A NEW METHOD TO MEASURE FLARE COMBUSTION EFFICIENCY IN REAL-TIME

Presented by

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INTRODUCTION

2010 Tulsa Flare Study

- Captured flare plume gases, analyzed composition, and determined Combustion Efficiency (CE) and Destruction and Removal Efficiency (DRE)
- Yielded important findings regarding steam and air assist and their impact on CE and DRE
- Demonstrated high variability in CE and DRE – potential benefits if CE could be monitored and fed back to operator in real time
- Extremely large effort; not suitable for routine monitoring

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FTIR-Based Hyper-Spectral Imager

- Advantages
  - Imaging the flare plume (2-D compared to a path measurement; 3-D data cube)
  - High spectral resolution
- Disadvantages
  - Low frame rate (~1 scan/sec) – flare plume may have changed significantly during the same measurement cycle
  - Specialist required for data reduction and analysis
  - Not suitable for unmanned operations or long-term monitoring

Passive FTIR

- Advantages
  – High spectral resolution
- Disadvantages
  – Path measurement – representativeness and aiming issues
  – Low scan rate with respect to the rate of change in flare plume
  – Specialist required for data reduction and analysis

The Concept of Flare CE Monitor

- Patented and patent-pending technologies using a 4-band MWIR imager that can
  - Image the flare plume, and
  - Measure flare CE at pixel level
  - Determine overall flare CE
- Major difference from FTIR based measurement – high frame rate: ~30Hz. As a result, temporal and spatial changes of flare plume within each CE measurement cycle become negligible
- Design objective: real time CE output suitable for integration into plant data systems for
  - Flare operators, or/and
  - Process control

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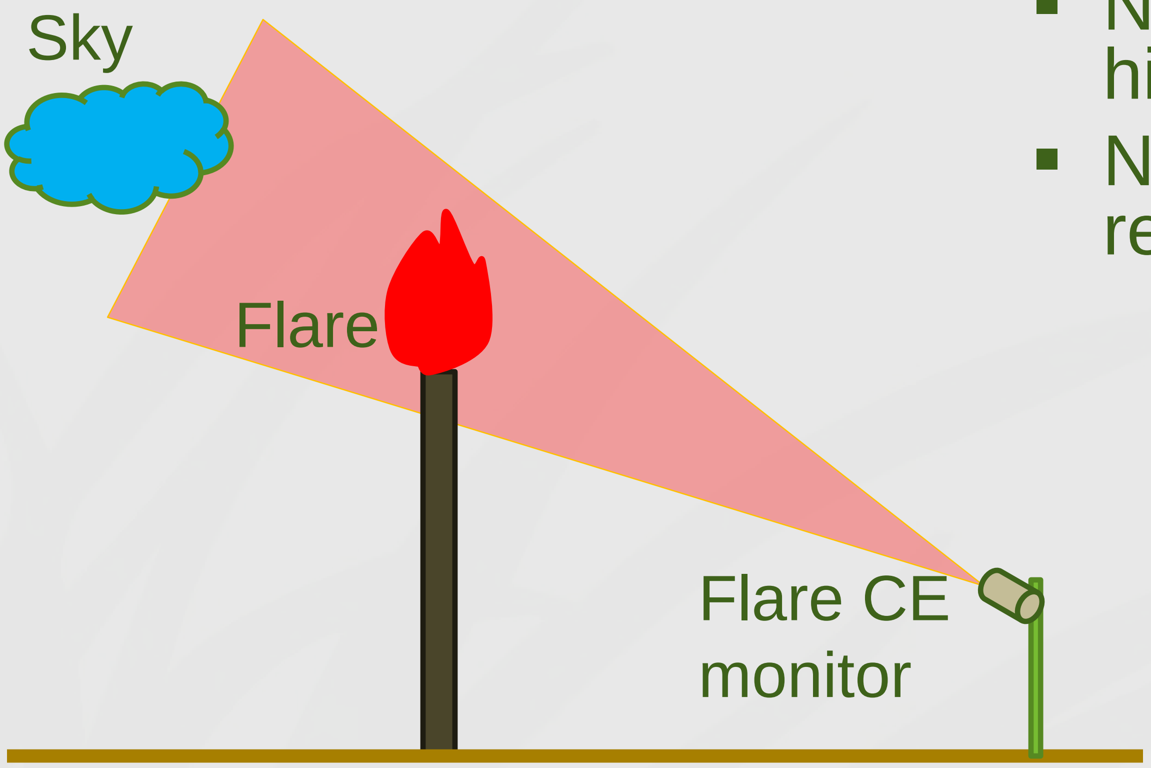
Setup of the New Flare CE Monitor



- Not a path measurement
- No scanning; high frame rate
- No operator required

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THEORETICAL BASIS FOR THE NEW FLARE CE MONITOR

Typical Flare Combustion:

Fuel = hydrocarbon (HC); generically expressed as C_nH_y

$$C_nH_y + n\frac{y}{2}O_2 \rightarrow nCO_2 + \frac{y}{2}H_2O$$

plus some CO if combustion is incomplete

Flare Combustion Efficiency (CE):

$$CE(\%) = \frac{[C]_{CO2}}{\sum_i \; n_i[C]_{HCi}+[C]_{CO2}+[C]_{CO}} \qquad \text{Eq. (1)}$$

