Current Challenges for Flares:
Black Carbon, NOx, & the Hidden Implications of Hydrofracturing

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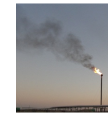
M&AE Department of Mechanical & Aerospace Engineering

Current Perspectives in 2012

- Global flaring still exceeds 139 billion m^3 annually (as visible to satellites)
  - Most flaring is poorly measured
  - Near term trends in improved well-completions should result in increased flaring where applicable
- Focussed international attention through new Climate & Clean Air Coalition (CCAC) on short-lived climate forcers:
  - Black carbon
  - Methane
  - NOx (via tropospheric ozone)

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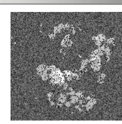
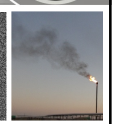
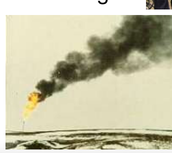
Current Perspectives in 2012

- Growing recognition that role of global flaring in climate change and air quality may be quite significant (e.g. CCAC, EPA)
- Still, there are serious shortcomings in all aspects of our understanding:
  - Raw volume measurements & reporting,
  - Emissions estimates & reporting,
  - Emission factors and models,
  - Measurement technologies & compliance monitoring
  - Fundamental / scientific understanding sufficient to weigh & compare options
- What about flares & hydrofracturing?
  - Is there any science we can trust?

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(*Some of the*) Current Challenges in Flares:

1. Black Carbon
2. NOx
3. Hidden Implications of Hydrofracturing?
4. Mitigation Options?

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Challenges for Flares:
1. Black Carbon

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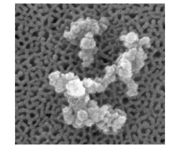
Particulate Matter & Black Carbon

- Climate forcing of Black Carbon:
  - Total effect in atmosphere could be second only to CO_2 *(e.g. Ramanthan & Carmichael, 2008)*
  - Effects are complex, not well summarized by a “Global Warming Potential” *(e.g. U.S. EPA, Report to Congress, March 2012)*
    - 100-year timescale: 330-2240
    - 20-year timescale: ~4900 or more
    - Variations are in large part due to the limits of using single-valued GWPs to model black carbon



- Air Quality:
  - PM2.5 linked ***directly*** to human mortality (& myriad other adverse effects) (e.g. U.S. EPA, 2011)

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Black Carbon Emission Factors for Flares:
Why is this so hard?

- Measuring and modelling soot formation in flames is perhaps the most challenging research problem in the field of combustion science
- Flare operating conditions, gas compositions, operating practices, and design vary widely
- Flares themselves are not amenable to direct measurement (large, unconfined, elevated, turbulent plumes)
- Accurate diagnostics for black carbon in particular have been lacking

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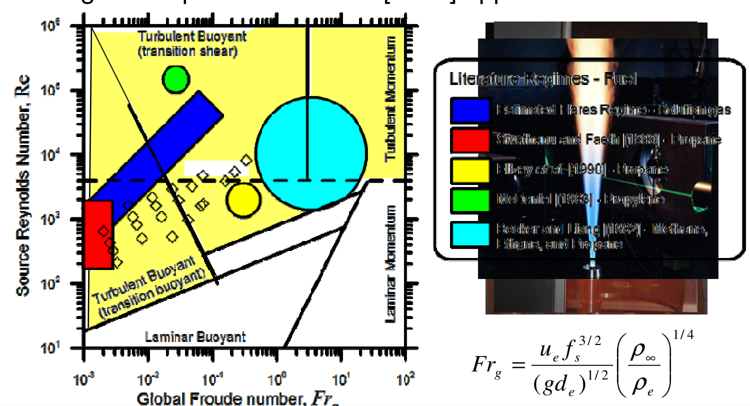
Black Carbon Emission Factors for Flares:
Why is this so hard?

- Regime map of Delichatsios [1993] applied to Flares



$$Fr_g = \frac{u_e f_s^{3/2}}{(gd_e)^{1/2}} \left(\frac{\rho_\infty}{\rho_e} \right)^{1/4}$$

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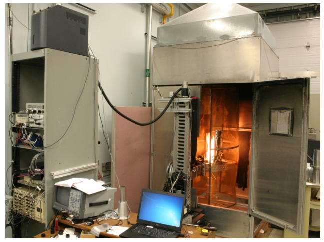
Black Carbon Emissions from Flares

Objectives (1)

- Controlled Lab-scale Experiments:
  - Critical review & assessment of currently available PM / black carbon emission factors for flares
  - Controlled lab-scale measurements of flare black carbon emission rates over wide range of conditions
  - Gas-phase pollutant emissions measurements including NOx
  - Apply novel laser diagnostics to understand formation and emission from flare



Black Carbon Emissions from Flares

Objectives (2)

