quality Planning and Standards (OAQPS). The report provides an examination of several factors that are important for a properly designed and operated flare. Based on the analysis provided in the report, the data suggest that over steaming on steam-assisted flares and excess aeration on air-assisted flares degrade flare performance. In addition, the data suggest that high winds and flame lift off can influence flare performance on all types of flares. This document will be the focus of review by the Flare Review Panel that must be completed by the end of the day on May 21st, 2012.

Background

In May 2005, the Ohio Environmental Protection Agency (OhioEPA) installed monitors at a school to investigate odor complaints. The monitoring showed high human health risk (i.e., hazard quotient 6.21 and cancer risk of 5 in 10,000) and the district closed the school. The school was located across the street from a chemical plant. In September 2005, the U.S. EPA Region 5 began investigating the chemical plant and determined that over steaming at the facility's steam-assisted flare was the likely cause of the ambient air issues.

In February 2010, the EPA, OhioEPA, and facility agreed to a consent decree requiring a new paradigm in flare monitoring that focuses on steam usage at the flare tip (i.e., combustion zone heating value and steam-to-vent-gas ratio). The consent decree also required that Passive Fourier Transform Infrared Spectroscopy (PFTIR) remote testing be performed. PFTIR remote sensing involves using a spectrometer positioned on the ground to view hot gases from the flare plume, which radiate spectra that are unique to each compound. Around the same time this consent decree was being drafted, the EPA

Office of Enforcement and Compliance Assurance (OECA) requested testing be conducted pursuant to section 114 of the Clean Air Act on several other flaring facilities using PFTIR remote sensing technology. OECA's request included a requirement to test a range of operating conditions (including typical conditions) at each flaring facility. All of the PFTIR testing carried out through these actions and used as part of this report were performed and analyzed by a single company.

In May 2009, the Texas Commission on Environmental Quality (TCEQ) contracted with The University of Texas at Austin to conduct a comprehensive flare study project on full-scale steam- and air-assist flares at the John Zink Company flare demonstration facility in Tulsa, Oklahoma. The purpose of the project was to conduct field tests to measure flare emissions and collect process and operational data in a semi-controlled environment to determine the relationship between flare designs, operation, flare vent gas lower heating value and flow rate, destruction efficiency, and combustion efficiency. The study also evaluated the performance of remote sensing technologies against extractive techniques.

EPA Review of Flares

EPA used the test data from the recent PFTIR testing and TCEQ flare studies (as well as other older experimental flare efficiency studies conducted by the EPA in the early 1980s) to investigate the effects of flare performance with varying amounts of steam (for steam-assisted flares) and air (for air-assisted flares); and high wind and flame lift off situations (for both types of flares). EPA also reviewed available scientific information from peer-reviewed studies and other technical assessments about flammability, wind, and flame lift off to support our observations. Based on an analysis of the data, we have determined that there are numerous operating parameters that should be considered in order to be confident that a flare is operated consistently and properly to achieve good combustion efficiency.

We have developed a report that is organized into nine sections and nine technical appendices. Section 1.0 introduces the report and provides a summary of our primary observations. Section 2.0 identifies the experimental flare efficiency studies and flare performance test reports used in this investigation. Sections 3.0 through 8.0 describe the development of our observations. Section 9.0 provides a list of documents referenced in this report.

The primary observations made in this report are as follows:

- To identify over steaming situations that may occur on steam-assisted flares, the data suggest that the lower flammability limit of combustion zone gas (LFL_{CZ}) is the most appropriate operating parameter. Specifically, the data suggest that, in order to maintain good combustion efficiency, the LFL_{CZ} must be 15.3 percent by volume or less for a steam-assisted flare; *i.e.*, ≤0.153. As an alternative to LFL_{CZ}, the data suggest that the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit ($NHV_{VG\text{-}LFL}$) must be greater than 6.54. (Quoted from FINAL USEPA Flare Technical Report, p.1-2)

- To identify excess aeration situations that may occur on air-assisted flares, the data suggest that the stoichiometric air ratio (SR) (the actual mass flow of assist air to the theoretical stoichiometric mass flow of air needed to combust the flare vent gas) is the most appropriate operating parameter. Specifically, the data suggest that, in order to maintain good combustion efficiency, the SR must be 7 or less for an air-assisted flare. Furthermore, the data suggest that the lower flammability limit of the flare vent gas (LFL_{VG}) should be 15.3 percent by volume or less to ensure the flare vent gas being sent to the air-assisted flare is capable of adequately burning when introduced to enough air. (Quoted from FINAL USEPA Flare Technical Report, p.1-2)