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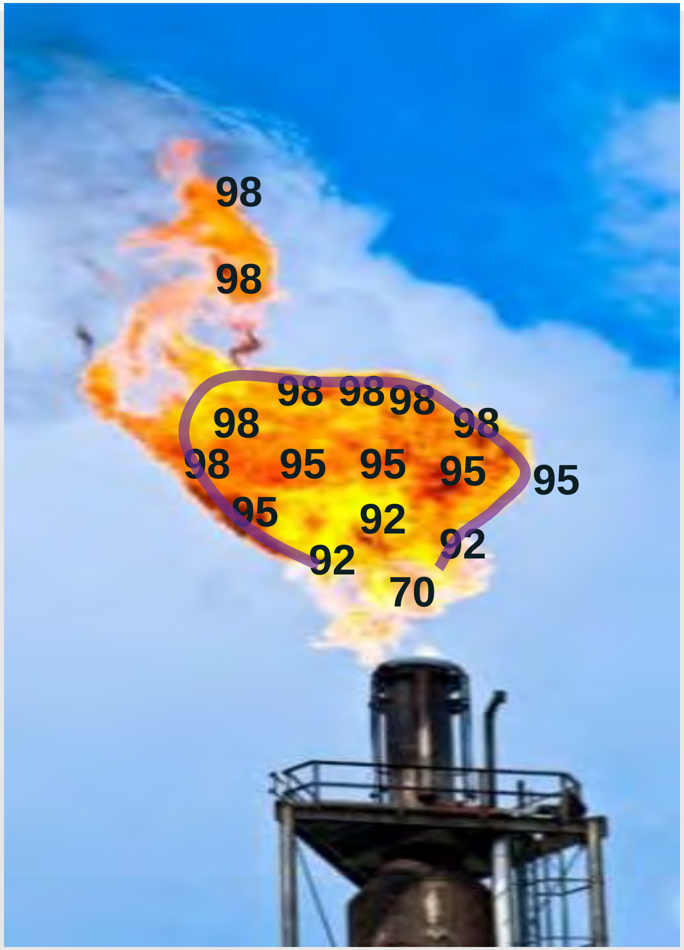
GENERAL IDEA

- Use a 4-band, high frame rate (~30 fps) Infrared (IR) imager to measure CO_2, CO, and HC and calculate CE
  - Band 1 (Ch1) for HC
  - Band 2 (Ch2) for CO_2
  - Band 3 (Ch3) for CO
  - Band 4 (Ch4) for reference
- Each pixel in the image represents a region in the flare plume; CE measured at pixel level
- Relative strength of signals are measured per Eq. (1); calibrations are achieved through the Ref. Channel (Ch4)
- Overall CE is determined by averaging pixel level CE on pixels that form the flare plume "envelope" (pattern recognition algorithms are used to determine the envelope)



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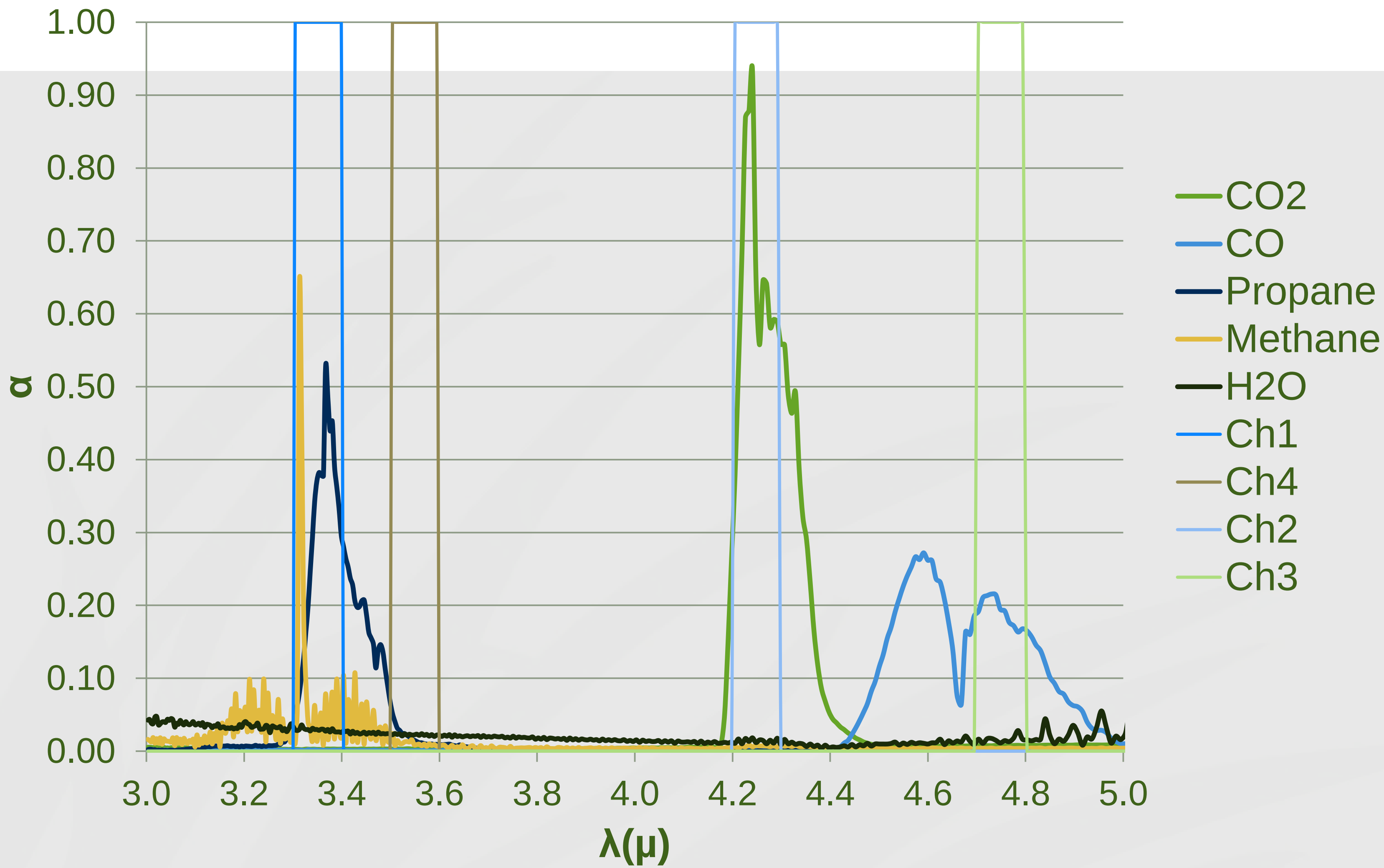
Selection of Four Spectral Bands