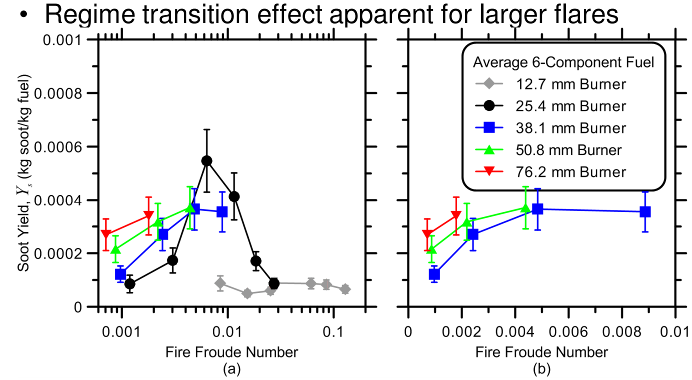
- Field Measurements
  - Develop pioneering 2nd generation sky-LOSA technology and integrate new sCMOS camera technology
  - Work with World Bank to conduct field measurements
- Research improved emission factor models
- Dissemination via invited consultations, conferences, journal articles

Recent Progress

- Peer-reviewed journal article on lab-scale measurements of black carbon emission rates *(McEwen & Johnson, J. Air Waste Manage. Assoc, 2012)*
  - Instrumental in fixing error in existing EPA WebFIRE emission factors
  - Working model for black carbon emission factors from flares operating in regime typical of solution gas flaring
  - Discussion of the role of operating regimes and fuel composition in predicting soot/black carbon emissions
  - Recognition of the critical need for larger scale experiments

Published Results

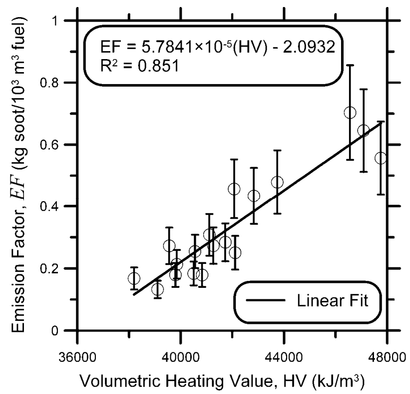
- Critical steps toward predictive models
  - Regime transition effect apparent for larger flares



McEwen & Johnson, J. Air Waste Manage. Assoc, Feb 2012

"Engineering Attempt" EF model

- In the absence of anything better, can form a simple linear *EF* model based on heating value
- Larger-scale experiments critical to link a useful model with fundamental understanding
- Field measurements will also be essential to success



McEwen & Johnson, J. Air Waste Manage. Assoc, Feb 2012

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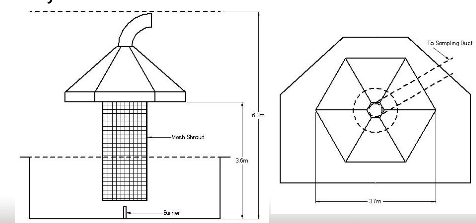
Current Work: Large-scale Flare Experiment

- Partnership with Natural Resources Canada, Environment Canada, CAPP, Univ. of Alberta, & NSERC to conduct larger scale experiments to:
  - Push past soot emission regime transitions to enable robust emission factor models
  - Research issuse specific to shale-gas hydrofracturing, especially impact of chlorine laden aerosols in flare stream which can lead to chlorinated hydrocarbons



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Large-scale Flare Experiment

- Maximum allowable velocity for a given flare diameter between the two experiments shown below, along with Froude number:

	NRC Lab-scale Flare		Large-scale Flare	
Flare Diameter [mm]	Maximum Exit Velocity [m/s]	Froude Number	Maximum Exit Velocity [m/s]	Froude Number
12.7	8.4	566	70.0	39330
25.4	2.5	25	19.0	1449
38.1	1.0	3	8.8	207
50.8	0.6	0.68	4.9	48
76.2	0.3	0.12	2.2	6

- "Typical" UOG flare of 101.6 mm diameter with an exit velocity of 4 m/s corresponds to Froude number of ~16
- Apparatus is specifically designed to facilitate research on flares associated with hydrofracturing operations

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Ongoing Work: Field measurements in Mexico with World Bank

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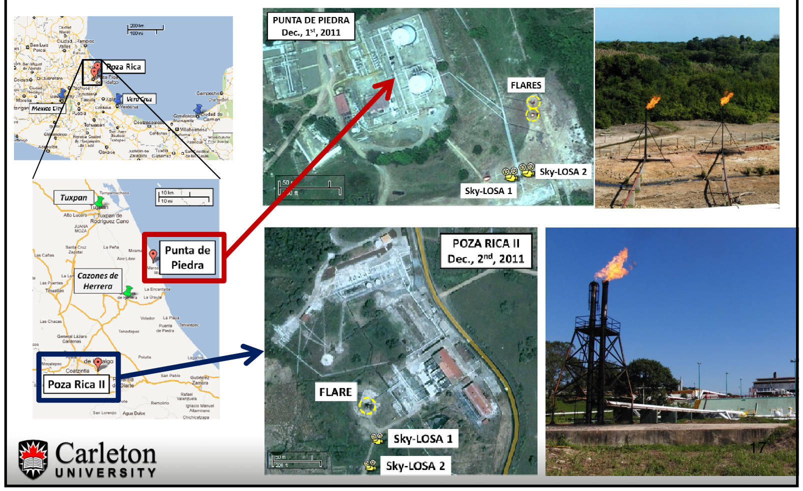
Field Measurements using Sky-LOSA in Mexico



