Conclusion of Flare-In-A-Box™ Baseline Testing.

TUV SUD FLOW MEASUREMENT WORKSHOP ABERDEEN

GCL ENGINEERING DEPARTMENT

Presenter : Simon Kretzschmar - Engineering Manager

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Presentation Outline

- A background to historical testing and the enclosed flare testing concept.
- Newest updates to the GCL enclosed flare test facilities.
- Measurement certainty and evaluation.
- Test results from generic pipe flares of variable sizes.
- Test results from generic pipe flares with variable gas composition.
- Prediction model development.

Flare Combustion Efficiency – A Background

- Flares are firstly safety relief devices; however, now they are being critically looked as emissions sources.
- Flaring burns excess hydrocarbons; efficiency determines emissions. Fugitive methane from unburnt hydrocarbons has considerable global warming implications.
- Regulations often assume a flat **98% combustion efficiency**. This is the fraction of carbon compounds combusted entirely to CO2.
- This number comes from **limited early studies**, not broad real-world data which is often very difficult to obtain.
- With the advent of methane monitoring via satellite there have been indications for years that emissions from flares may be significantly higher than expected.
- Actual efficiency can vary with **wind, gas composition, flare tip design, and condition**.
- Historical test work is limited in scope and in many cases not defensible under scrutiny from regulators.
- Bottom line: **98% is uncertain and may not reflect reality.**
- Should **all flares** be treated in the same manner under **all operating** conditions?

Traditional Hood Testing of Full Sized Flares

Traditional flare testing provided significant information on tip efficiencies through the 80s and 90s but uses broad assumptions that don't give the overall picture.

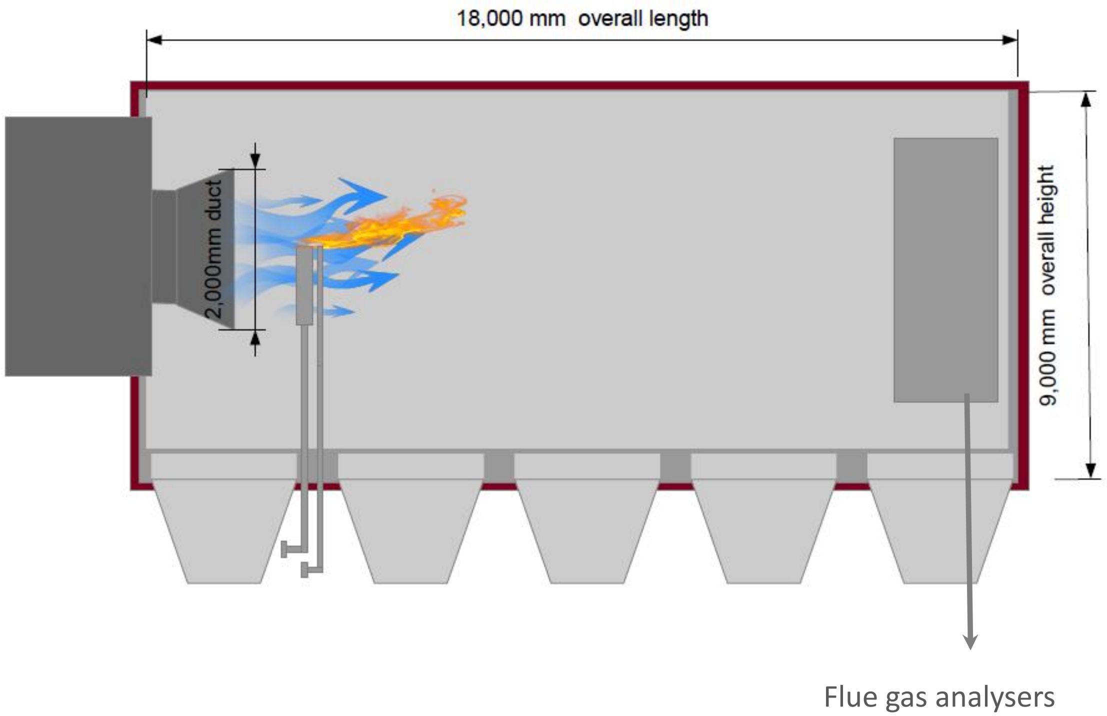
Defensibility?

1. Inaccurate plume location.
2. Non-variability on wind and rain.
3. Inaccurate division sampling of total plume.
4. Inaccurate stream measurement at low flow rates.
5. Uncertainty quantification too poor.

The Flare-In-A-Box™ Concept

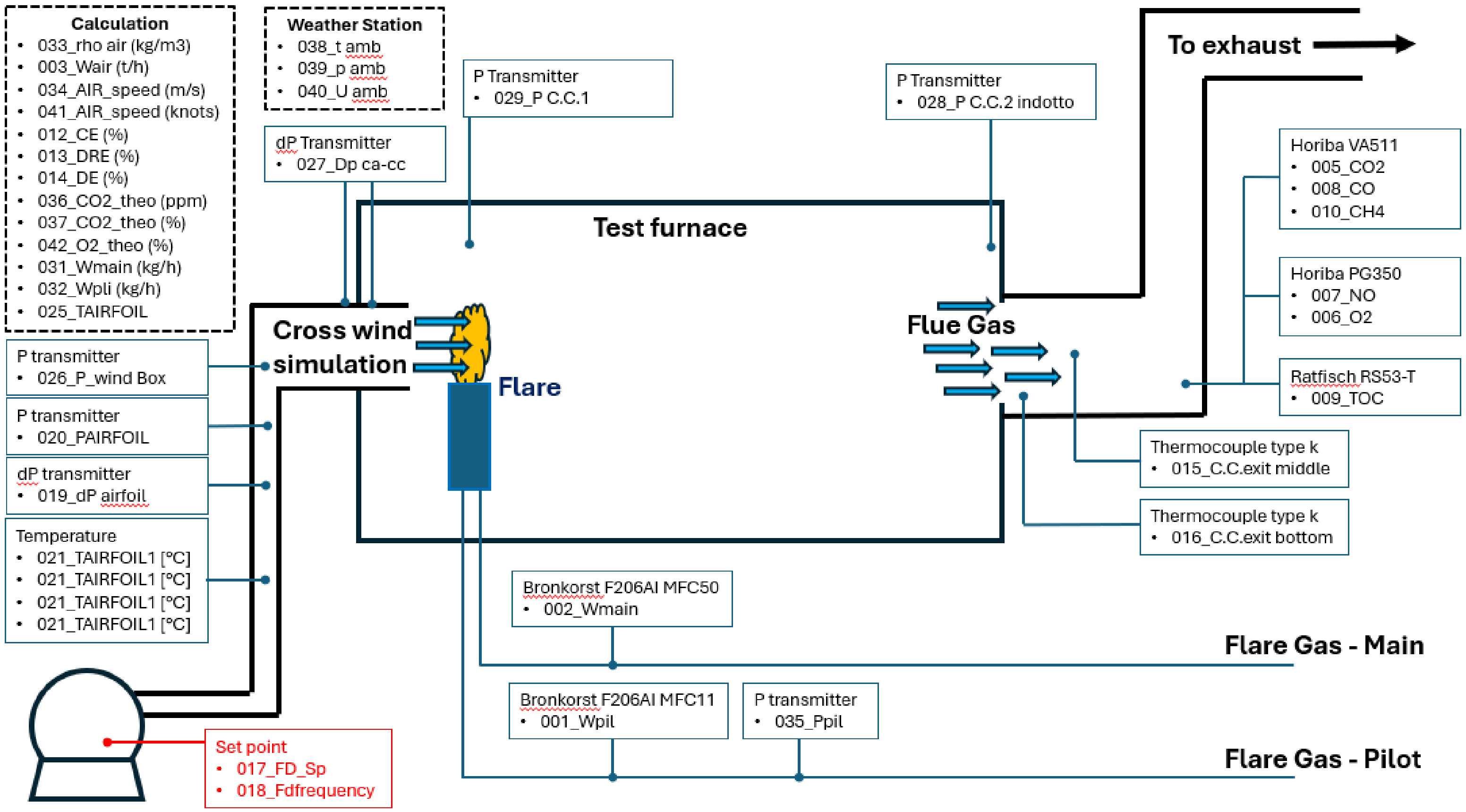
Full sized and scale testing of real world flare tips is possible.

- The concept of enclosed testing was proven in 2023. Throughout 2024 Greens Combustion and CCA, together with a major owner operator, other engineering companies have been testing and validating the efficiency of multiple flare tip types and operating cases.
- Not only is it possible to test the impact of variable atmospheric conditions but also gas blends and mixtures from Natural Gas to LPG, N_2, CO_2, H_2 and NH_3.
- More testing is on the way, with results being placed into the public domain.
- This presentation will discuss the accuracy and ability of the Flare-In-A-Box™ System to test a wide range of scales, full sized tip designs and flare gases.