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Simplified Radiative Transfer Equation (RTE)

$$I = \varepsilon(\lambda) B(T_b, \lambda) exp^{[-\alpha(\lambda) CL]} + B(T_g, \lambda) - B(T_g, \lambda) exp^{[-\alpha(\lambda) CL]}$$

$$B(T \;, \lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

When $T_g >> T_b$,

$$I \approx B(T_g, \lambda) - B(T_g, \lambda) exp^{[-\alpha(\lambda) CL]}$$

Taylor Expansion: $e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots, \quad -\infty < x < \infty$

When $x << 1$, $e^x = 1 + x$

$$I \approx B(T_g, \lambda) - B(T_g, \lambda)[1 - \alpha(\lambda) CL] = B(T_g, \lambda) \alpha(\lambda) CL$$

$$C = \frac{I}{B(T_g, \lambda) \alpha(\lambda) L} \qquad \text{Eq. (2)}$$

Equation for Flare CE Measurement

- Substitute C in Eq. (1) with Eq. (2);
- Use subscripts 1, 2, 3 for HC (Channel 1), CO_2 (Channel 2), and CO (Channel 3), respectively;
- Cancel out L; and
- Use weighted avg. n and α for HC.

Eq. (2) becomes:

$$CE(\%) = \frac{\frac{I_2}{B(T_g,\lambda_2)\alpha(\lambda_2)}}{\bar{n}\frac{I_1}{B(T_g,\lambda_1)\bar{\alpha}(\lambda_2)} + \frac{I_2}{B(T_g,\lambda_2)\alpha(\lambda_2)} + \frac{I_3}{B(T_g,\lambda_3)\alpha(\lambda_3)}} \quad \text{Eq. (3)}$$

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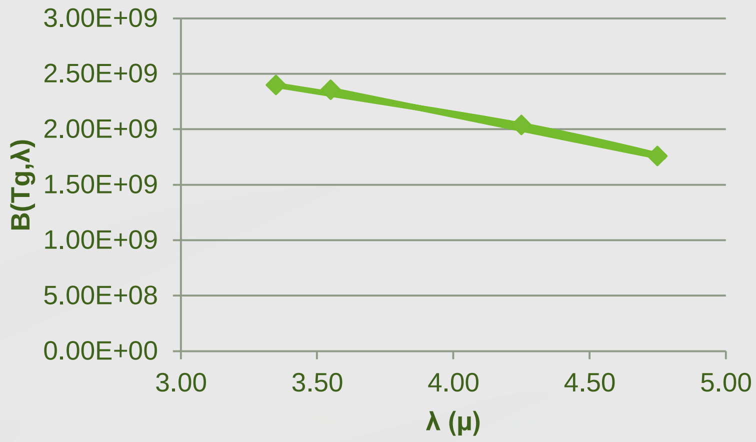
VARIOUS MEASUREMENT APPROACHES CONSIDERED

$$CE(\%) = \frac{\frac{I_2}{B(T_g,\lambda_2)\alpha(\lambda_2)}}{\bar{n}\frac{I_1}{B(T_g,\lambda_1)\bar{\alpha}(\lambda_2)} + \frac{I_2}{B(T_g,\lambda_2)\alpha(\lambda_2)} + \frac{I_3}{B(T_g,\lambda_3)\alpha(\lambda_3)}} \quad \text{Eq. (3)}$$

- $B(T_g,\lambda_i)$:
  - Method 1 – Assume the 4 λ's are close enough and $B(T_g,\lambda)$ for the three channels are equal (and cancelled out)
  - Method 2 – Use the Ref. Band (Ch4) and Planks law to determine T_g and calculate $B(T_g,\lambda_i)$ for other 3 channels – Not desirable and not used at this time
  - Method 3 – Calculate ratios of $B(T_g,\lambda_i)/B(T_g,\lambda_{Ref})$ in the expected temp. range (e.g., 800-1200 ^{O}F)



VARIOUS MEASUREMENT APPROACHES CONSIDERED

$$CE(\%) = \frac{\frac{I_2}{B(T_g,\lambda_2)\alpha(\lambda_2)}}{\bar{n}\frac{I_1}{B(T_g,\lambda_1)\bar{\alpha}(\lambda_2)} + \frac{I_2}{B(T_g,\lambda_2)\alpha(\lambda_2)} + \frac{I_3}{B(T_g,\lambda_3)\alpha(\lambda_3)}} \qquad \text{Eq. (3)}$$

- $\alpha(\lambda_i)$:
  - For CO_2 and CO, values of α(λ) are calculated based on their IR spectra
  - For HC, use weighted avg. (need some knowledge of flare gas composition)
  - Correction for H_2O – see next slide