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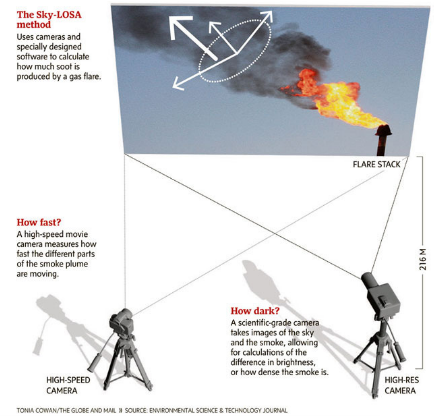
The sky-LOSA Technique

- In-situ, optical quantification of black carbon mass emission rates in a plume
- **LOSA** = **L**ine **o**f **S**ight **A**ttenuation at fixed λ
- **SKY**–light used as light source

Johnson, M.R.; Devillers, R.W.; Thomson, K.A.; *Env. Sci. Technol.* **2011**, *45*, 345-50. (doi: 10.1021/es1024838)

Johnson, M.R.; Devillers, R.W.; Yang, C.; Thomson, K.A.; *Env. Sci. Technol.* **2010**, *44*, 8196-8202. (doi: 10.1021/es102230y)



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Sky-LOSA: principle

- Concept: Can we use sky-light to make a quantitative, open-ended, optical measurement of soot in a plume?
- Mathematical basis:

$$\dot{m}_{\text{soot}} = \frac{-\rho_{\text{soot}}\lambda}{6\pi E(m)_{\lambda}(1+\rho_{\text{sa}})} \int U(y) \frac{1}{N} \sum_{i=1}^{N} \ln[\tau_{\lambda}(y)]\, dy$$

- If we can develop a quantitative system to measure transmissivity, we can make field measurements of soot plumes
  - Need optical properties of soot (Coderre *et al.*, Appl. Phys. B, 2011)
  - Need good estimate of plume velocity (see subsequent slides)

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2nd Generation Sky-LOSA System

- **sCMOS camera**
  - Single camera, up to **100fps**
    ICV & LOSA
  - Collection filter **531nm ±20nm**
  - Camera lens
- **Field deployable computer**
  - Powered from car battery
- **Laser range finder**
  - Remote spatial calibration
- **GPS**
  - Sun position & tracking

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Field Measurements at Punta de Piedra

Field Measurements in Poza Rica

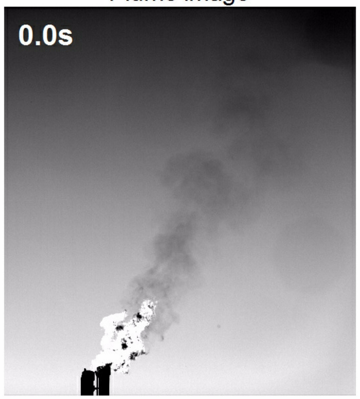
Results: *Turbocompressor station*

- **Turbocompressor station**
  - ***Poza Rica II - December, 2nd, 2011***
- Set-up at two locations
  - 46 m from the stack
  - 68 m from the stack
- Acquisitions over 1 hour 30 min
  - 10 minutes of acquisition in total
  - > 30,000 frames

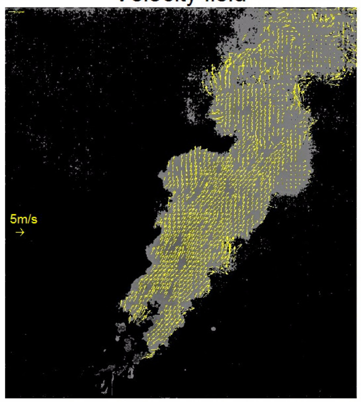
Flare as Apparent to Naked Eye

Plume Velocity Measurement

Plume image



Velocity field



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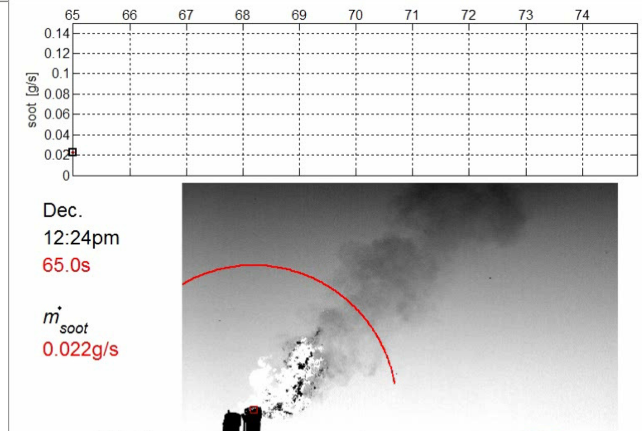
Quantification of Black Carbon Emission Rates