- The data suggest that flare performance is not significantly affected by crosswind velocities up to 22 miles per hour (mph). There are limited data for flares in winds greater than 22 mph. However, a wake-dominated flame in winds greater than 22 mph may affect flare performance. The data available indicate that the wake-dominated region begins at a momentum flux ratio (MFR) of 3 or greater. The MFR considers whether there is enough flare vent gas and center steam (if applicable) exit velocity (momentum) to offset crosswind velocity. Because wake-dominated flames can be identified visually, observations could be conducted to identify wake-dominated flames during crosswind velocities greater than 22 mph at the flare tip. (Quoted from FINAL USEPA Flare Technical Report, p.1-3)

- To avoid flame lift off, the data suggest that the actual flare tip velocity (i.e., actual flare vent gas velocity plus center steam velocity, if applicable) should be less than an established maximum allowable flare tip velocity calculated using an equation that is dependent on combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. (Quoted from FINAL USEPA Flare Technical Report, p.1-3)

- LFL_{CZ} could apply to non-assisted flares (i.e., the LFL_{CZ} must be 15.3 percent by volume or less in order to maintain good combustion efficiency). Also, the same operating conditions that were observed to reduce poor flare performance associated with high crosswind velocity and flame lift off could apply to non-assisted flares. Finally, because of lack of performance test data on pressure-assisted flare designs and other flare design technologies, it seems likely that the parameters important for good flare performance for non-assisted, steam-assisted, and air-assisted flares cannot be applied to pressure-assisted or other flare designs without further information. (Quoted from FINAL USEPA Flare Technical Report, p.1-3)

Document Availability

The report is being made available to the Panel in the form of the attached electronic file, which we request be forwarded to all members of the Panel.

Specific Charge in Reviewing the *Parameters for Properly Designed and Operated Flares*

We ask the Panel to focus on the charge questions below in their review of the report, but we would appreciate comments on any aspects of the information in the report or other flare topics. In addition, all references used in this report are available upon request.

Section 2: Available Flare Test Data

1. Please comment on the agency's criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have led to inappropriate exclusions of relevant data points.

Section 3: Steam and Flare Performance

2. Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?

3. Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?

4. Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to $LFL_{VG\text{-}LFL}$) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?

Section 4: Air and Flare Performance

5. Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning? Does the flare data adequately support the EPA's observations?

Section 5: Wind and Flare Performance

6. Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities greater than 22 mph at the flare tip to indicate wake-dominated flame situations. Additionally, also comment on the agency's observation that in the absence of crosswind greater than 22 mph, a low MFR does not necessarily indicate poor flare performance. Comment on the effectiveness of observations identifying wake-dominated flames. Does the flare data adequately support the EPA's observations?

7. Did the agency adequately examine other operating parameters (different from MFR) for identifying wake-dominated flames? Are there specific other parameters that should be given more or less emphasis?

Section 6: Flare Flame Lift Off

8. Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. Does the flare data adequately support the EPA's observations? Are there specific other parameters or methods/equations that should be given more or less emphasis?

Section 7: Other Flare Type Designs to Consider

9. Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity to non-assisted flares, pressure-assisted flares, and other flare designs.

Section 8: Monitoring Considerations

10. Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters: LFL_{CZ}, LFL_{VG}, $LFL_{VG, C}$, the ratio of NHV_{CZ} to $NHV_{VG\text{-}LFL}$, C_{CZ}, SR, MFR, and V_{max}. Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.

Attachment H

Dr. Joseph Smith

Laufer Endowed Chair of Energy

Missouri University of Science and Technology

A Technical Review of Parameters for Properly Designed and Operated Flares

Report for Flare Review Panel
April 2012

U.S. EPA Office of Air Quality Planning and Standards (OAQPS)

This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by EPA. It does not represent and should not be construed to represent any Agency determination or policy

Review Performed By:

Joseph D. Smith, Ph.D.

Professor and Laufer Endowed Energy Chair
Department of Chemical and Biological Engineering
Missouri University of Science and Technology
Rolla, Missouri

Submitted:

June 5, 2012

Evaluation Rubric:

Scoring: 1 = POOR, 2 = FAIR, 3 = AVERGAE, 4 = GOOD, 5 = EXCELLENT

Technical Content

Poor (1):
- No reference to literature
- Inconsistent conclusions and/or recommendations
- Incorrect statements and/or calculations

Fair (2):
- Missing some references
- No conclusions/recommendations
- Incomplete calculations that partial support conclusions/recommendations
- Little support for technical statements

Average (3):
- Includes most references
- Limited conclusions/recommendations
- Limited calculations support conclusions/recommendations
- General support for technical statements

Good (4):
- Includes key references
- High level conclusions and recommendations
- Key calculations included in discussion (no foundation for calculations or assumptions used)
- Key technical statements based on supporting evident from literature and/or calculations

Excellent (5):
- Includes key references plus additional supporting references
- Strong conclusions and recommendations included
- Detailed calculations included with clear explanation and sample calculations to illustrate
- All technical statements supported with clear evidence from literature and/or calculations