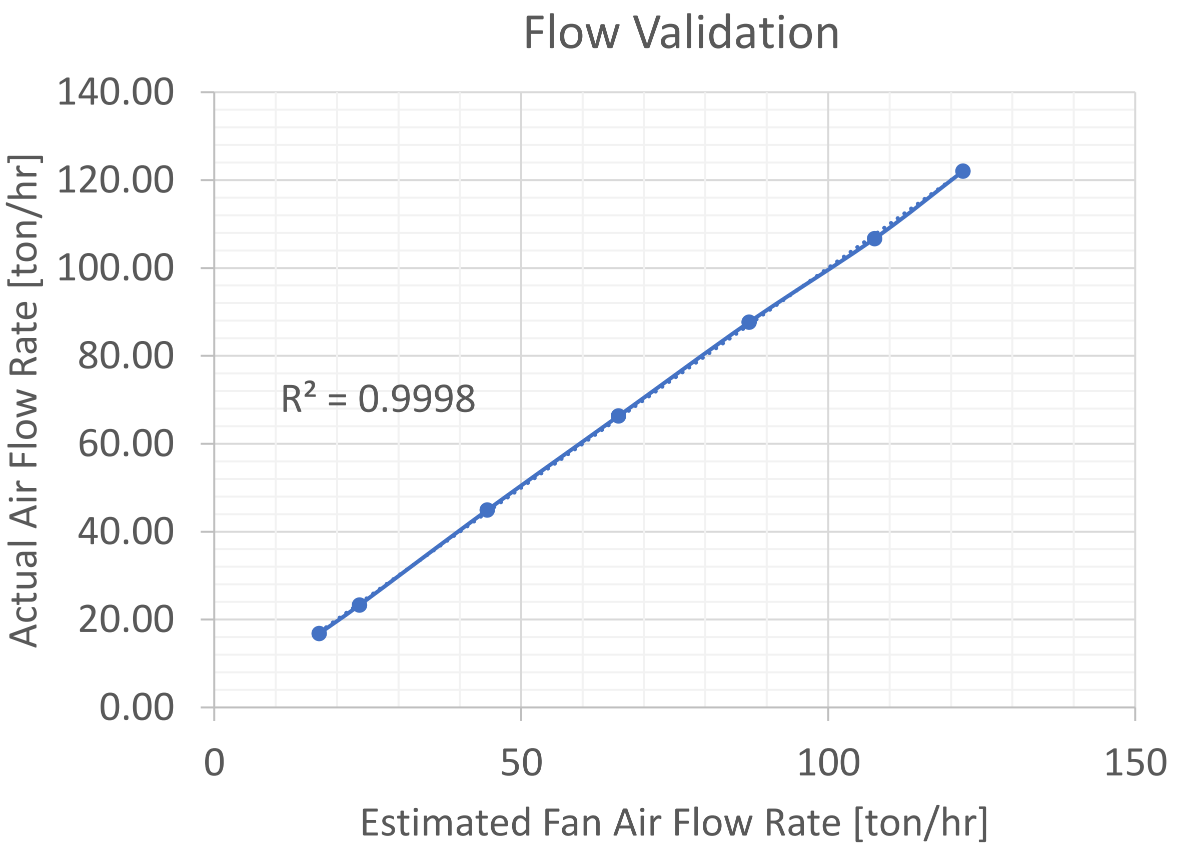
Upgrades in Controls And Emissions Calibration

- There were some initial difficulties and inaccuracies during concept testing.
- Extensive enhancement work completed improving ranges of detection and accuracy.
- The upgrades to emissions sampling and measurement systems now allowed for significant accuracy improvement across the range of operation as well as determination not only of the flare efficiency but even emissions measurement of components such as NO and N2O.

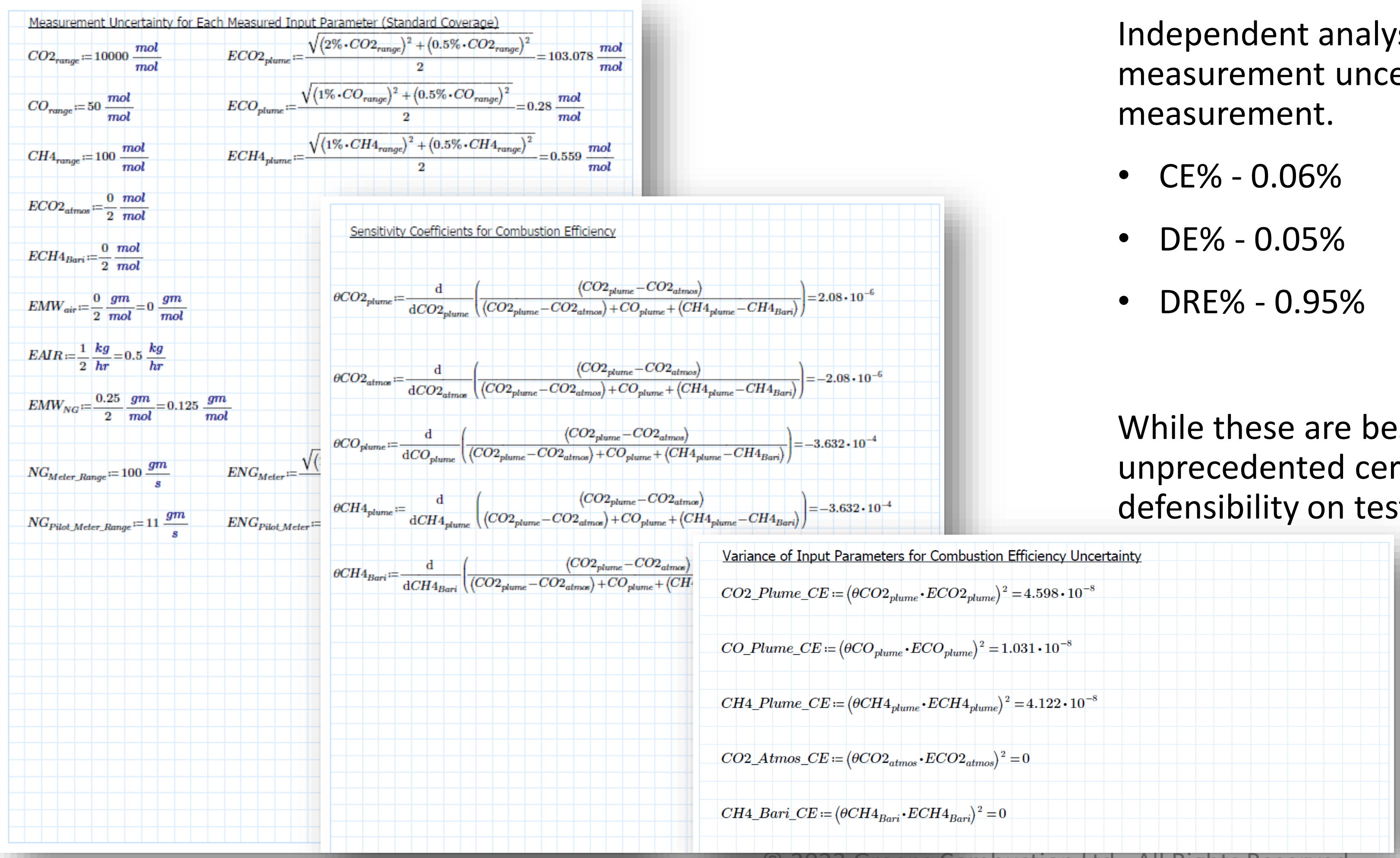


Example: Validation of Flow – Preliminary Calibrations

- To validate the test rig metering devices, a comparison was made between the theoretical CO_2 and that measured via HORIBA PG350.
- Verification of the air flow supplied through the combustion air fan is a critical component in the overall uncertainty analysis.
- Due to the high accuracy of flow determination through the mass flow meters it was decided that set flows of CO2 would be sent to the flare tip at fan set points.
    - ➢ CO2 concentrations would then be measured in the flue gas plume which would indicate that actual flow of the combustion air fan at that set point.
    - ➢ These values showed repeatability and allowed for the creation of a combustion air correction curve as illustrated.



Independent Uncertainty Analysis



Independent analysis conducted by Accord on measurement uncertainty based on flow and emissions measurement.

- CE% - 0.06%
- DE% - 0.05%
- DRE% - 0.95%

While these are best case figures it means we can get unprecedented certainty, repeatability and therefore defensibility on testing of real-world flare tip designs.

ACCORD

Flare-In-A-Box™ Testing Results Review – Impact of Crosswind On Generic Pipe Flares

BFRC 2025 FLAME DAY

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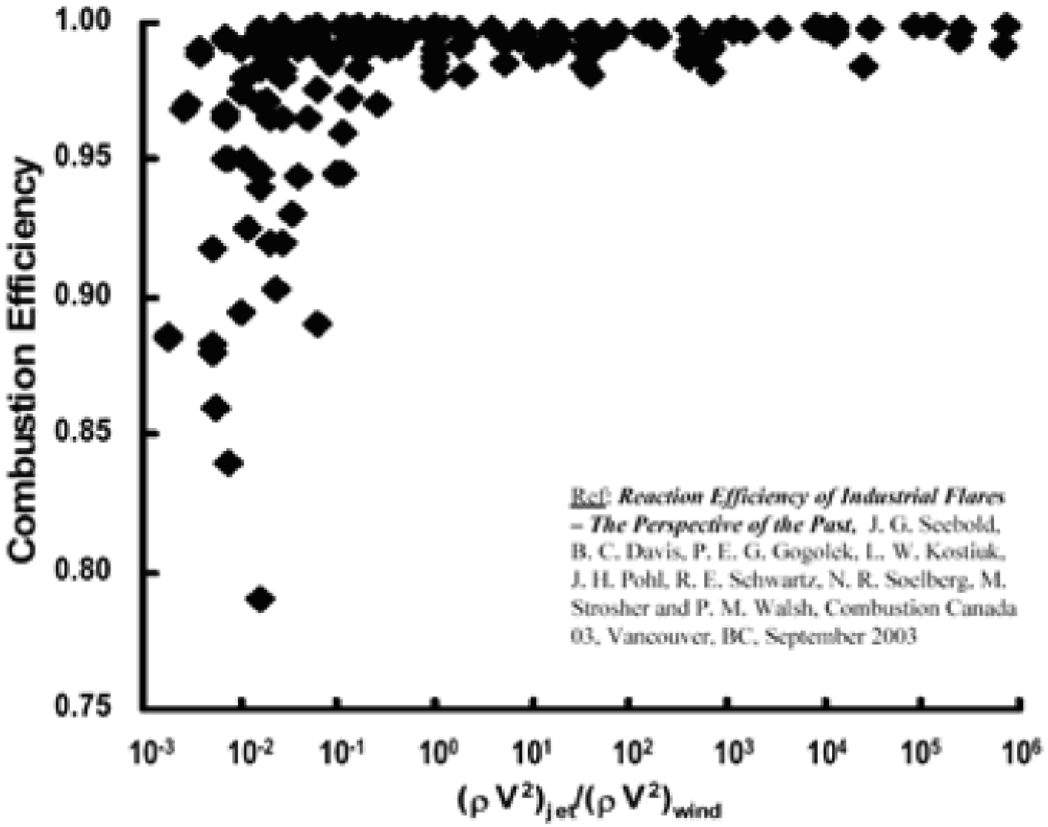
Historical Basis – Momentum Flux Ratio as a Methodology for Determination of Flare CE

- The flare gas exit velocity, or more correctly its momentum relative to the localized wind momentum is a parameter that has been viewed to be key in maintaining high combustion efficiency.
- Seebold et al[1] presented the following figure showing the impact of relative momentum flux ratios between the flare jet and cross wind on the flare tip combustion efficiency, however there was postulation in later papers by Seebold[2] that real world larger flare might not be subject to these inefficiencies in cross wind.