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Natural Resources Canada

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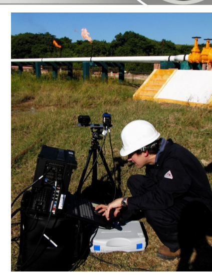
Site 2: Pipeline Terminal

- **Punta de Piedra**
  - December, 1st, 2011
  - 2 flares, each with 10m height located in a valley
- Acquisitions over 30min
  - 3 minutes of total acquisition
  - > 14,400 frames
- Measurements from two locations
  - Both approx. 60 m away from stack



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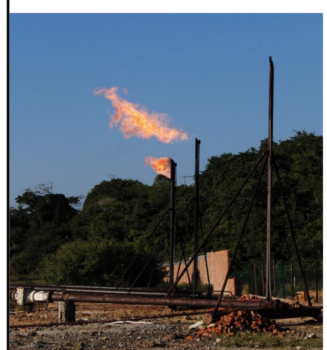
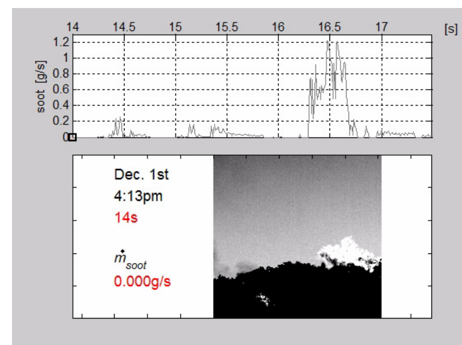
Site 2 Results:





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Significantly Improved Uncertainties

- **Soot properties** ±14% *(unchanged)*
  - *E(m)* ±3.7%
  - *ρ_{soot}* ±6%
  - *ρ_{sa}^** ±12%
- **Spatial scaling** ±2% *(was ±5%)*
- **Velocity** ±5-10% *(was ±21%)*
  - *Scaling* ±2%
  - *Exposure* ±5% to ±10%
- **Sky interpolation** up to ±0.0067 g/s *(was ±20%)*
  - *Interpolation width* 0 to ±0.005 g/s
  - *Conditional average* +0.003 to +0.005 g/s

TOTAL error (for 0.05 g/s) ±16% to ±21% *(was ±35%)*

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Context: *Comparing Field & Lab Data*

- Pemex did not provide data or access for measurements to determine the mass flow and composition of fuel entering the flare stream
  - To date no direct, *in situ*, evaluation of emission factors as mass of black carbon per mass or volume of fuel have been possible
  - Clear objective moving forward
- Based on recent lab-work and preliminary model publication (*McEwen & Johnson, JAWMA 2012*) can make preliminary estimates for discussion

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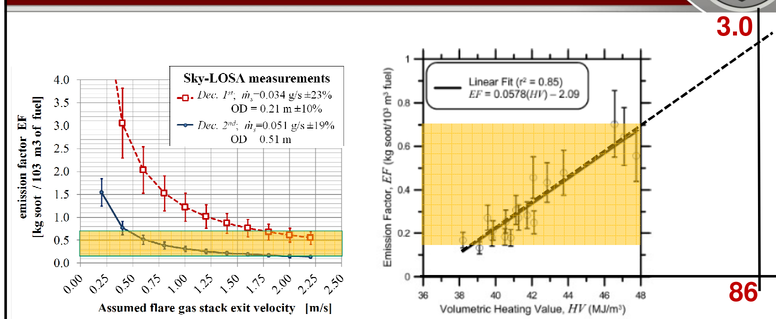
Context: *Comparison of Field & Lab Data and EFs*



- **Comparison with *EF* correlation from McEwen & Johnson, 2012**
  - ***Dec. 2nd***: mean emission of 0.051 g/s consistent with low heating values and u_{exit} > 0.5m/s
  - ***Dec. 1st***: mean emission of 0.034g/s (smaller stack) suggest low u_{exit} or high heating value (propane *HV* = 86 MJ/m³)

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Sky-LOSA: Required Next Steps

- **Sky-LOSA measurement for known conditions**
  - **Fuel gas flow rate**
  - **Gas composition**
- Improving the use of sky-LOSA in the field
  - Better processing software, more automated
- Careful study of direct sun-light scattering
  - Sun light leads to scattering from soot
  - Additional light intensity $\rightarrow\tau$ is overestimated $\rightarrow m_{soot}$ is underestimated
  - Modelling required for accurate estimation of bias (sun model, soot model…)