I- Design and execution of the research activity 25/30

- *Did the approach show creativity or new thought in attacking the design problem?* Score: 7/10

Based on the analysis reported in this document, the following specific conclusions are made:

1. To identify over steaming situations that may occur on steam-assisted flares, the lower flammability limit of combustion zone gas (LFL_{CZ}) is the most appropriate operating parameter,
2. To identify excess aeration situations that may occur on air-assisted flares, the stoichiometric air ratio (SR) (the actual mass flow of assist air to the theoretical stoichiometric mass flow of air needed to combust the flare vent gas) is the most appropriate operating parameter,
3. Flare performance is not significantly affected by crosswind velocities up to 22 mph,
4. Wake-dominated flare operation begins at a momentum flux ratio (MFR) of 3 or greater,
5. Actual flare tip velocity (i.e., actual flare vent gas velocity plus center steam velocity, if applicable) should be less than an established maximum allowable flare tip velocity calculated using an equation dependent on combustion zone gas composition, effective flare tip diameter, flare vent gas density, and air density,
6. For non-assisted flares, the same criterion $LFL_{CZ} \leq 15.3\%$ by volume is applicable to ensure good combustion efficiency.

This work introduces a new metric LFL_{cz} (Lower Flamability Limit of gases in the combustion zone above a flare stack) with a criterion to quantify flare performance (i.e., $LFL_{cz} \leq 15.3$). The validity of using this metric to evaluate flare performance was quantified using several key factors known to impact flare performance (i.e., tip diameter, tip velocity, waste fuel composition, inert composition, ambient wind speed, ambient air density, flare gas density, etc.). A method to calculate the LFL for a mixture including inert gases (i.e., nitrogen, carbon dioxide, and water vapor) was also introduced. Test results from several flare experiments from industry, academia, and government research organization were analyzed using this metric and criterion. It was concluded that this metric is valid and effective for quantifying flare performance for steam/air assisted flares, non-assisted flares, and pressure assisted flares. In addition, two additional performance metrics were briefly considered including "Net Heating Value" and "Steam Ratios".

In general, two phenomena control flare performance: 1) reaction kinetics, and 2) gas mixing. The report compares available flare performance data in terms of levels of steam (for steam assisted flares); or air (for air assisted flares); high ambient wind conditions, and flame lift off. Unfortunately, the analysis did not evaluate the metrics proposed by Smoot, et.al. (2010)[1] which was developed and reported to the EPA and used to evaluate steam flare performance for the Department of Justice. As a recommendation for future work, this additional analysis should be conducted.

---

[1] Smoot, L.D., Jackson, R.E. and Smith, J.D., "Toward Combustion Efficiency Control Criteria in Open Industrial Flares," Advances in Combustion Technology: Improving the Environment and Energy Efficiency, *American Flame Research Committees - International Pacific Rim Combustion Symposium*, Sheraton Maui, Hawaii, September 26 –29 (2010)

The project plan was not documented in the report that was reviewed. However, the clear objective of this work was to assess flare performance to identify key operating parameters that quantify "efficient" flare operation. In this regard, the project plan appeared well designed and executed.

However, reading the analysis indicated a clear bias related to establishing the proposed metric LFL_{cz}. In many instances data points that did not meet the proposed criterion were excused as "bad data resulting from inaccurate testing procedure or analysis". The proposed metric is a single number that is being used to assess the very complex nonlinear interaction between reaction kinetics and turbulent gas mixing. Thus, it is expected by this author that this metric should not reasonable be expected to account for all flare performance data. No mention was made of instances where certain data points agreed with the metric but may also have been inaccurate due to poor testing procedure or data analysis. This data quality error is related to accepting bad data as good data to confirm a hypothesis. If certain data that do not agree with the proposed hypothesis are rejected to confirm the applicability of the metric, then the same standard must be applied for all data evaluated from a given test. Unfortunately, this did not appear to be the standard taken in this analysis.

- *Was the project plan well designed?* Score: 10/10
- *Was the project executed efficiently?* Score: 8/10

II- Evaluation of the research results: 32/40

- *How reliable are the results?* Score: 15/15

The flare test data as reported are reliable with discrepancies highlighted (i.e., plot of Combustion Efficiency vs. Momentum Flux Ratio by Seebold, et.al., 2004). The data are well referenced and are presented in a comprehensive fashion. It would be nice to have the original data sets for comparison against what is reported in this report. However, based on my review of the literature the data as presented appear reliable thus any analysis will be reliable.

- *Are the results interpreted correctly?* Score: 10/15

For the most part, the test results are evaluated in a consistent basis and the conclusions drawn are correct. However, there are examples throughout the report that illustrate a bias toward justifying all performance data based on this single parameter. Thus, the results are not interpreted correct but do reflect the most comprehensive analysis of existing flare test data available in the open literature.