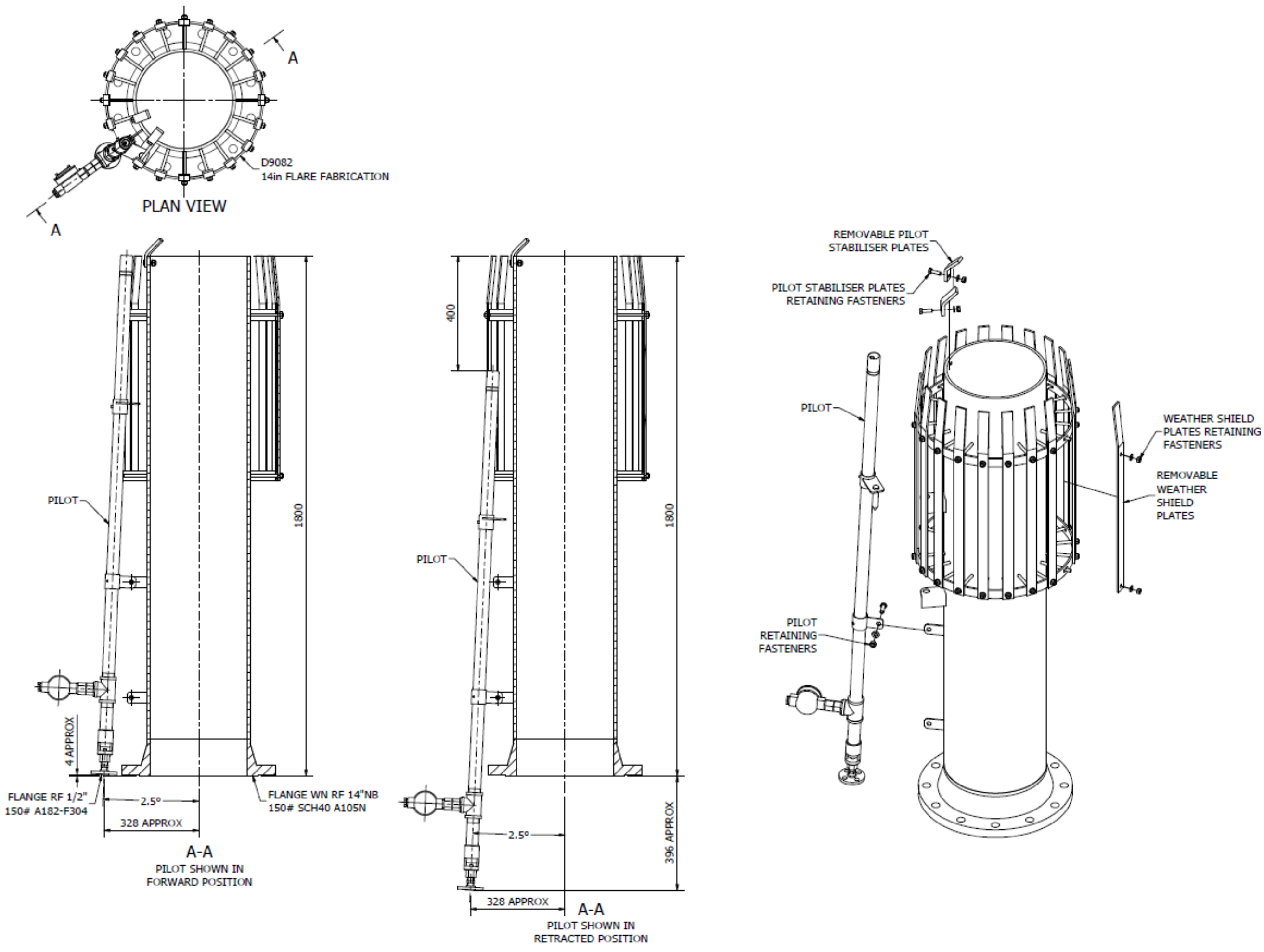


1-Seebold, J., Gogoloek, P., Pohl, J., & Schwartz, R. (2004, October). Practical implications of prior research on today's outstanding flare emissions questions and a research program to answer them. In AFRC-JFRC 2004 Joint International Combustion Symposium, Maui, HI.

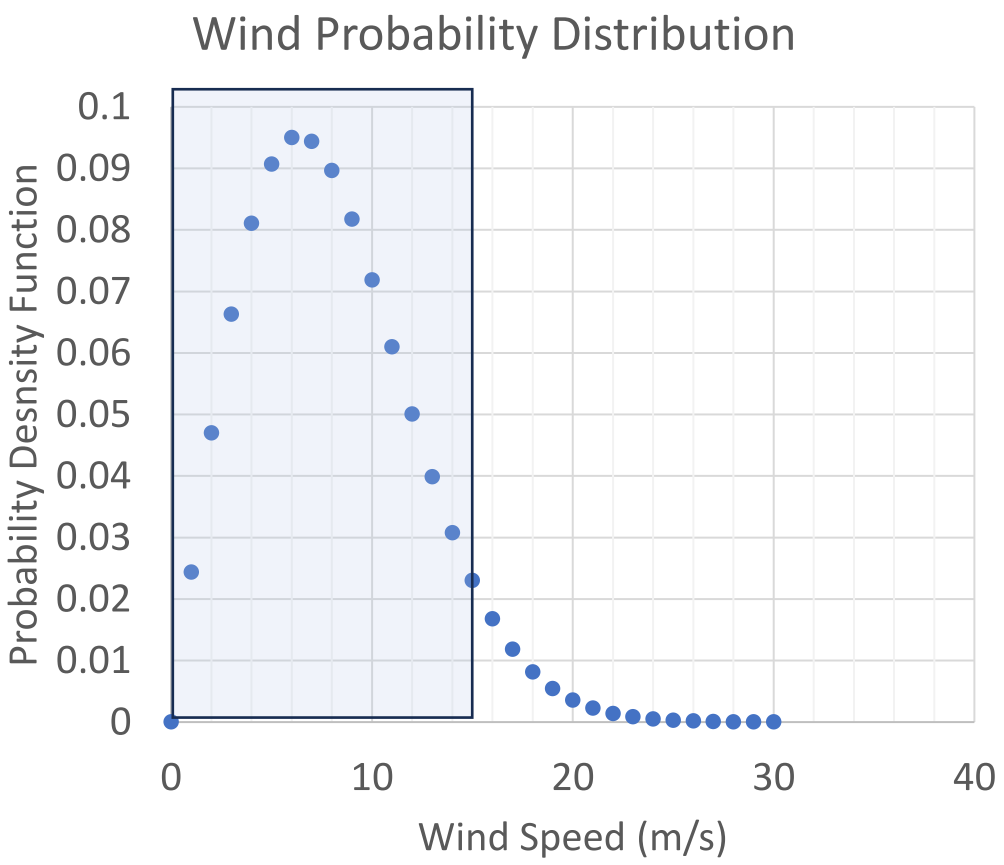
2-Seebold, J. G. (2012). Peer review of the U.S. EPA Office of Air Quality Planning and Standards report "Parameters for Properly Designed and Operated Flares." Independent Consultant Report, American Flame Research Committee.

Testing a Real-World Generic Pipe Flare

FLARE DATASHEET	
Test Flare ID (")	14
Full Scale Tip (kg/hr)	175,000.00
Full Scale Eq Diameter (")	32
Reduced Scale Flow (kg/hr)	35,000.00
1/100th Scale Flow (kg/hr)	350.00
1/500th Scale Flow (kg/hr)	70.00
1/1,000th Scale Flow (kg/hr)	35.00
HUSA Defined Purge Rate (kg/hr)	1.164
Design Pressure Drop (Barg)	0.20
Flare Gas Composition (mol%)	
CCA Natural Gas	100.00
Gas Temperature (deg C)	15.00
Cp/Cv	1.296
MW	17.453
LHV (kJ/Nm3)	37,627.00