Effect of Gas Phase H_2O

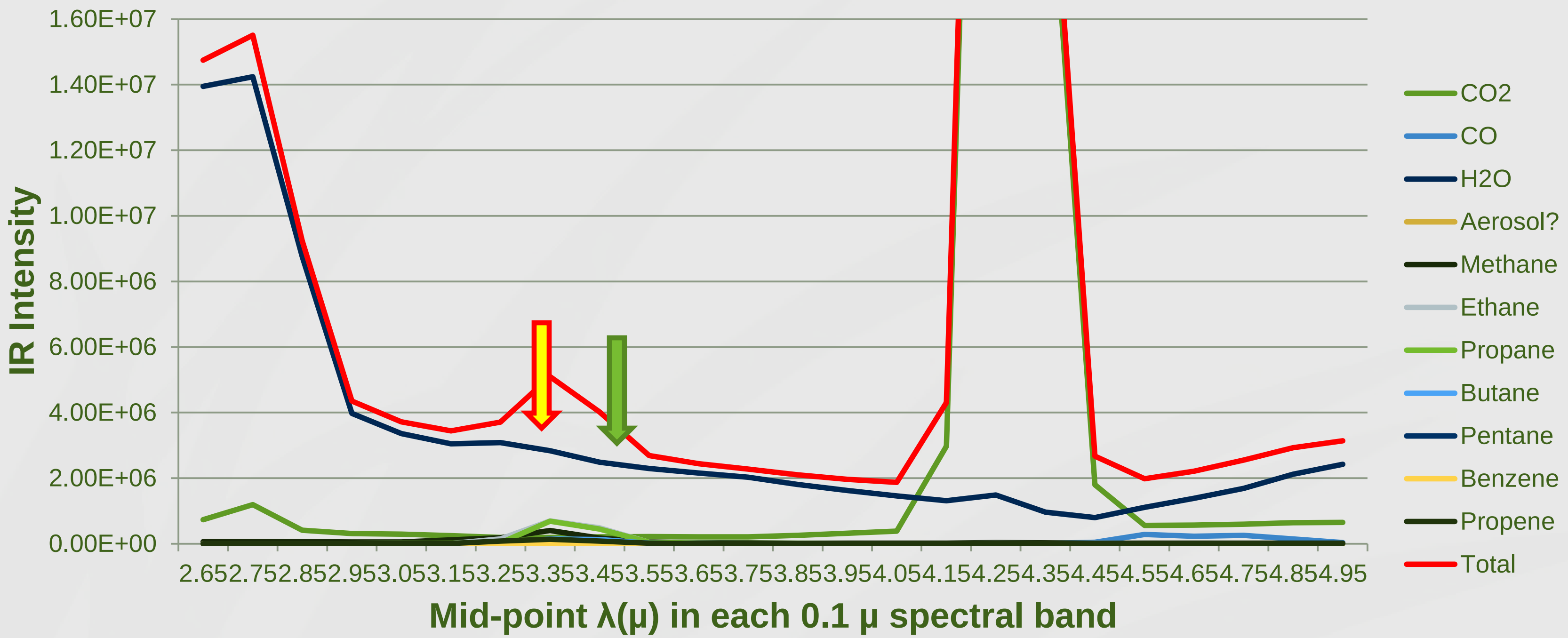
- Correction factor= $\frac{\alpha(\lambda_1)}{\alpha(\lambda_4)}$

Independent of H_2O conc.!

$$\frac{I_1}{I_4} = \frac{B(T_g,\lambda_1)\alpha(\lambda_1)C_{H2O}L}{B(T_g,\lambda_4)\alpha(\lambda_4)C_{H2O}L}$$

$$\frac{I_1}{I_4} = \left[\frac{B(T_g,\lambda_1)}{B(T_g,\lambda_4)}\right]\left[\frac{\alpha(\lambda_1)}{\alpha(\lambda_4)}\right]$$