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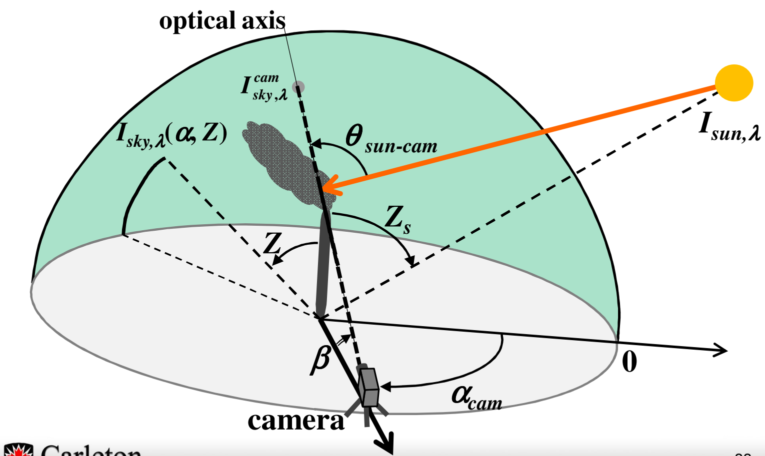
Next Step Challenges: *sun-light scattering*



Challenges for Flares:
2. NOx

Current NOx Emission Factors

Source	Reported Emission Factor	Converted Emission Factor [g NOx/m³ fuel]	Fuel	Scientific Source
US EPA AP-42 Section 13.5	0.068 lb NOx/10^6 BTU	1.28	80% Propylene, 20% Propane	McDaniel, 1983
US EPA WebFIRE	40 lb NOx/10^6 SCF dry methane	0.64	Landfill waste gas	US EPA, 1998 (Municipal Solid Waste Landfills)
CAPP	1.345 kg/10^3 m^3	1.345	45 MJ/m^3	US EPA AP-42, Sec. 13.5, 1995

- None of particular relevance to UOG flares
- Less than ideal!

Experimental Overview

- Conducted on the NRC lab-scale flare under the following conditions:

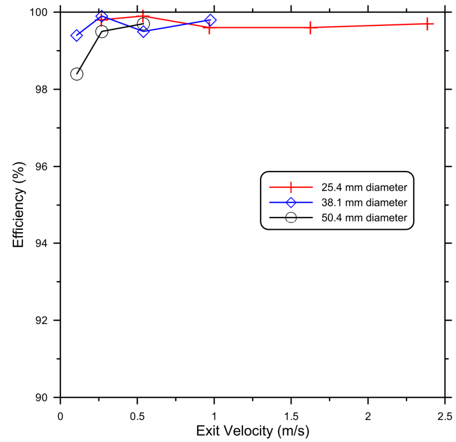
Diameter (mm)	Velocities (m/s)	Froude number
25.4	0.27, 0.54, 0.97, 1.63, 2.39	0.28 - 22.84
38.1	0.11, 0.27, 0.54, 0.98	0.03 - 2.55
50.8	0.11, 0.27, 0.54	0.02 - 0.58

- Fuel mixture: 85.24% methane, 7.06% ethane, 3.11% propane, 1.44% butane, 1.91% CO_2, 1.24% N_2
- NOx emission factor calculated using the following equation:

$$EF_{NO_x}\left(\frac{g\ NO_x}{kg\ fuel}\right) = \frac{\dot{m}_{NO,produced} + \dot{m}_{NO_2,produced}}{\dot{m}_{fuel}}$$

- Flare efficiency calculated as outlined previously from gas phase composition measurements

Experimental Results - Efficiency



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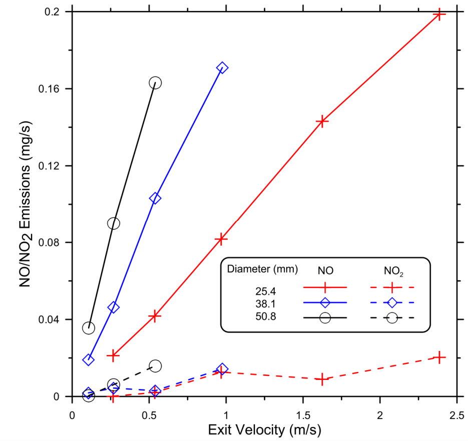
Experimental Results – NO and NO_2



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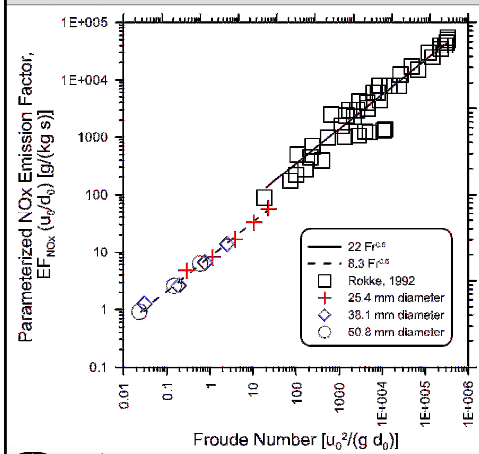
Scaling Based on Theory of NOx Formation



- Very good correlation
- Preliminary data suggests may be a regime shift for different operating conditions consistent with soot measurement data
- Close to having a new workable model!