Selection of Wind Speeds

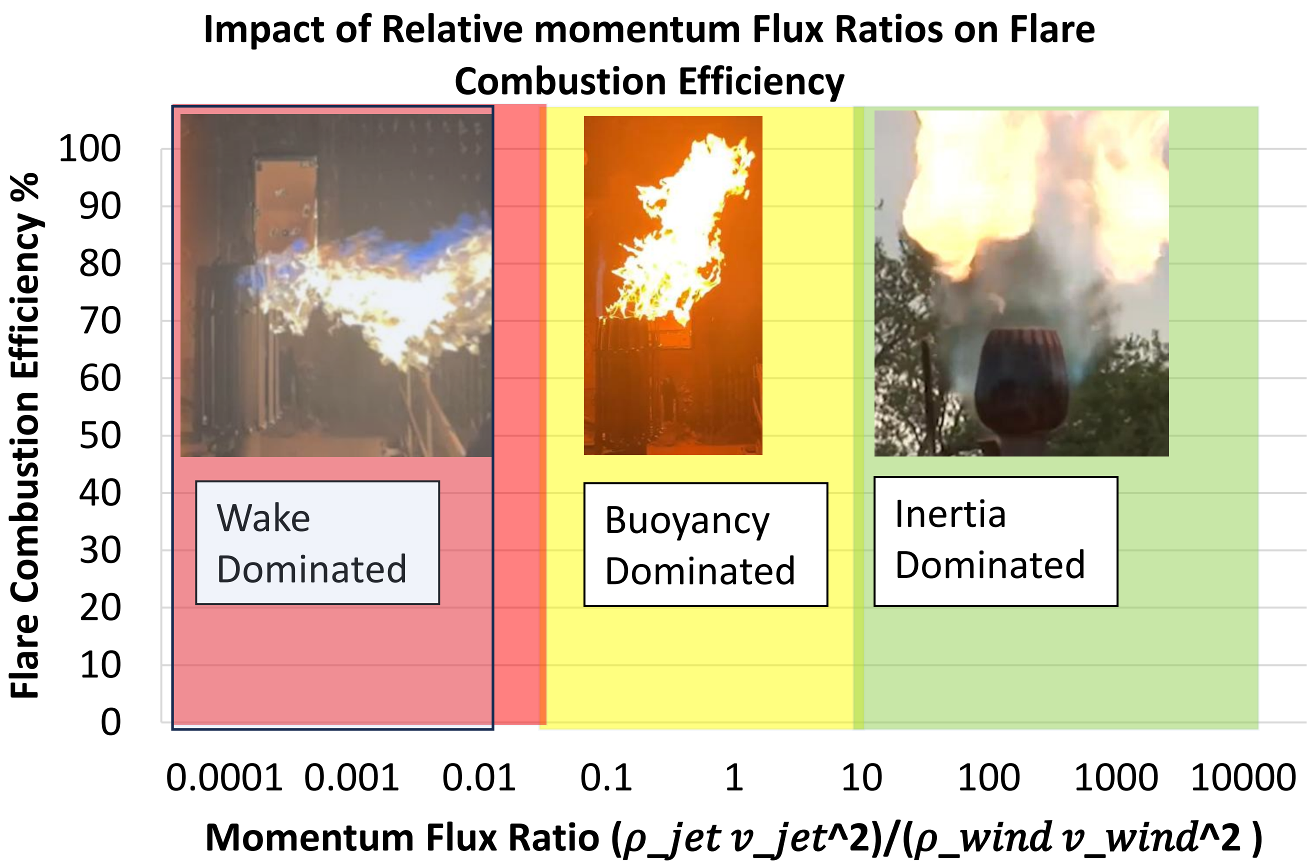


When defining the rig operational zones understanding required flare gas and simulated windspeed represents a key initial development. A typical windspeed based of North Sea operational conditions was selected as a baseline for looking into flare combustion efficiency.

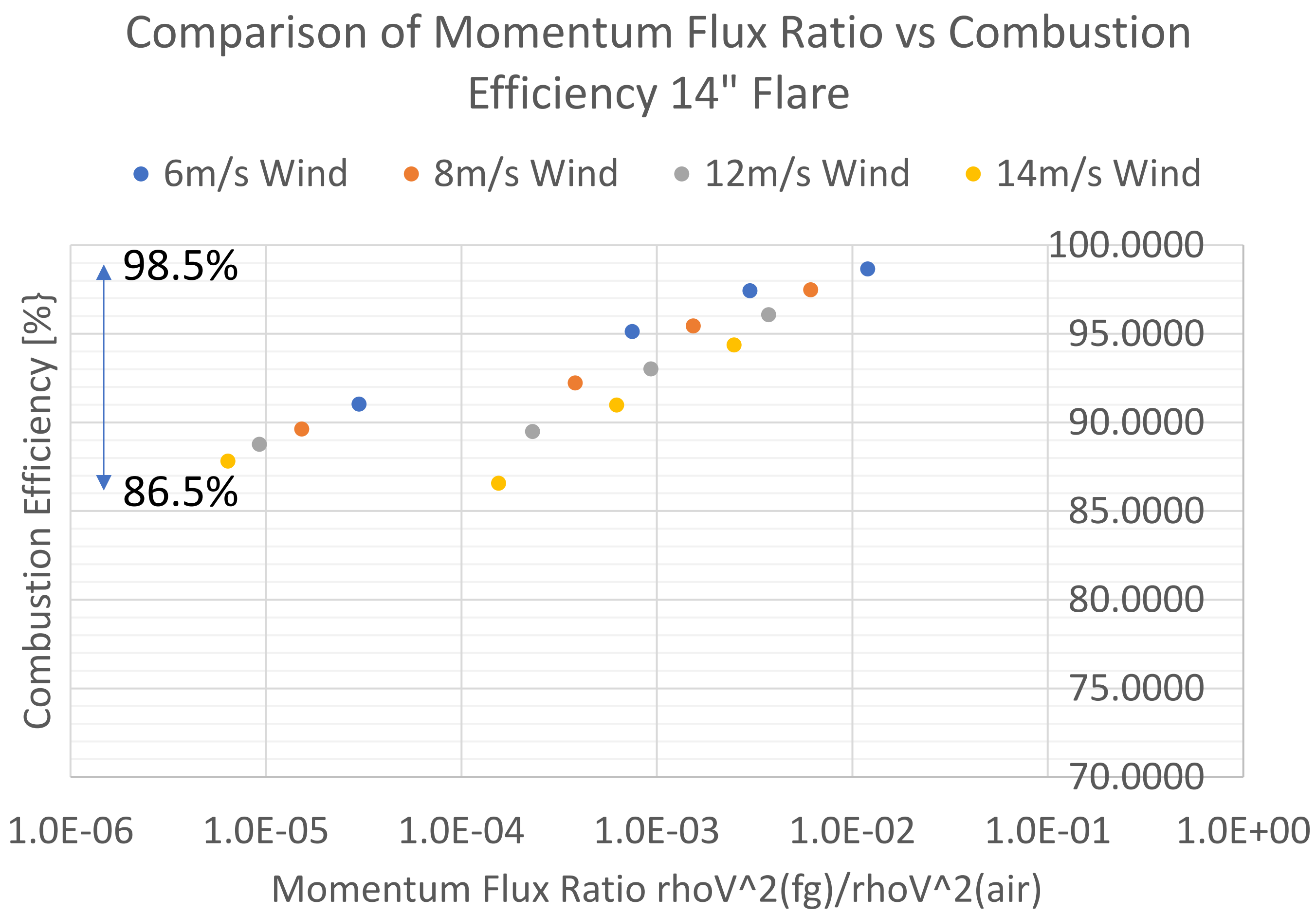
Based on a Weibull Distribution of windspeed in the North Sea. 85% of wind cases should therefore be found between 0 and 15 m/s. As such these will be used as part of the determination of the testing wind speeds.

Understand Wake Dominated Regimes

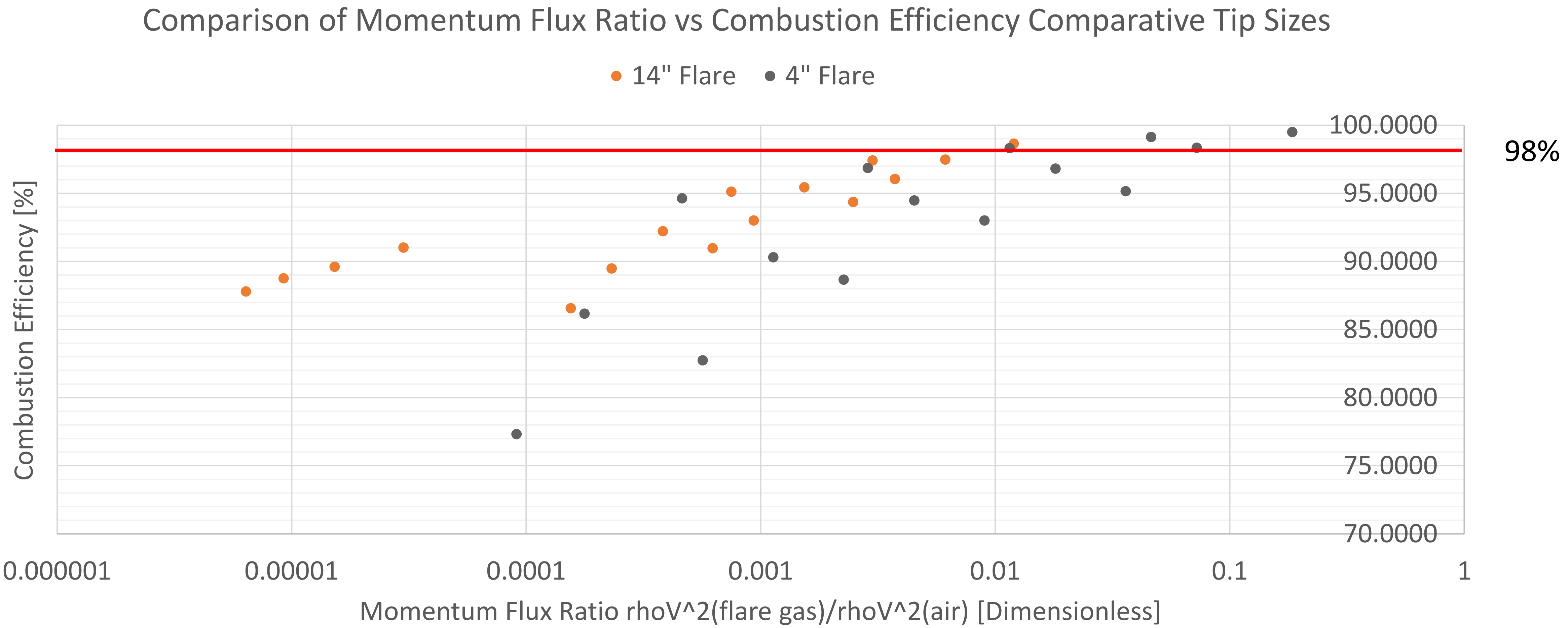
	Wind Flow (m/s)			
	6.2	8.7	11.1	13.7
Gas Flow (kg/hr)	MFR	MFR	MFR	MFR
11	3.0*10^-5	1.5*10^-5	9.2*10^-6	6.4*10^-6
55	7.5*10^-4	3.8*10^-4	2.3*10^-4	1.5*10^-4
110	3.0*10^-3	1.5*10^-3	9.3*10^-4	6.2*10^-4
220	1.2*10^-2	6.1*10^-3	3.7*10^-3	2.5*10^-3



Is Flare Efficiency Impacted by MFR?



Does Flare Tip Size Impact Efficiency?



Buoyancy Factor – As an Improved Mechanism for Determination of CE

It is difficult to find a direct correlation for modelling flare combustion efficiency. Not least because there are so many flare tip types, geometries and operational conditions.

- It is known that several mechanisms contribute to the mixing process, including Kelvin- Helmholtz instabilities in the shear layer, outer turbulence, inner turbulence and buoyancy of the gas.
- As part of the development of correlations for determining combustion efficiency, Johnson and Kostiuk proposed the use of a buoyancy factor. This dimensionless number at least presents a method by which steps can be made to quantify models for various flare tip sizes.
- It does not however look at impacts of combustion zone and flare gas heating value (LHV).

$$BF = \frac{v_w}{(D v_f g)^{1/3}}$$

V_w is the wind speed in m/s

D is the outside diameter of the flare in m

V_f is the exit velocity of the flared gas in m/s

g is gravitational acceleration m/s^2

Johnson, M.R. & Kostiuk, L.W., 2002. A parametric model for the efficiency of flare in cross wind. Proc. Combustion Institute, 29(2), pp.1943–1950

Historical Basis – Methods of Determining Combustion Efficiency.