- *Are the conclusions based on sound data?* Score: 7/10

The conclusions drawn as a result of this analysis appear to be based on a thorough evaluation of valid data. However, it appears there remains unaccounted for factors that affect flare performance. Clearly, kinetics is critical to the combustion process. Wang et.al., (1996) shows that small amounts of H2O increase the burning rate by modifying the OH radical. Brouwer et.al., (1994) points out that the production of products of incomplete combustion (PIC) is controlled by complex interactions between turbulent mixing and chemical kinetics. This fact is evident when the authors attempt to explain why several data points exhibit combustion efficiency less than 96.5% for a LFLcz < 15.3, which is proposed as the criteria for good flare performance.

III-Importance and/or relevance of the research: 10/30

- *Did the report clearly identify relevance/importance of gas flaring and flare technology?* Score: 10/10

  Yes, the importance of defining the stable flame envelope of operating conditions for a flare was discussed in terms of 40 CFR60.18 and 40 CFR63.11(b) and the impact of reduced waste gas sent to flares on their operating efficiency (i.e., combustion efficiency).

- *Did the report address the practical applications of gas flaring and flare technology* Score: 0/10

  No, this was not part of this report.

- *Did the report discuss the economic and environmental implication flare technology?* Score: 0/10

  No, this was not part of this report.

Overall Score 67/100

As requested of the Flare Review panel, I have focused my report review on the charge questions listed below. The comments listed below are a summary of my review comments and the entire report with my hand written review comments are available on request.

Section 2: Available Flare Test Data

1. *Please comment on the agency's criteria for excluding available flare test run data from final analyses, and whether application of these criteria may have led to inappropriate exclusions of relevant data points.*

   Data quality has been assessed using the following questions[2]:

   - What decision is being made that leads to action?
   - What is the cost of being wrong?
   - What is the cost of being right?
   - What data are critical to the decision being made?
   - How accurate and precise must the data be to ensure the correct decision is made?
   - What are the time and resource constraints on data collection?
   - How will the data be evaluated?
   - How will clear and concise documentation for effective communication be achieved?

   These questions were used to assess the flare test data evaluated in the present report considering the project objective (listed earlier):

   - *What decision is being made that leads to action?* Identifying an accurate and defendable performance metric to assess flare efficiency will allow the EPA to regulate flare operation. The recent attention to flare emissions indicates that identifying the "correct" metric is an important decision that will allow the agency to act.
   - *What is the cost of being wrong?* If the EPA selects a metric that is overly restrictive (inaccurate) in quantifying flare performance, it may result in unnecessary fines and additional legal costs of >\$100MM (estimate assumes approximate legal costs/case of ~\$1MM, >100 U.S. chemical plants/refineries subject to restriction). If the inaccurate metric is too lax and allows excessive emissions (i.e., low combustion efficiency) the cost in human health could easily exceed this amount but may be unquantifiable.
   - *What is the cost of being right?* The cost of performing additional testing to more fully quantify the reaction kinetic and turbulent mixing effects on combustion efficiency for the conditions described in the present report (i.e, high olefins/hydrogen content, varying inert composition and levels, ambient wind speed, tip velocity, tip design). Previous work reported in the literature and summarized in this report represent a cost of >\$3MM (assumes ~\$10,000/data point for >300 data points listed in report). Additional testing based on this analysis may cost on the same level.

---

[2] C. Christensen, Private Communication to J.D. Smith, Dow Chemical Company, 1993.

- *What data are critical to the decision being made?* Reproducible combustion efficiency measurements taken from flares operating in a controlled (quantified) condition using validated test procedures with established monitoring equipment (see Section 8) is the critical data required to make this decision. A complete data set must include information from the different levels of the "Validation & Verification" pyramid (see Figure 1).