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Preliminary Thoughts: NOx

- "Typical" NOx emissions might be lower than predicted by current emission factors (AP-42, WebFIRE, CAPP), especially at low Froude numbers
  - But beware influence of regimes / operating conditions
- Need to improve experiment and rigorously quantify and refine uncertainties
- Successful application of formation theory to predict preliminary results very encouraging for future development of a robust emissions model
- Planned experiments on new larger-scale lab-flare (Froude and Reynolds more relevant to UOG flaring) will provide badly needed data

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Challenges for Flares:
3. Hidden Implications of Hydrofracturing?

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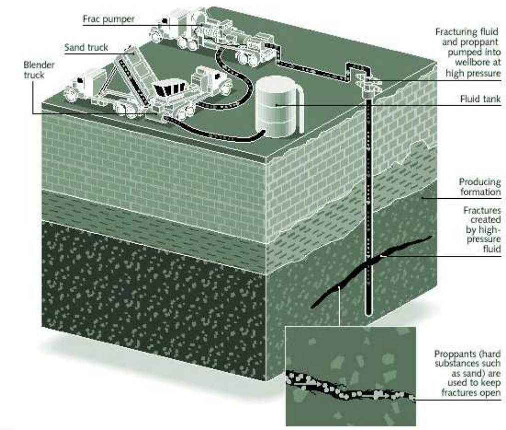
Hydrofracturing



http://www.wordsearchinc.com/wladimir/2010/01/23/energy-101-hydraulic-fracturing/

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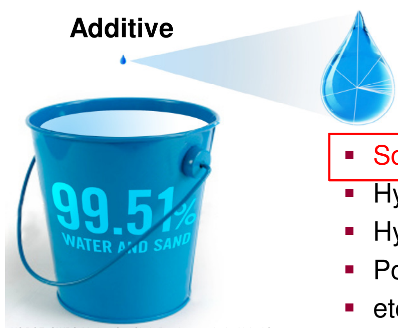
Hydrofracturing Fluids

Additive



US DOE, GWPC: Modern Gas Shale Development In the United States: A Primer (2009)

3 billion m^3 only in US (2005-2009)

- Sodium chloride
- Hydrochloric acid
- Hydrocarbons
- Polymers
- etc.

• BC Oil & Gas Commission is a Global Leader (fracfocus.ca)

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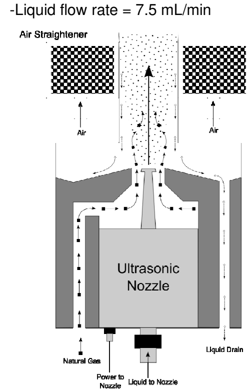
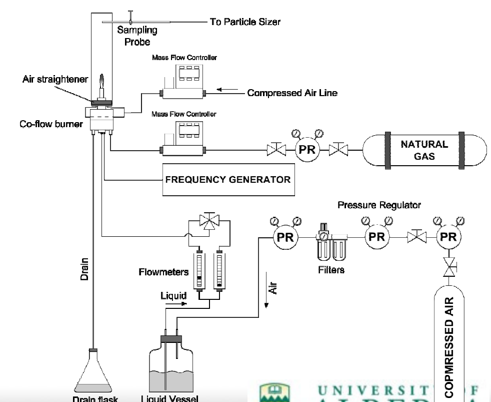
Experimental Setup for Exploratory Measurements at U of A

-Natural gas flow rate = 0.3 slpm
-Liquid flow rate = 7.5 mL/min

-Air flow rate = 13.4 slpm
-Droplet number median diam. = 19 µm





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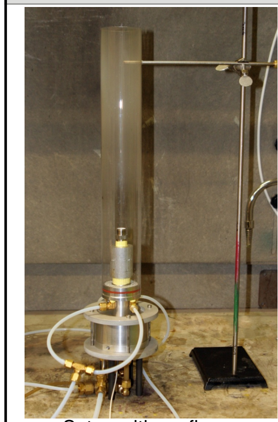
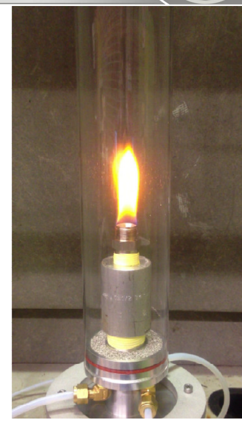
Exploratory Measurements at U of A