Where α(λ)=absorption coefficient of H2O at wavelength of Ch1 and Ch4



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SIMULATION RESULTS

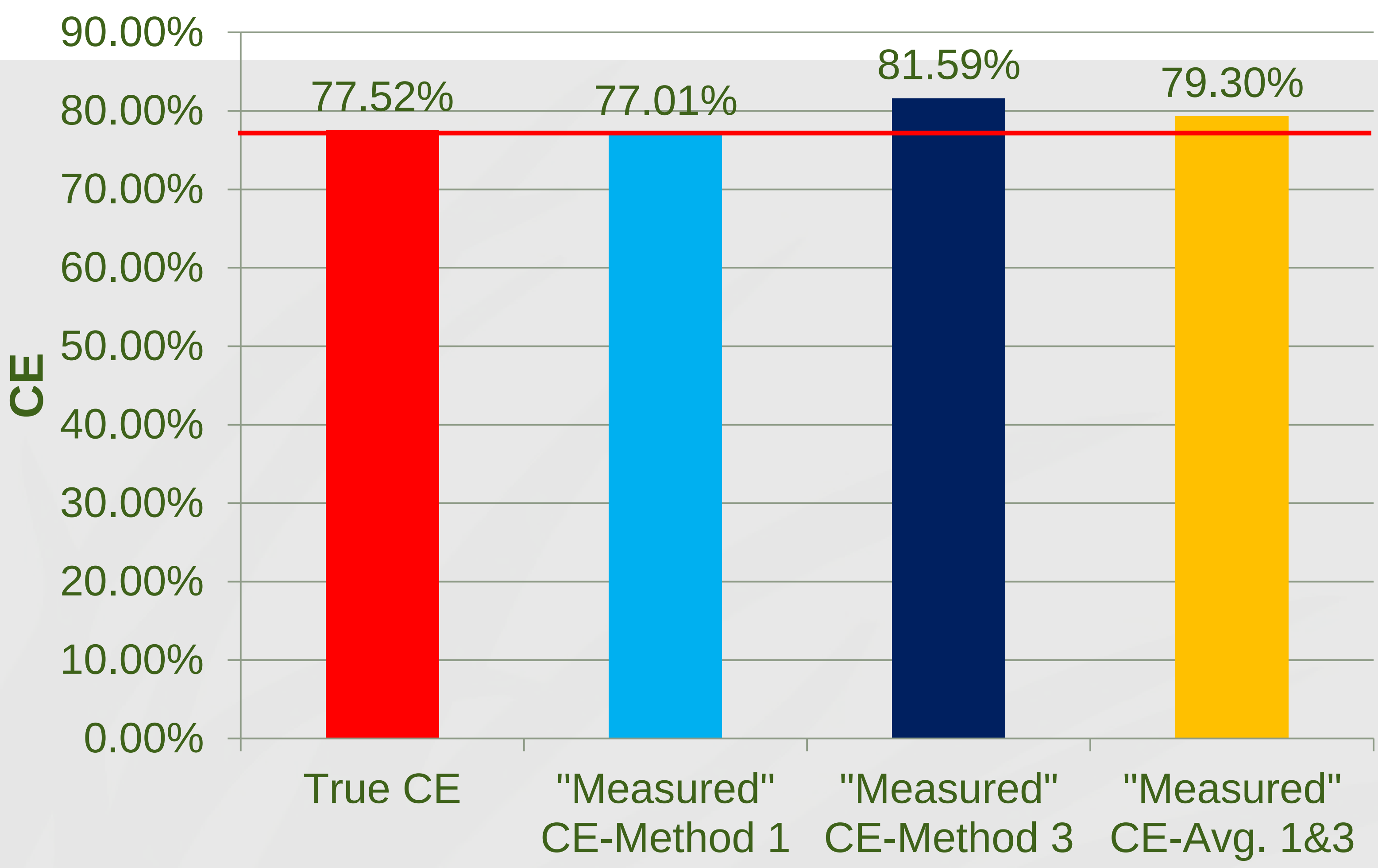
Simulated Flare Plume

- Flare gases: typical refinery fuel gas (ref. John Zink Combustion Handbook)
- Assumptions for Base Case (Case 1):
  - Plume temp=800 F
  - Plume depth=1 m (3.28 ft.)
  - Distance from flare to the CE monitor=300 ft.

Assumed Composition in flare plume

Compound	Conc.
CO2	12.000%
CO	0.200%
H2O	15.960%
Methane	0.720%
Ethane	0.360%
Propane	0.400%
Butane	0.040%
Pentane	0.000%
Benzene	0.000%
Propene	0.160%

SIMULATED RESULT – BASE CASE (CASE 1)