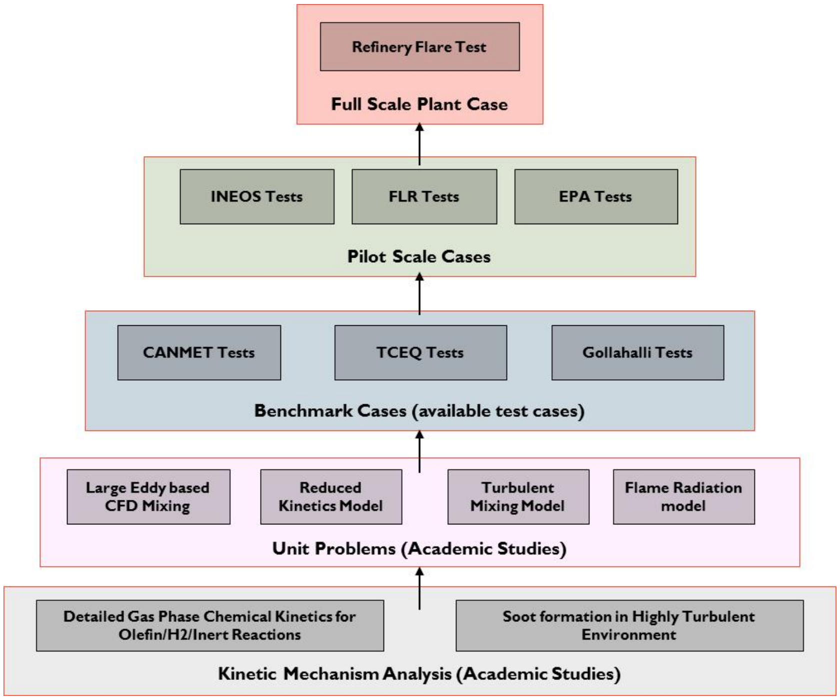


Figure 1 - Validation and Verification Pyramid for Flare Testing

- *How accurate and precise must the data be to ensure the correct decision is made?* Combustion efficiency > 96.5% ±1.5% at a 99% confidence interval was been established as representative of "good flare performance" (see Section 3.1). This implies the collected combustion efficiency data must be accurate to at least 3 significant figures. Given that the combustion efficiency is based on the measured composition of gases, this implies these measurements must also have at least 3 significant figures.

- *What are the time and resource constraints on data collection?* Since this data will be used to establish EPA guidelines, the time and resource constraint to collect this data will be determined by the EPA.

- *How will the data be evaluated?* To avoid biasing in the data collection and analysis, this work should be performed by a dis-interested third party (not industrial consortium nor regulatory agency).

- *How will clear and concise documentation for effective communication be achieved?* Results from this analysis should be published in the open literature with appropriate peer review to ensure the data and its analysis is thoroughly and critically reviewed. Results of this data and its analysis should be made available on the EPA website to ensure broad distribution to the technical community.

In addition to the data quality assessment, I've including the following conclusions based on my review of the data sets included in this analysis and the assessment of which data points should (should not) be included in the analyses.

Table 2.1 in section 2 lists ten different data sets that were analyzed including 582 steam-assisted flare test runs (270 test runs eliminated because no steam was used in the tests or there was not enough data to quantify flare performance) and 111 air-assisted flare test runs (67 test runs eliminated due to lack of test information). The report clearly states why each data set (point) was eliminated. However, later in the report in section 3 several data points appear to be dismissed because they don't conform to the proposed metric. Eliminating data because of problems in the testing methodology (i.e., shaping steam ring failure)[3] is a valid argument but no discussion was found throughout the report where a data point that agreed with the proposed metric was dismissed because of poor testing methodology or incorrect analysis. This gives the impression that the data analysis may be biased to support a proposed hypothesis. The authors do provide reasons for excluding 66 data points that do not fit the overall trend including: 1) inaccurate calculation of LFL_{cz}, 2) combustion efficiency measurements were inaccurate, 3) flammability is not an appropriate parameter to represent flare performance because it does not completely explain the performance of a flare. Of these three reasons for excluding the 66 data points it appears that the last reason is likely most accurate since it is hard to imagine that either the LFL_{cz} calculation or the combustion efficiency measurements were incorrect for this many data points. This conclusion is not surprising since flare performance is governed by the nonlinear relation between reaction kinetics (see Figure 2) and turbulent mixing. Small reaction zones that sustain combustion have been shown to form inside small turbulent eddies generated by the shearing action occurring in the turbulent flow present inside the flare tip. Thus, the complex kinetics describing olefin/hydrogen/oxygen combustion reaction chemistry is closely linked to turbulent fluid mixing. Both of these phenomena are highly non-linear so the chance of fully quantifying this behavior with a single parameter is highly unlikely.