Setup with no flame

Combustion with distilled water

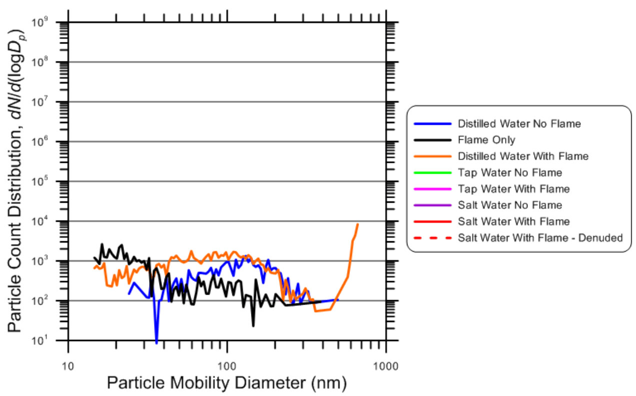


Combustion with salt water

Particle Count & Sizing Measurements

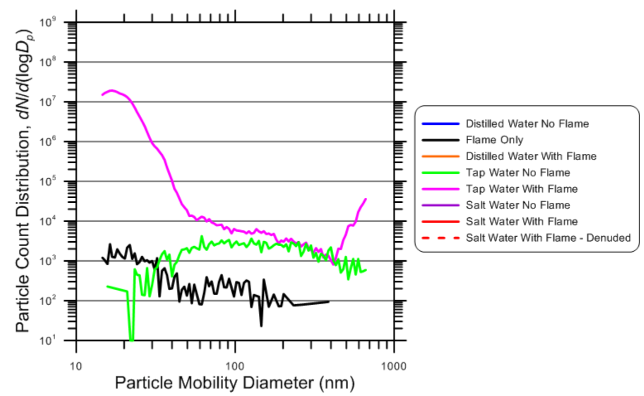
- Scanning Mobility Particle Sizer (SMPS)
  - Differential Mobility Analyzer (DMA)
    - Classifies particles by electrical mobility which is proportional to particle size
  - Particle Counter (CPC)
    - Condenses vapour onto particles to make them large enough to count in a laser beam

Results: Distilled Water



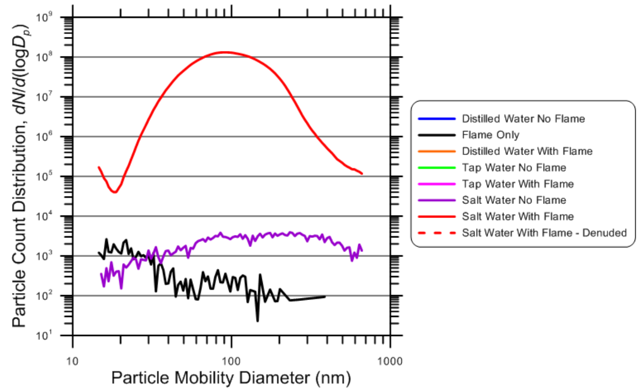
Total number concentrations: 639 #/cm^3; 497 #/cm^3; 1350 #/cm^3

Results: Tap Water



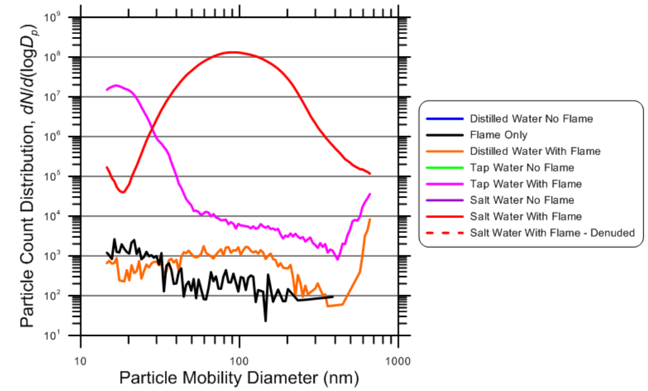
Total number concentrations: 639 #/cm^3; 2.65x10^3 #/cm^3;3.65x10^6 #/cm^3

Results: Salt Water (10%)



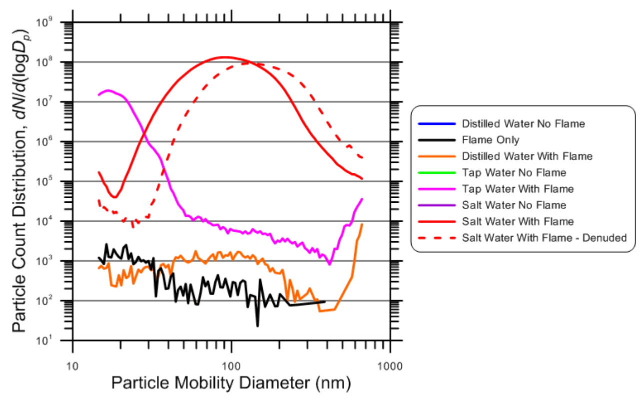
Total number concentrations: 639 #/cm^3; 3.48x10^3 #/cm^3; 6.21x10^7 #/cm^3

Results: Effects of Droplet Composition



Total number concentrations [#/cm^3]: 639; 1350; 3.48x10^3; 6.21x10^7

What is Emitted???