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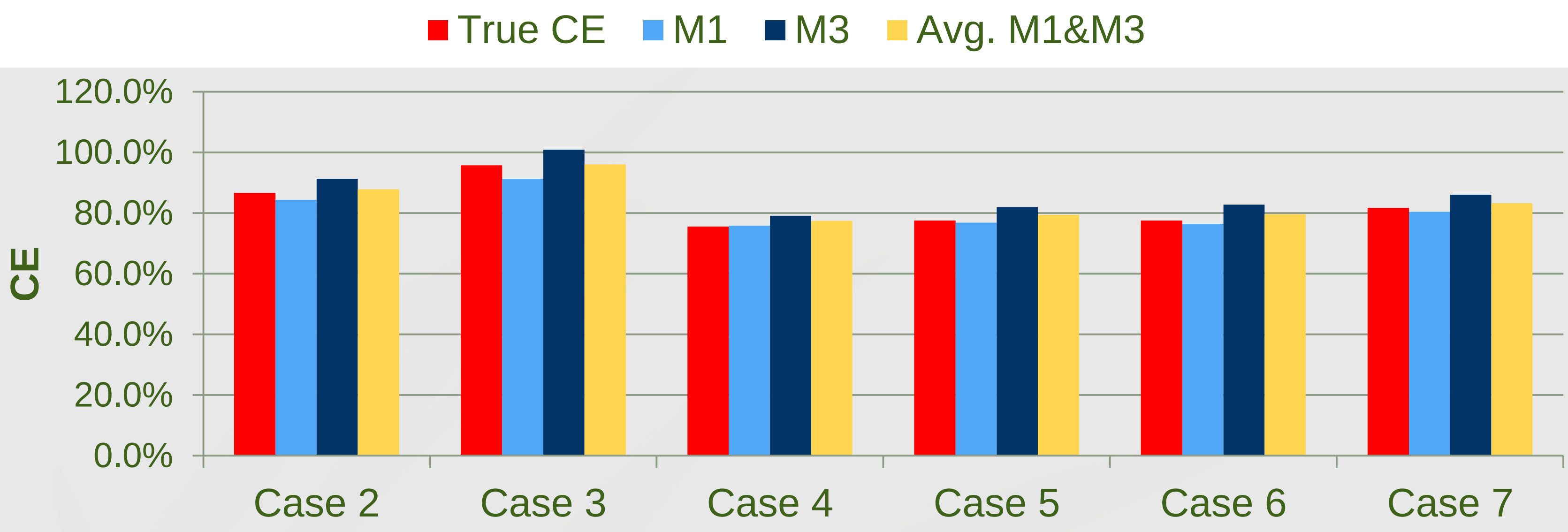
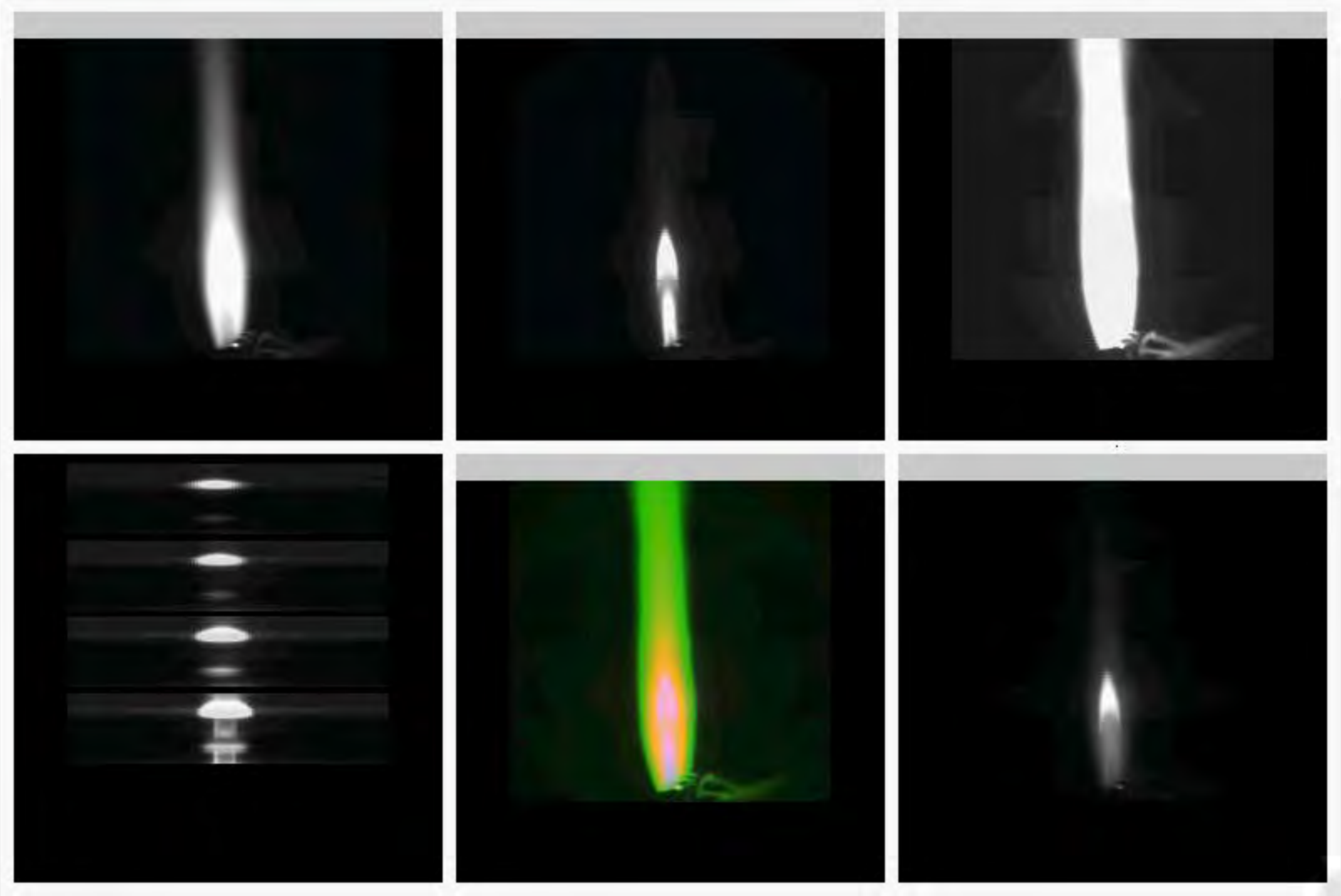
Simulated Results – Cases 2-7
Effect of flare gas composition and H_2O



- Case 2: Unburned fuel=1/2 of Case 1
- Case 3: Unburned fuel=1/10 of Case 1
- Case 4: Double the conc. of ethane and add pentane and benzene
- Case 5: Add 10% more H_2O in the plume
- Case 6: Add 30% more H_2O in the plume
- Case 7: Add 30% more CO_2 in the plume