Assumption of Fixed Combustion Efficiency

Many regulatory agencies assume 98% efficiency under all operating conditions based off of EPA hood Testing in the 1980s, but the IEA proposed a global average of 92%.

Industry Accepted Models

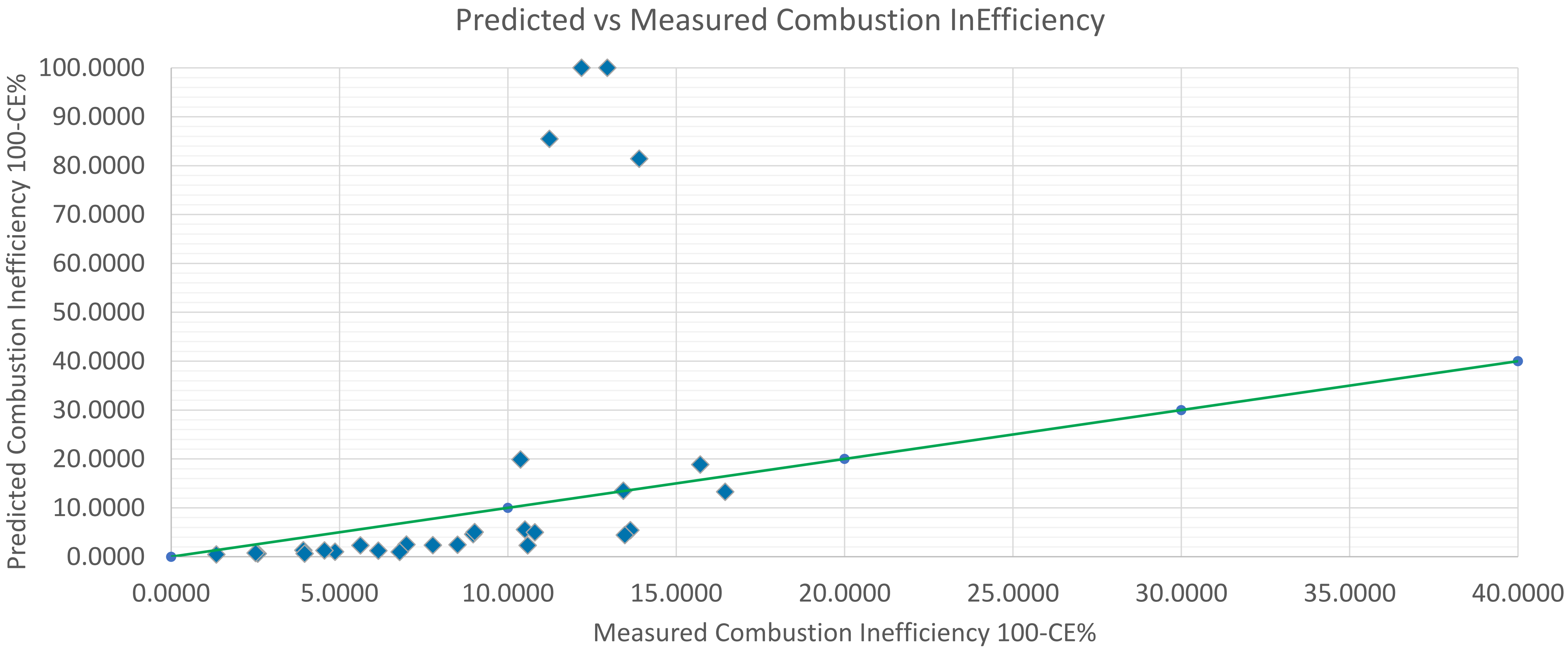
The University of Alberta (UoA) model of combustion efficiency is based on research conducted on wind tunnel performance of pipes to simulate flare efficiency in cross wind.

- This research developed a semi empirical equation that calculates the combustion efficiency of flare combustion as a function of flare gas net heating value, wind speed, flare jet exit velocity and flare tip outside diameter. However, this research was mainly focussed on pipes of 1-4" in diameter and has been challenged as not fitting real world designs nor being applicable for large scale flares.

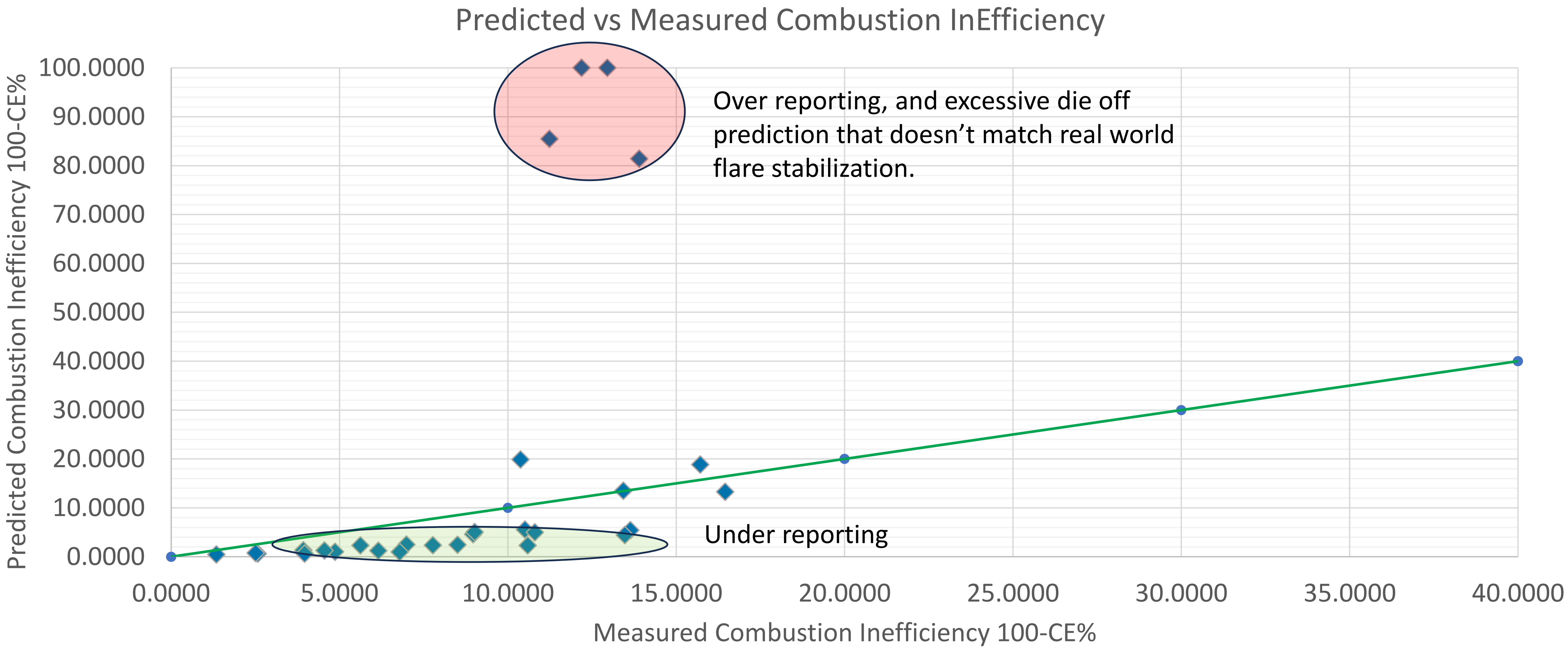
$$\mathrm{CE[Fraction]} = 1 - 0.001066 \times \left(\frac{LHV_{CH4}}{LHV_f}\right)^3 \times e^{\left(\frac{0.317 u_W}{\left(g d u_f\right)^{\frac{1}{3}}}\right)}$$

- Generally accepted in industry and is included in the OGMP Technical Guideline Document for Flare Efficiency as part of its Level 4 Quantification Methodologies.

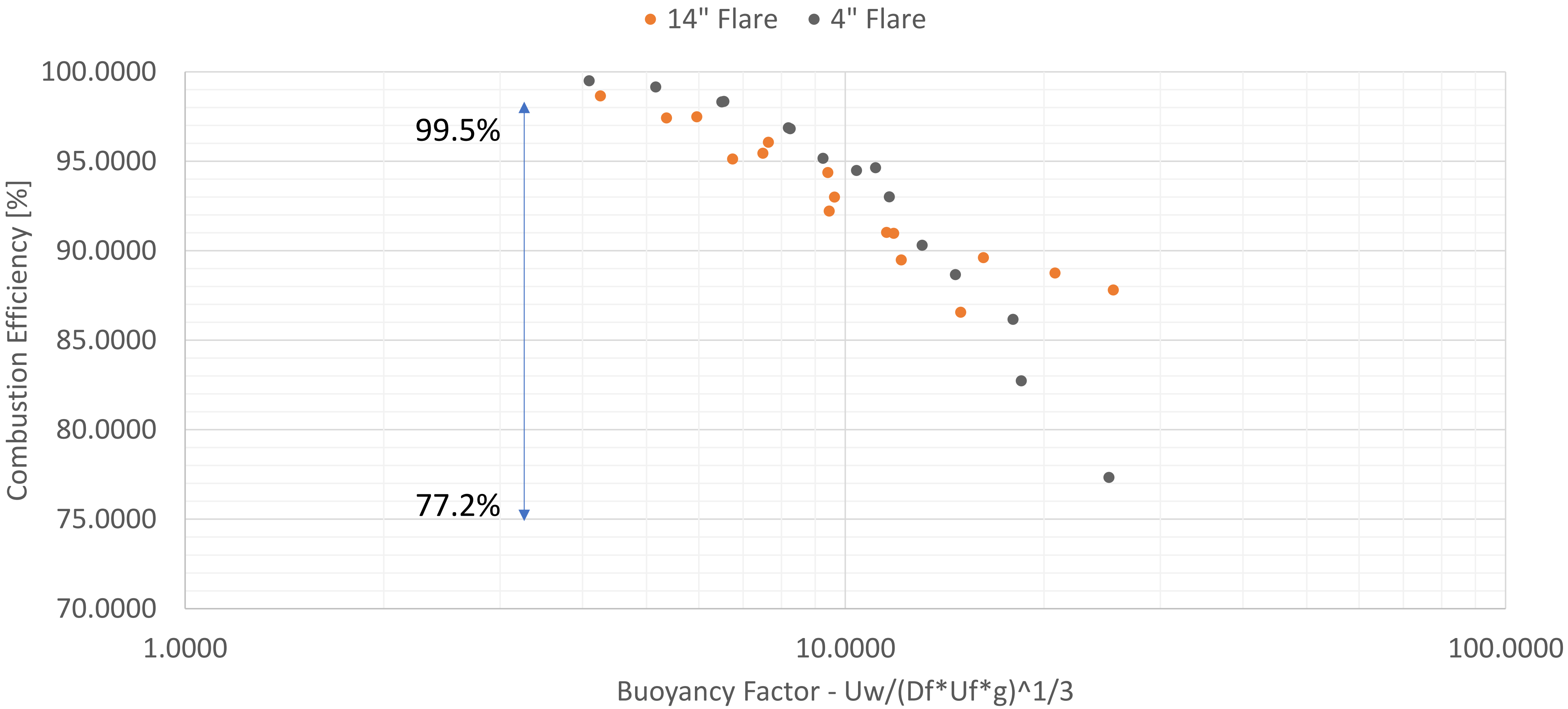
How do our Prediction Tools Hold Up (UoA)