Section 3: Steam and Flare Performance

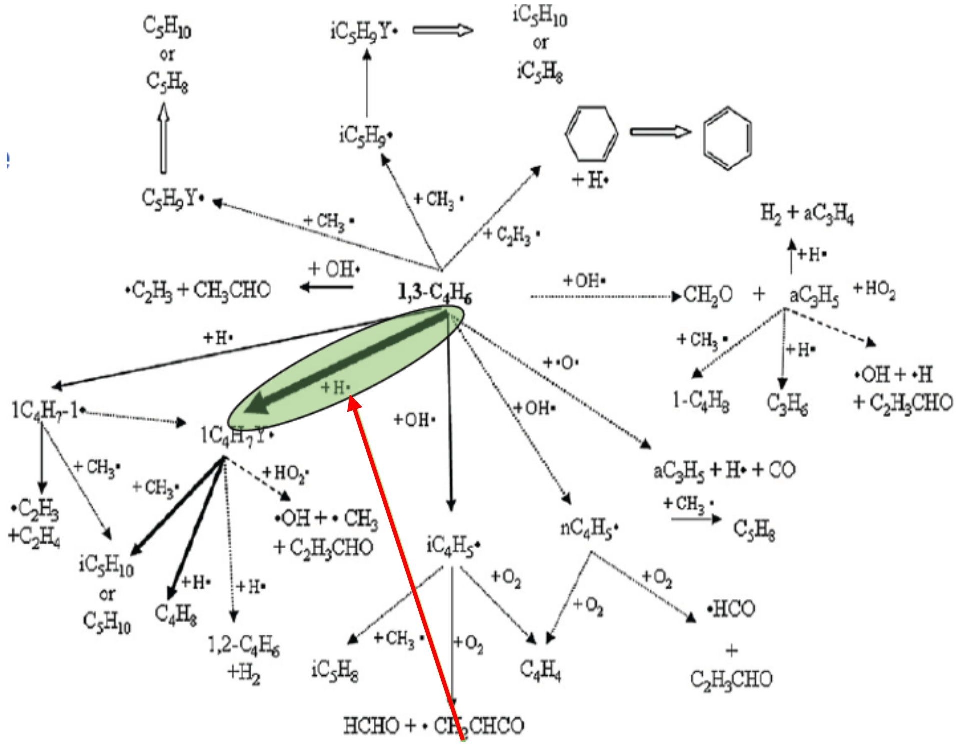
1. *Please comment on the lower flammability limit of combustion zone gas (LFL_{CZ}) as an operating parameter for indicating over steaming situations on steam-assisted flares. Comment on the agency's use of the ratio of the net heating value of the combustion zone gas (NHV_{CZ}) to the net heating value of the flare vent gas if diluted to the lower flammability limit (NHV_{LFL}) as an alternative to LFL_{CZ}. Does the flare data adequately support the EPA's observations?*

   The application of LFL_{cz} as a performance metric for flare operation is explained very well and clearly has some justification. As discussed earlier, flare performance is controlled by reaction kinetics and turbulent mixing. Finding a single parameter to quantify these highly

---

[3] See pages 3-13 and 3-17 for a discussion of a potential problem with reported test data as a reason to exclude it from the combustion efficiency vs LFL_{cz} plot shown in Figure 3-4.

non-linear coupled phenomena is highly unlikely. However, as shown in Figure 3-4, a majority of the test data included in the analysis have a combustion efficiency above the 96.5% level judged as representative of "good" flare performance. Thus, based on this and the subsequent analysis of the outliers not conforming to this metric, the LFL_{cz} appears a good measure of flare performance. When the LFL_{cz} metric is compared to the net heating value ratio (shown in Figure 3-11), little improvement difference is shown. Both metrics fail to capture 100% of all data accepted as quality data and the same argument holds for the second metric as the first – using a "single" number to quantify the complex behavior of reaction kinetics coupled to turbulent mixing is unreasonable.



67% of reaction goes through this channel

Figure 2 - Reaction path analysis for combustion of 1,3 Butadiene at 980 K at a distance of 0.47 cm in front of burner[4]

2. *Is there sufficient evidence that chemical interactions are occurring that make the calculated LFL_{CZ} inaccurate with respect to the 15.3% LFL_{CZ} threshold discussed? Is there other data available (that is not discussed in this report) that may help clarify our discussion about specific chemical interactions related to lower flammability limits of gas mixtures?*

To assess this issue, the report discusses three conditions: 1) equal olefin/hydrogen cases (Table 3-3), 2) low olefin/high hydrogen (Table 3-4) and 3) high olefin/low hydrogen (Table 3-5). Based on this analysis, it appears that the olefin concentration doesn't seem to impact the measured combustion efficiency. Understanding that specific chemical compounds are more reactive than others (i.e., flame speed for acetylene is much higher than flame speed for

---

[4] Gueniche, H.A., Glaude, P.A., Fournet, R., Battin-Leclerc, F., "Rich Premixed Laminar Methane Flames Doped by Light Unsaturated Hydrocarbons: II. 1,3-Butadiene," Combustion and Flame, 151, 245-261 (2001).

methane) this conclusion does not make sense. Thus, it appears that this effect is somehow missed using the LFL metric. To properly capture these phenomena will require more detail related to complex chemical kinetics coupled with turbulent mixing. The best way to accomplish this is using detailed computational fluid dynamics models based on transient flow and reaction chemistry as discussed by Smith et.al., (2007)[5] and Smith et.al, 2009[6].

3. *Did the agency adequately examine other operating parameters (different from LFL_{CZ}; or the ratio of NHV_{CZ} to LFL_{VG}-LFL) that could indicate over steaming situations? Are there specific other parameters that should be given more or less emphasis?*

   As discussed by the agency, "compounds with a high carbon to hydrogen ratio have a greater tendency to smoke and require better mixing for smokeless flaring. The required steam rate is dependent on the carbon to hydrogen ratio of the gas being flared."[7] This clearly indicates other parameters that should be given more emphasis. Nowhere in the discussion of the LFL_{cz} metric is the carbon-to-hydrogen ratio discussed other than indirectly when considering flare performance for various ratios of olefin and hydrogen (discussed earlier).