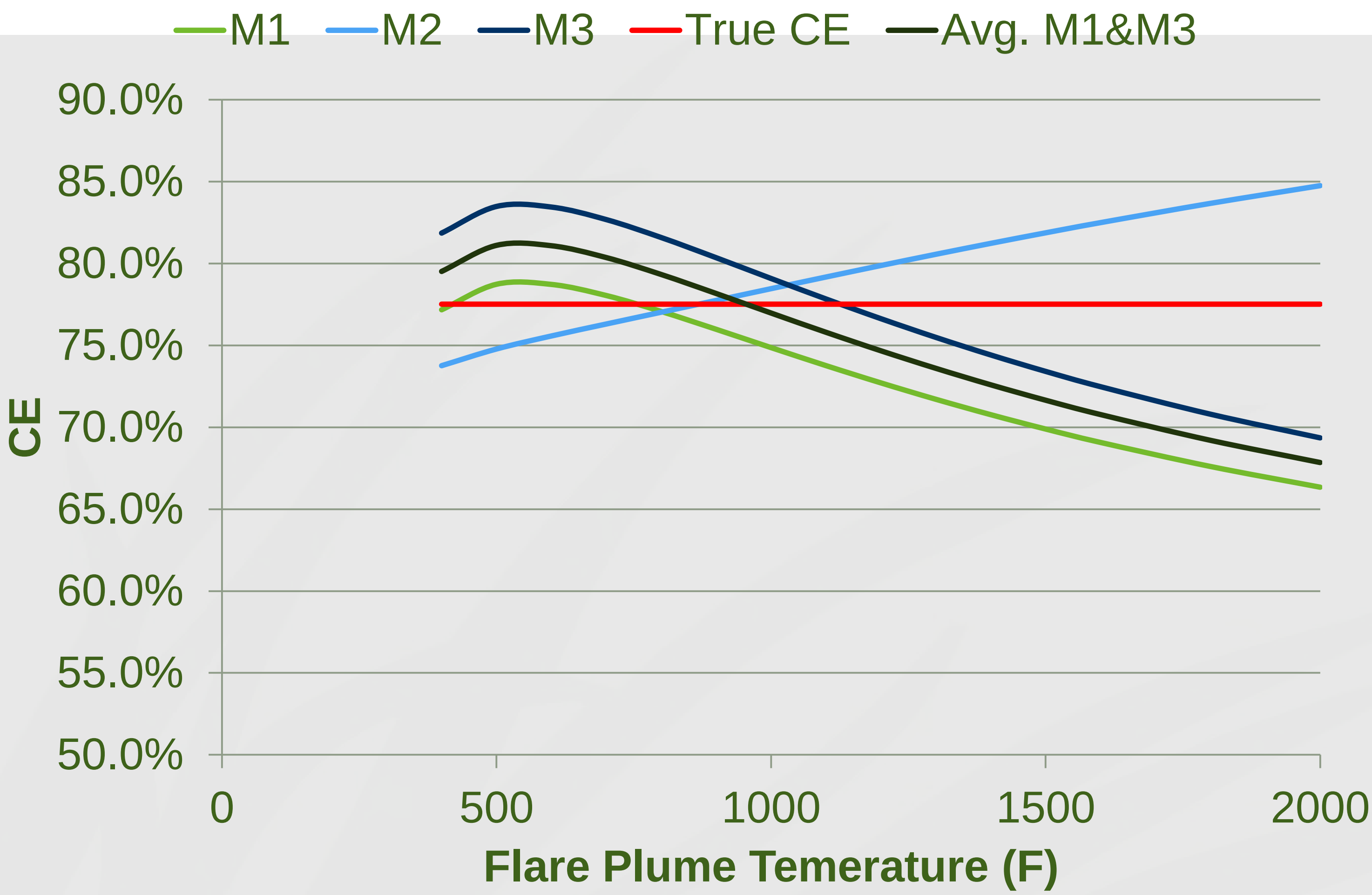
A Simple Experiment
Using a Butane Burner and Lab Multi-spectral IR Imager



A Simple Field Experiment Using 2 Spectral Bands

- Dual cooled Mid-Wave IR cameras with different spectral filtering (i.e., 2 of the 4 bands required for CE monitor)
- Emission plume with steam and propane thoroughly mixed
- Steam emission rate: 1200 lb/hr
- Propane emission rate: 3 lb/hr
- Plume diameter at release: 3 inches
- Distance from cameras: 175 feet
- Demonstrated the ability to identify and isolate propane from steam at the pixel level using spectral radiance