How do our Prediction Tools Hold Up (UoA)



Scale Impact of Flare Tips and BF



Flare-In-A-Box™ Testing Results Review – Impact of Flare Gas LHV and Crosswind On Generic Pipe Flares

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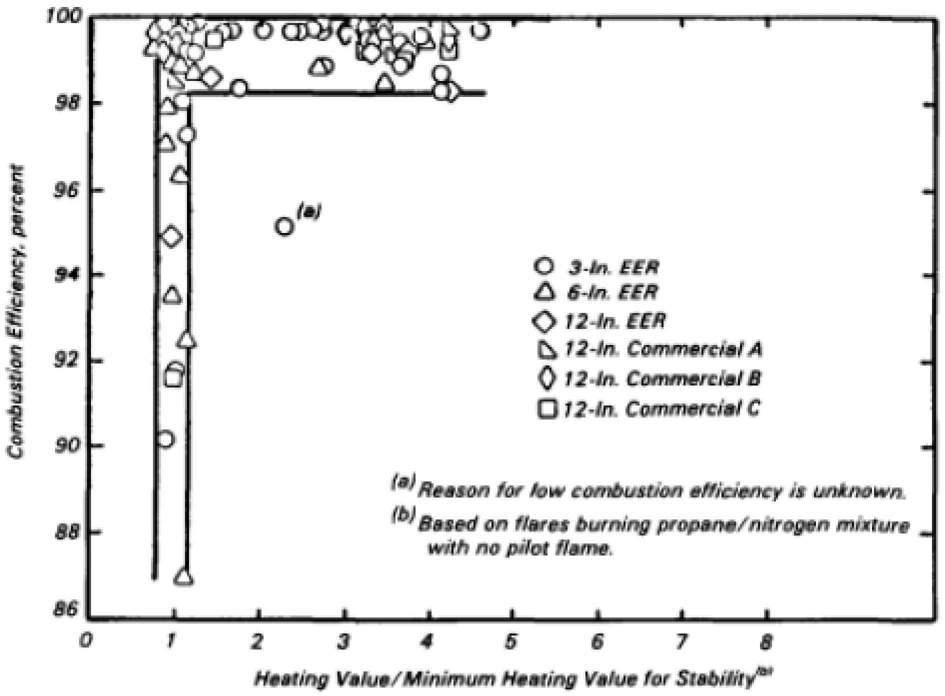
Historical Basis – LHV as a Methodology for Determination of Flare CE

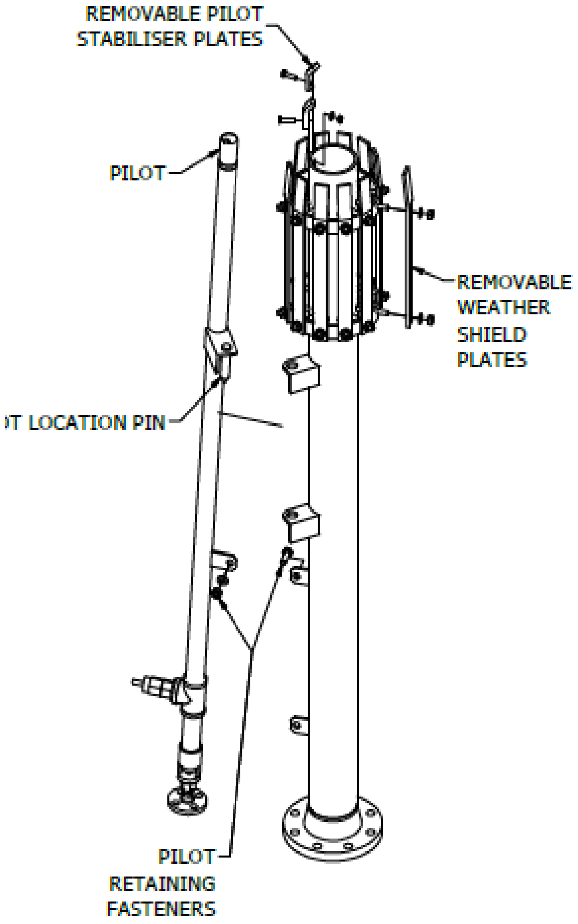
- Gas Composition is a critical parameter in the establishment of a stable flame. Presence of inerts (such as Nitrogen, Carbon Dioxide or Water Vapour) lower the peak flame temperatures and the resultant lower heating value makes it harder to sustain a stable, efficient flame. Pohl et al[3] indicated the impact of flare gas heating value on combustion efficiency in a still air hood based test.
- **Flare Operating Limits (e.g. 40 CFR 63.670)**

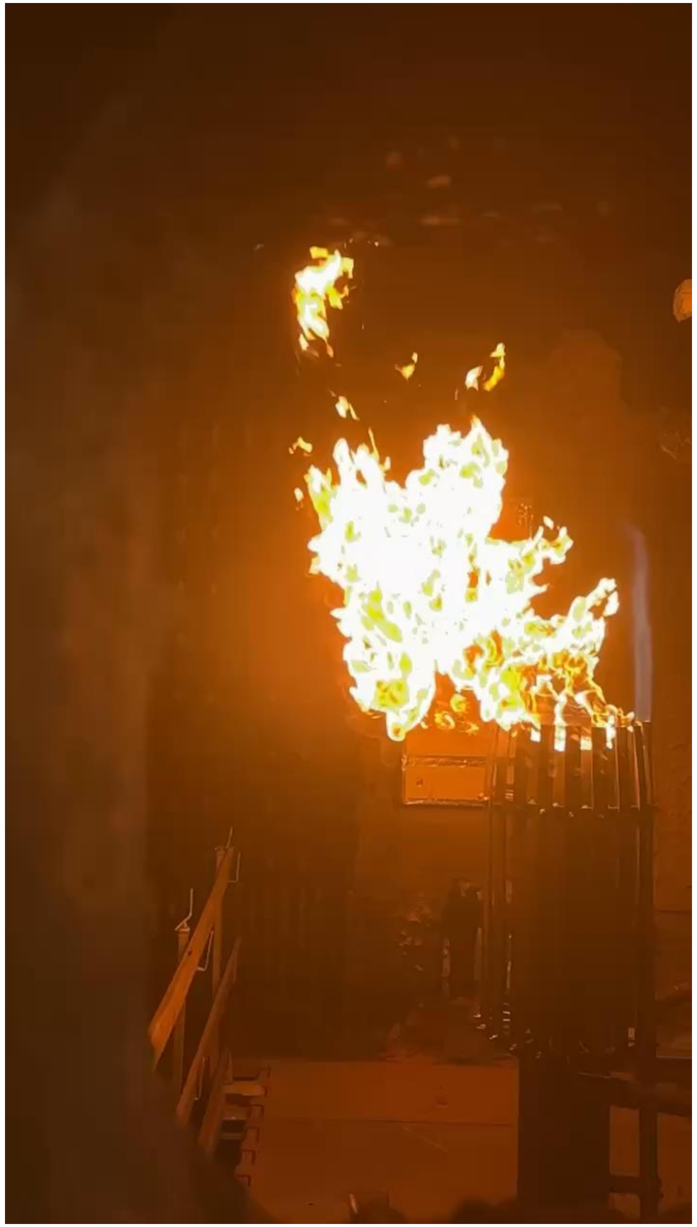
The regulation mandates that operators maintain the net heating value of **combustion zone gas ($NHV_{(cz)}$)** at or above **270 Btu/scf** (for non–pressure-assisted flares) to ensure good performance above which you should achieve **96.5% or greater CE**.