Total number concentrations [#/cm^3]: 639; 1350; 3.48x10^3; 6.21x10^7

Hidden Implications for Hydrofracturing?

- Exploratory lab experiments on idealized flames show surprisingly significant increases in particle emissions with small amounts of chlorine or salt containing water carried into a flame as aerosols
- Lots (too much) room for speculation
  - On the internet a lack of science is readily filled!
  - Significant risk management issue
- Flaring is seen as an important, regulated solution for excessive venting associated with hydrofracturing well completions
  - Likely still true, but critical need for further investigation

Challenges for Flares:
4. Mitigation of Higher-hanging Fruit?

Recent Progress

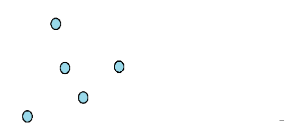
- Technoeconomic analysis case-study on mitigation potential for individual batteries in Alberta recently published
  - *Johnson & Coderre, Int. J. Greenhouse Gas Control, 8:121-131, 2012. (doi: 10.1016/j.ijggc.2012.02.004)*
- Positive feedback and interest from a number of sources

Future Directions

- PTAC/CAPP RFP to study air emissions from hydrofracturing awarded to Carleton/Clearstone Engineering collaboration
- Environment Canada looking to fund broader analysis of flaring/venting mitigation opportunities:
  - Include other provinces
  - Further analysis of aggregation potential (see next slide)
  - Opportunity for members of this forum to collaborate

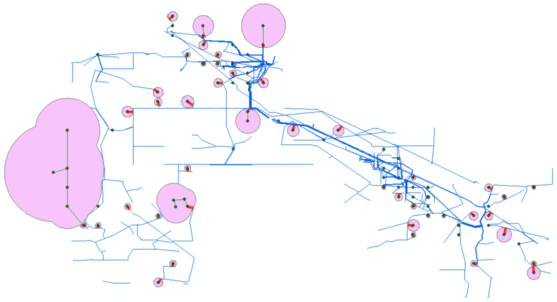
Peak at Opportunities for Mitigation Analysis

- Some of the largest mitigation potential lies in possibility of low-pressure gas collection options to share infrastructure costs
- Non-trivial problem:



Peak at Opportunities for Mitigation Analysis

- Low-pressure gas collection options



- Further possible opportunities with Clearstone Eng. Analyzing mitigation based on economics of high-value liquid / higher-hydrocarbon recovery

Final Thoughts on the Bigger Picture

- Significant progress has been made in a number of fronts (research, regulation, technology, operating practices) and in a number of jurisdictions
- Still, there are many significant remaining and emerging challenges for flaring and venting driven primarily by increased attention on short-lived climate forcers, rapid development, and emerging dominance of hydrofracturing
- Opportunities to continue leading on a number of these fronts

Particulate Matter Emissions from Flares

- Collaborators & Funding Partners

Natural Resources Canada
CAPP CANADIAN ASSOCIATION OF PETROLEUM PRODUCERS
NRC·CNRC Canada
Environment Canada
THE WORLD BANK
GGFR
Carleton UNIVERSITY Canada's Capital University
PEMEX
CLEANAIR TASK FORCE
PETROLEUM TECHNOLOGY ALLIANCE CANADA PTAC

Current Research Team

- Principle Investigators:
  - Matthew Johnson, *Canada Research Chair in Energy & Combustion Generated Pollutant Emissions, Associate Prof., Carleton University*
  - Kevin Thomson, *Research Officer, National Research Council*
  - Jason Olfert, *Assistant Prof., University of Alberta*
- Graduate Students / Post Doctoral Fellows:
  - Carol Brereton, *M.A.Sc. candidate*
  - Brian Crosland, *Ph.D. candidate*
  - Ian Joynes, *M.A.Sc. candidate*
  - Stephen Schoonbaert, *M.A.Sc. cand.*
  - Mohsen Kazemimanesh, *M.A.Sc. cand. (U of A)*
  - Darcy Corbin, *M.A.Sc. candidate*
  - Robin Devillers, *Post. Doc.*
  - Clifton Pereira, *M.A.Sc. candidate*
  - David Tyner, *Post. Doc.*
- Graduates:
  - Pervez Canteenwalla, *M.A.Sc. 2007*
  - James McEwen, *M.A.Sc. 2010*
  - Chen Yang, *M.A.Sc. 2008*
  - Adam Coderre, *M.A.Sc. 2009*
  - Stephanie Trottier, *M.A.Sc. 2005*