EFFECT OF PLUME TEMPERATURE



Note: pixels are expected to cover flare's high and low T regions

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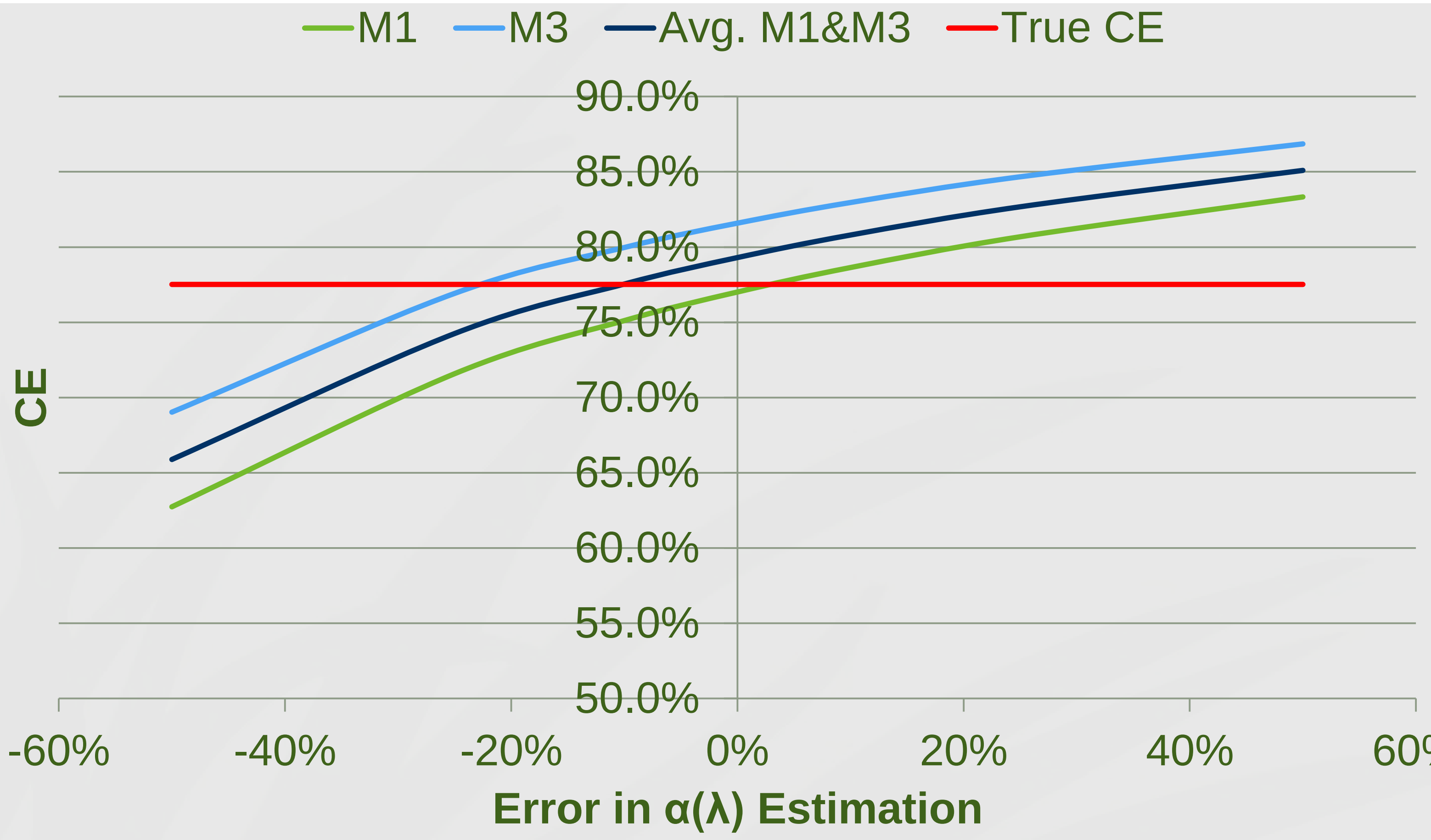
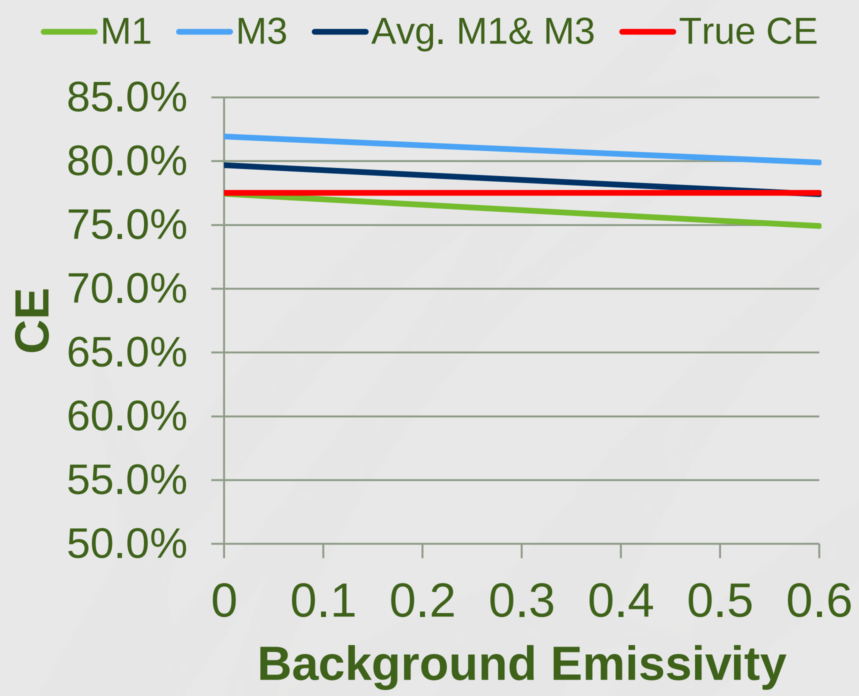
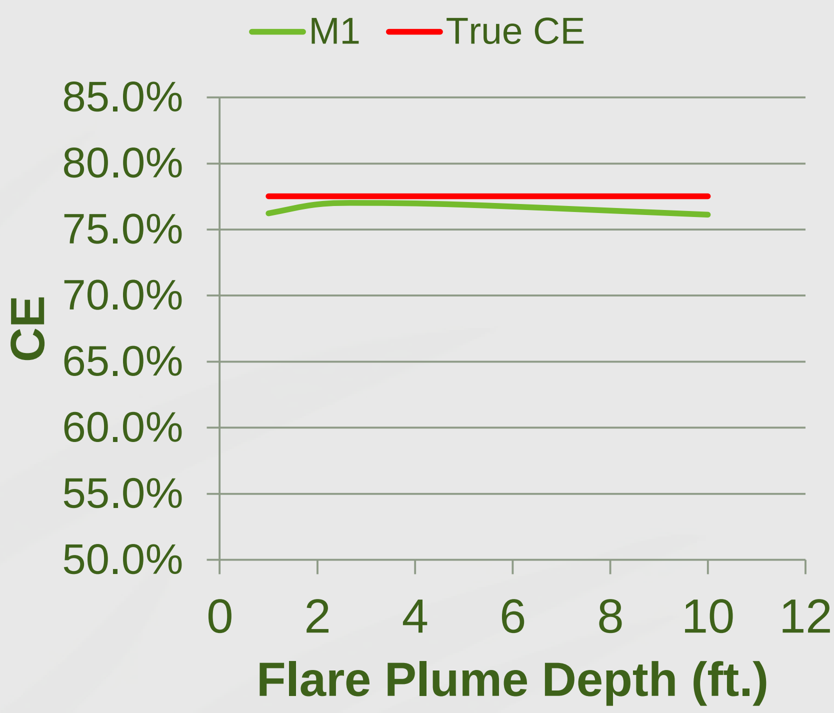
Effect of Error in HC Absorption Coefficient Estimation



Effect of Background Emissivity and Flare Plume Depth





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CONCLUSION

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- Theoretical analysis and model simulation results demonstrate the feasibility of the real-time flare CE monitoring device
  - Influential factors: plume temperature, estimate of HC absorption coefficients based on knowledge of flare gas composition
  - Less significant factors: plume depth, background, flare gas composition, actual CE
  - Calibration is accomplished inherently through the Reference Channel in the CE calculation which relies on *relative* measurements at the pixel level; no external calibration is required
- Field experiment with propane and steam demonstrates the feasibility of cancelling out interferences by using two spectral bands

NEXT STEPS

- Perform field experiment using a 42-band laboratory spectral imager to further prove the concept and narrow the design parameters
- Design and develop the first prototype
- Extensive field testing
- Launch commercial product

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