   An entire separate analysis originally funded by the agency has not been included in this discussion nor has this work been referenced in this report. The work by Smoot et.al. (2009)[8] (also discussed by Smoot et.al., [2010][1]) evaluates the correlation between flare gas adiabatic flame temperature (T_{ad}) and flare gas Lower Heating Value (LHV) and finds that the flare gas LHV value may be a useful criterion for regulating flare operation. A similar graph for vent gas LHV vs. vent gas T_{ad} indicates that vent gas LHV is not a reliable criterion for regulating flare performance. Computations also evaluated the Flammability Ratio (FR) in relation to the Lean Flammability Limit (LFL) to identify cases where flare gas combustion would not occur or would be highly inefficient. Adiabatic flame temperature correlated linearly with FR and declined with decreasing fuel molecular weight. A key recommendation from this work was to evaluate the FR criteria for flare performance using available flare performance data, as has been presented in the current work.

Section 4: Air and Flare Performance

1. *Please comment on the stoichiometric air ratio (SR) as an operating parameter for indicating excess aeration situations on air-assisted flares. Additionally, also comment on whether the lower flammability limit of the flare vent gas (LFL_{VG}) is an appropriate operating parameter for determining whether the flare vent gas being sent to an air-assisted flare is capable of burning? Does the flare data adequately support the EPA's observations?*

---

[5] Smith, J.D., Suo-Ahttila, A., Smith, S.K., and Modi, J., "Evaluation of the Air-Demand, Flame Height, and Radiation Load on the Wind Fence of a Low-Profile Flare Using ISIS-3D," *AFRC-JFRC 2007 Joint International Combustion Symposium*, Marriott Waikoloa Beach Resort, Hawaii, October 21-24, (2007).

[6] Smith, J.D., Smoot, L.D., and Jackson, R.E., "Technical Foundations of New Performance Criteria for Efficient Operation of Industrial Steam-Assisted Gas Flares," *IFRF 16th International Members' Conference: Combustion and Sustainability - New Technologies, New Fuels, New Challenges*, Boston, Massachusetts June 8-10 (2009).

[7] US EPA OAQPS, "Control Cost Manual: Chapter 7 – Flares," 5th Edition, February (1996).

[8] Smoot, L.D., Jackson, R.E., and Smith, J.D., "Combustion Efficiency Control in Single-Stage, Industrial, Steam-Assisted Open-Flares," Technical Report CR – SAS IF – 09A, May (2009). see http://sas-ieng.com/www/services/technical-seminars-presentations-papers-and-reports/

Using the Stoichiometric Ratio (SR) to quantify combustibility of a gas mixture is well established (see Glassman, 1996[9] and Kuo, 2005[10]). In the present application, the SR is being used to assess the combustibility of the vent gas coming up the flare stack. In this application, the SR is clearly applicable as is the LFL_{CZ} (or LFL_{VG}) for air flares. However, the fact remains that as with steam flares, it is difficult to completely characterize the complex coupled phenomenon of reaction kinetics and turbulent mixing which is clearly evident in the data plots of SR vs Combustion Efficiency (see Figure 4-1 through 4-4). The criteria of SR < 7 to quantify "good" air flare performance is questionable since most of the air responsible for smokeless flare operation comes from air entrained after the vent gas exists the flare stack[11].

Also, as the report correctly points out, relevant data for industrial air flare performance must be taken on flare tips with a diameter > 3" to be representative of larger flare tips (i.e., tips with diameters greater than 24"). Air flare data taken on small tips (i.e, < 3" Tip Diameter) is misleading because the mixing phenomena in these small tips is much different than occurs in large tips (i.e., mixing dominates the combustion process).

Finally, the report reasons that since the assist media is mixed with the vent gas in the flare stack it is appropriate to use LFL_{VG} instead of LFL_{CZ}. For standard air flares this conclusion may be correct but for non-standard air flares (i.e., John Zink's Annular Air Flare or Zeeco's high pressure air flare) this will not be correct and the criteria should continue to use LFL_{CZ} as was used for steam flares.

Section 5: Wind and Flare Performance

1. *Please comment on the momentum flux ratio (MFR) as an operating parameter in crosswind velocities >22 mph at the flare tip to indicate wake-dominated flame situations. Additionally, also comment on the agency's observation that in the absence of crosswind >22 mph, a low MFR does not necessarily indicate poor flare performance. Comment on the effectiveness of observations identifying wake-dominated flames. Does the flare data adequately support the EPA's observations?*

   As shown in Section 5, the MFR when based on wind speed and not flare gas tip velocity is an appropriate operating parameter. As pointed out, there are many examples where the MFR is less than 3 (or 0.1 for Figure 5-5 from Seebold)[12] but the combustion efficiency remains above 96.5%. Also, it is pointed out that completely different operating conditions can produce the same MFR. Thus, the conclusion that MFR may only be applicable when the transition to wake dominated combustion is caused by increasing crosswind velocity and not a decrease in flare tip velocity.