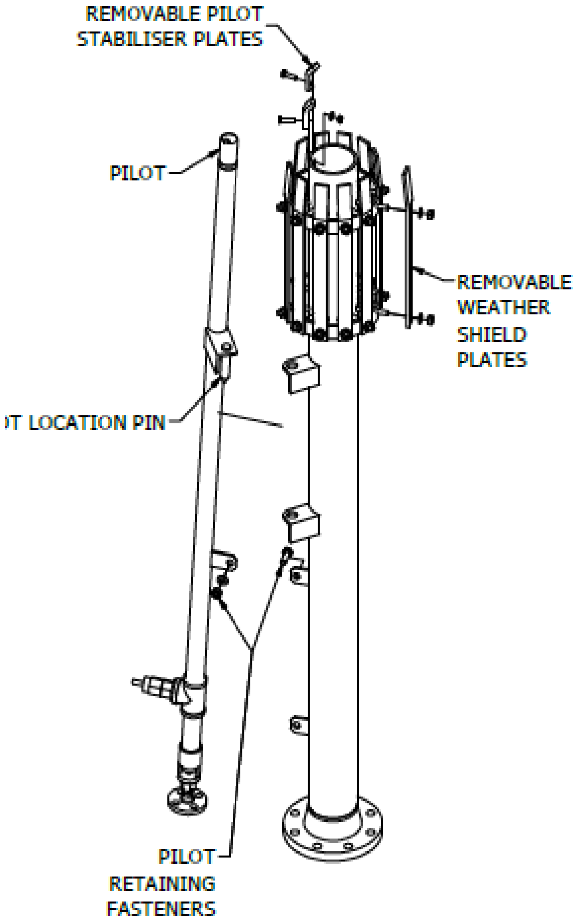
3- Pohl, J. H., Payne, R., & Lee, J. (1984). Evaluation of the efficiency of industrial flares: Test results (EPA-600/2-84-095). U.S. Environmental Protection Agency, Office of Research and Development

Test Validation
4” Flare Tip



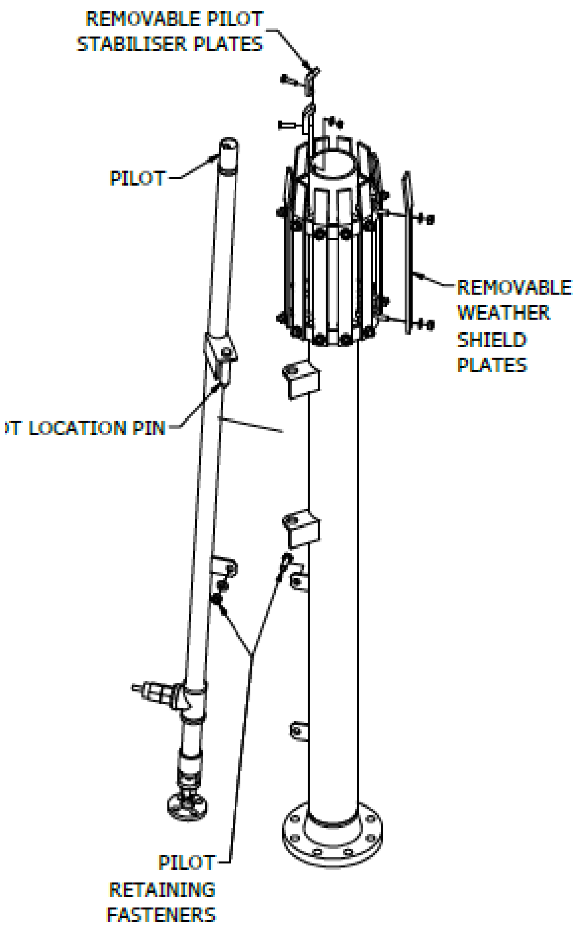


Test Validation 4” Flare Tip



FLARE DATASHEET	
Test Flare ID(“)	4
Full Scale Tip (kg/hr)	14,000.00
Full Scale Eq Diameter (")	9
Reduced Scale Flow (kg/hr)	2,800.00
1/20th Scale Flow (kg/hr)	140.00
1/100th Scale Flow (kg/hr)	28.00
1/500th Scale Flow (kg/hr)	5.60
1/1,000th Scale Flow (kg/hr)	2.80
HUSA Defined Purge Rate (kg/hr)	0.09
Design Pressure Drop (Barg)	0.20
Flare Gas Composition (mol%)	
CCA Natural Gas	Various
Nitrogen	Various
Gas Temperature (deg C)	15.00
Cp/Cv	Various
MW	Various
LHV (kJ/Nm3)	Various

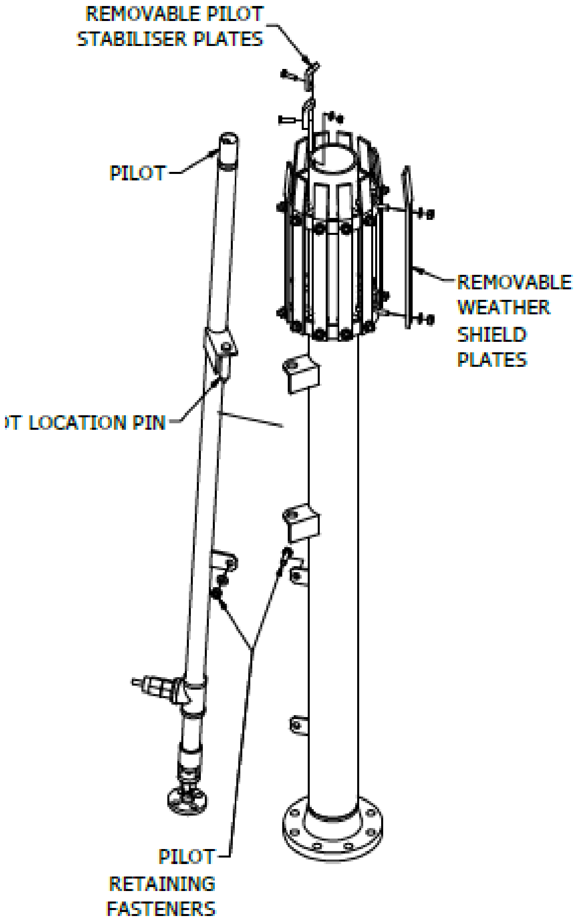
Test Validation
4” Flare Tip

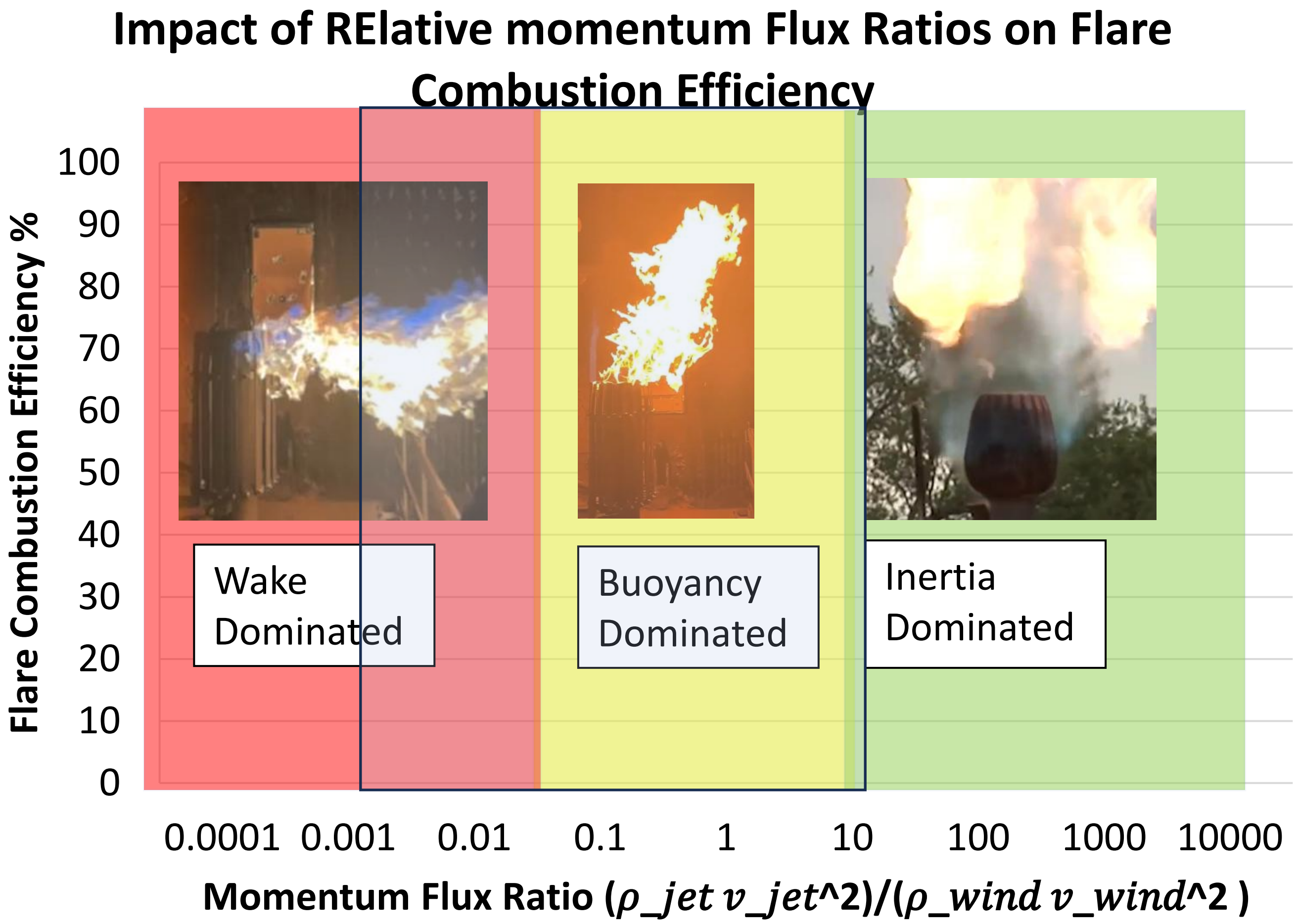


Blend Vol % (CH4 / N2)	80/20	60/40	40/60	20/80	30/70
GAS ID	1	2	3	4	5
LHV (MJ/kg)	34.83	23.12	13.83	6.27	9.86
LHV (Btu/SCF)	768.76	576.56	384.466	192.18	288.27

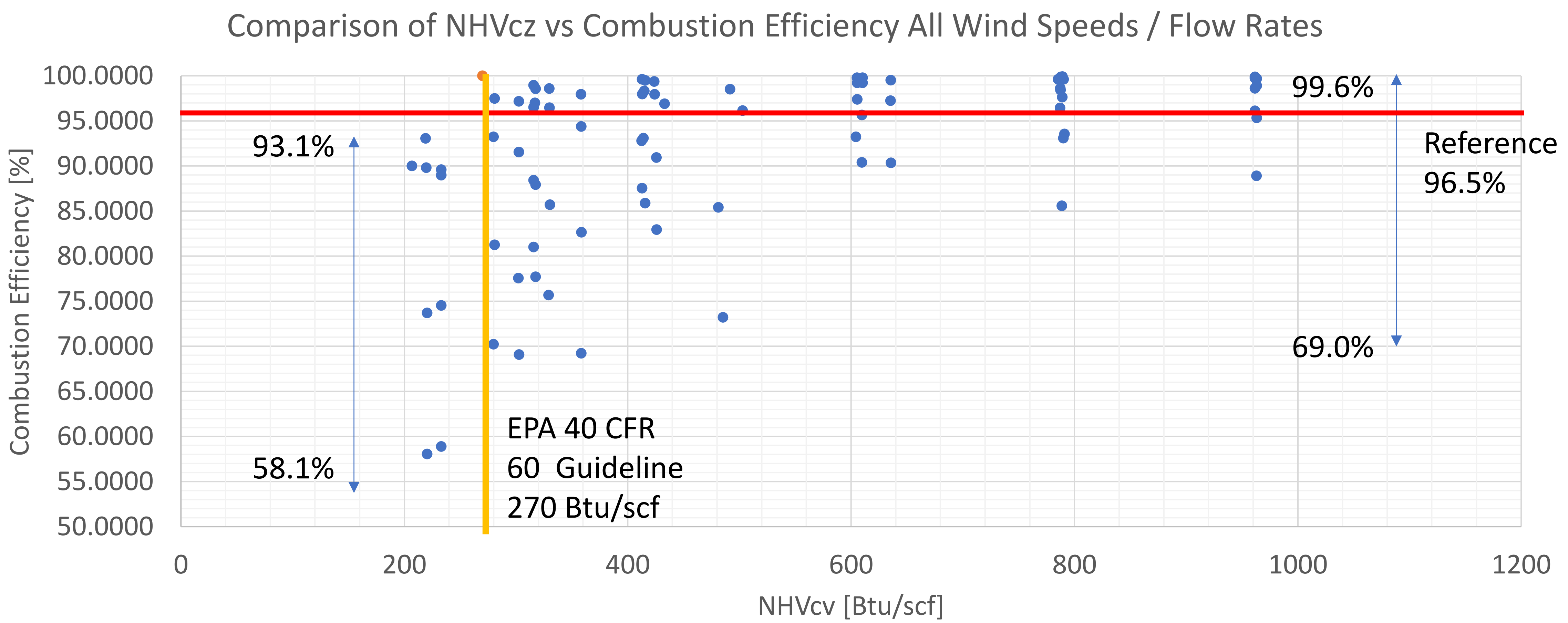
Momentum Flux Ratios of 0.001 to 12 to understand the full range of operation from wake dominated to inertia dominated.

Test Validation
4” Flare Tip

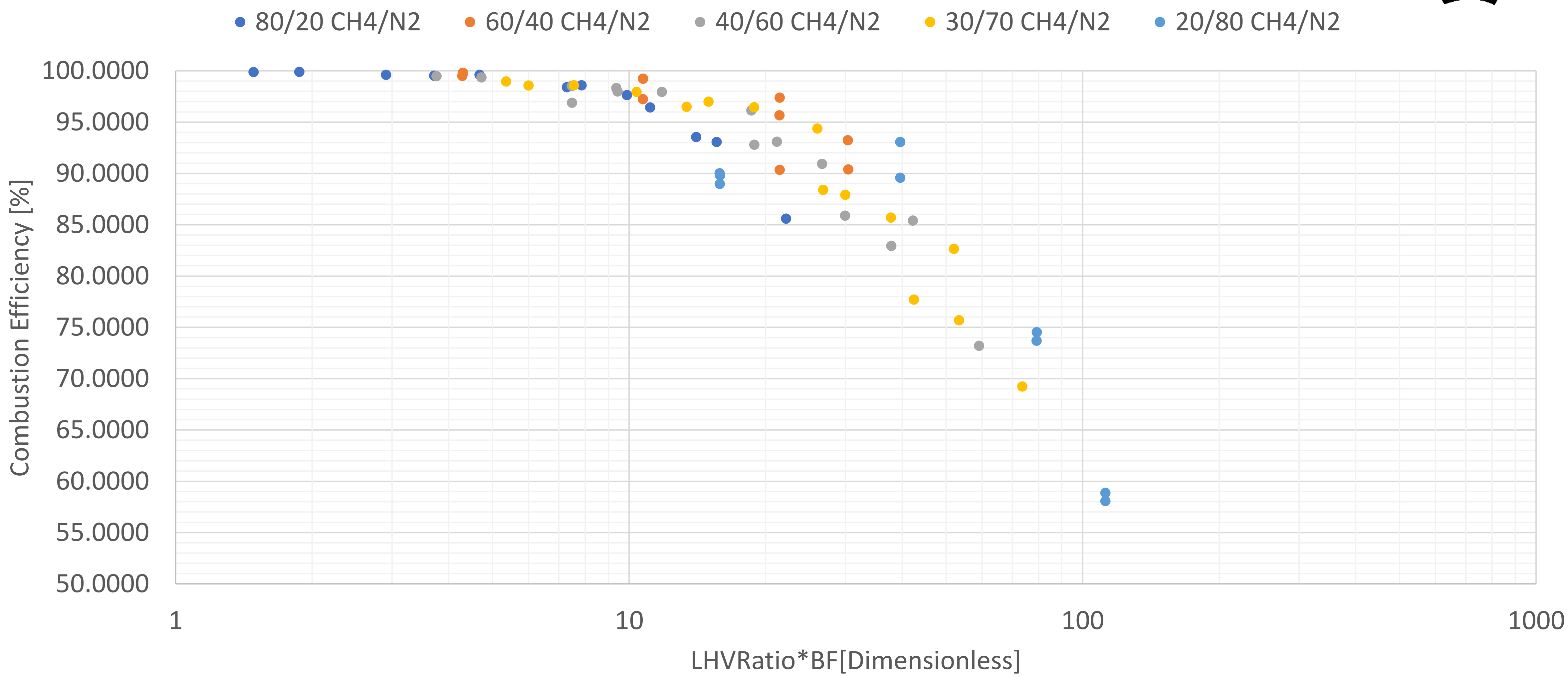




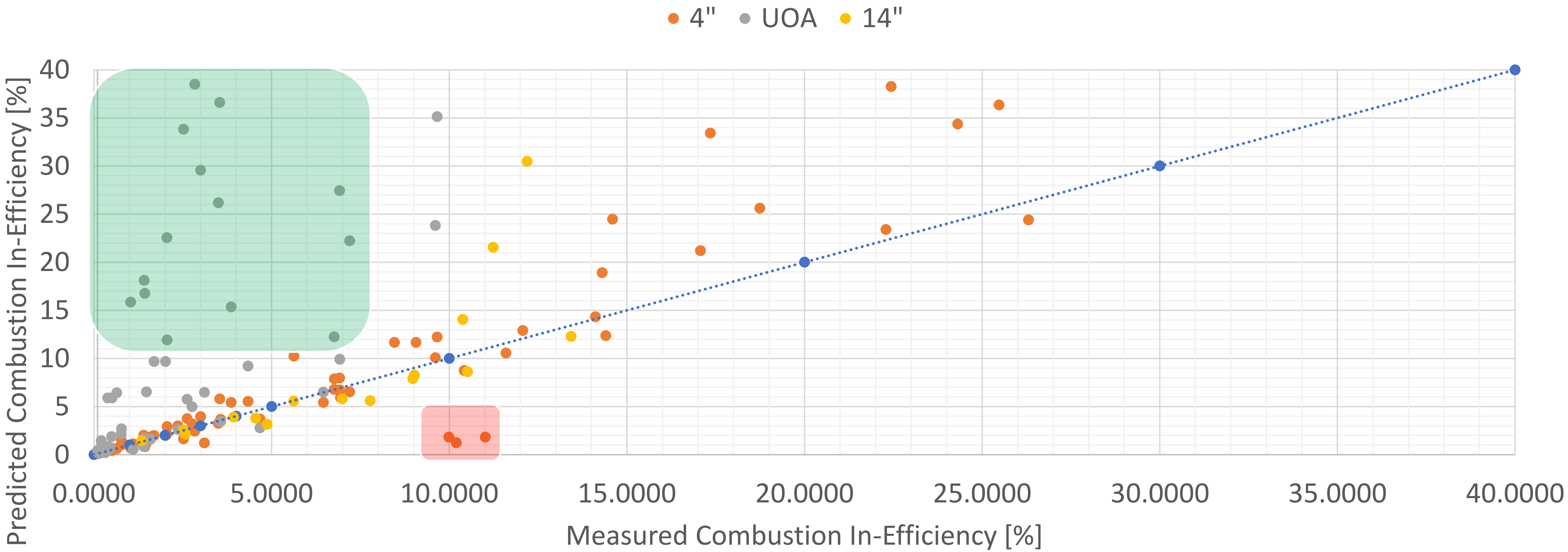
Results – Is LHV only a suitable method of determining CE?



Results : Finding a Nuanced Correlation



Bringing This All Together – **GCL ACCORD** model



Generic Pipe Flare Model due for publication October 2025

Bringing This All Together – **GCL ACCORD MODEL PIPE FLARE COMBUSTION EFFICIENCY**

$$CE\% = 100 - 0.0688 \times \left(\frac{LHV_{CH_4}}{LHV_f}\right)^{1.411} \times \left(\frac{{u_w}^3}{(gdu_f)}\right)^{0.569}$$

- CE% is combustion efficiency.
- LHV_f is the lower mass heating value of the flared gas
- LHV_{CH4} is the lower mass heating value of methane
- u_w is the wind speed in m/s
- d is the outside diameter of the flare in m
- u_f is the exit velocity of the flared gas in m/s
- g is gravitational acceleration m/s^2

Preliminary Conclusions

- **Flare-In-A-Box™ Testing presents a provable, defensible, repeatable and highly accurate method for conducting flare tip emissions evaluations under wide ranges of environmental and operating conditions.**
- This testing is suitable for determination of regulatory limits as well as understanding performance of various flare tip types.
- This testing could further enhance understanding of how flare tips change in their through life performance.
- It appears that current methods for predicting flare combustion efficiency are not suitable.
    - Blanket Value
    - Current Accepted Emissions Prediction Models based on LHV ratio and Buoyancy
    - Current Accepted Emission Prediction Models based on NHVcz
- There is extensive opportunity for industry, regulators and vendors to come together to more deeply understand the emissions of our flare tips and manage those emissions in a better manner without fundamentally impacting the primary role of a flare as a safety relief device. Better prediction methodologies need to be developed.
- Empirical equations for various tip types can be generated that should allow for more accurate determination of Flare Combustion Efficiencies.

Unfortunately, this does question the current regulatory methodology that is used today for Hydrocarbon Flares. This has to be a separate and open debate.