2. *Did the agency adequately examine other operating parameters (different from MFR) for identifying wake-dominated flames? Are there specific other parameters that should be given more or less emphasis?*

---

[9] Glassman, Irvin, Combustion, Third Edition, Academic Press, New York (1996).
[10] Kuo, Kenneth K. Principles of Combustion, Second Edition, John Wiley and Sons, NY (2005).
[11] Baukal, C.E., The John Zink Combustion Handbook. Boca Raton, Florida, CRC Press (2001).
[12] Seebold has indicated that the data shown in his 2004 paper represented a collection of all flare data he had gathered from the literature and plotted himself.

Certainly, a wake-dominated flame represents a condition where the unburnt hydrocarbon could be stripped from the flare plume thus reducing the combustion efficiency of the flare. The report correctly assesses the Plume Buoyancy Factor (BP) and the Power-Factor (PF) for a flare flame. Neither of these metrics captures the complex coupling between reaction kinetics and turbulent mixing occurring at the flare tip exit. For crosswinds > 22 mph, the latter phenomena appears to dominate (i.e., there is enough momentum to strip flare gas from the plume before it reacts). Therefore, it appears reasonable to focus on a metric that explicitly includes the kinetic effects and the turbulent mixing effects. Lastly, the report correctly points out the significant effect wind has on steam flare performance due to the upper steam jets not participating in the flare flame (i.e., the steam jets pass overhead of the reaction zone thus reducing the steam jet impact on combustion).

Section 6: Flare Flame Lift Off

1. *Please comment on the maximum allowable flare tip velocity equation which considers combustion zone gas composition, the flare tip diameter, density of the flare vent gas, and density of air. Does the flare data adequately support the EPA's observations? Are there specific other parameters or methods/equations that should be given more or less emphasis?*

The report focuses on the Shore equation because it considers the LFL. In this analysis, 213 of the 330 flare tests were excluded from the analysis due to limited data required to use the equation or the tests were judged outside of normal operation (i.e., too much assist air because SR > 7). Thus, only 108 data points were analyzed and of these 10 which met the LFL_{cz} criteria did not achieve "good" combustion efficiency (> 96.5%). In addition, the plot of flare metric vs lift off velocity using the Shore equation (see Figure 6-1) showed that all but three were judged as having no flame lift off. Several of the tests not having flame lift off had combustion efficiencies < 96.5%. This analysis shows that flame lift off is not itself an strong indicator of poor flare performance but flame liftoff does indicate unstable combustion which can lead to poor combustion efficiency.

Flame liftoff is a balance between reaction kinetics (i.e., flame speed) and mixing (reactants mixed with combustion radicals to maintain combustion zone). When the tip velocity exceeds the flame speed the flame is known to "lift-off" from the tip. In this case, detailed transient LES based CFD analysis is required to capture this affect and a single parameter is not appropriate.

Section 7: Other Flare Type Designs to Consider

1. *Please comment on the applicability of the LFL_{CZ} parameter, maximum allowable flare tip velocity equation, and the observations regarding crosswind velocity to non-assisted flares, pressure-assisted flares, and other flare designs.*

Pressure-assisted flares (i.e., multipoint ground flares) use momentum to induce (mix) surrounding air with the flare gas. For a Pressure-assisted flare, the LFL parameter may be appropriate as stated in the report. Also, the MFR and the V_{max} methodologies are also likely applicable to non-assisted flares.

Section 8: Monitoring Considerations

1. *Please comment on the appropriate monitoring equipment needed to ensure good flare performance and on any other known monitoring methods (not discussed in this report) for monitoring the following parameters:* LFL_{CZ}, LFL_{VG}, $LFL_{VG,C}$, *the ratio of* NHV_{CZ} *to* $NHV_{VG\text{-}LFL}$, C_{CZ}, *SR, MFR, and* V_{max}. *Also, please comment on operating scenarios and conditions where less robust monitoring equipment could be used to determine the operating parameters of interest.*

   The Panametric gas monitor has been used to measure combustion effluent gas (see expert report for DOJ case on Questar vs DOJ).

   The "presumptive" device for effectively and accurately monitoring flare gas effluent composition to determine flare combustion efficiency is the "Open Path" FTIR as developed and used by R. Spellicy and by Clean Air Engineering, Inc.

   Certainly, a performance metric for flares relies on measureable data. The instruments listed in the report for the various metrics appear correct and no additional information can be added by this reviewer.