GLOBAL FORUM

On Flaring and Venting Reduction and Natural Gas Utilisation

Flare Efficiency & Emissions:

Past & current research

Carleton UNIVERSITY

Canada's Capital University

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The Ubiquitous Gas Flare

- What are flare efficiencies? What is emitted? How can we quantify?
- Can we model emissions to support GGFR related initiatives & economic opportunities?





Emissions from flares

- “Flare efficiency” (Carbon conversion efficiency):

$$\eta = \frac{\textit{Mass}\text{ of Carbon Converted to CO}_2}{\textit{Mass}\text{ of Carbon Originally as Fuel}}$$

- Speciated emissions:
  - Key greenhouse gases
    - CH_4, CO_2
  - Priority pollutants
    - Soot (carbon based PM), SO_2, NOx
    - Soot has recently been implicated as a key climate forcer *(e.g. Ramanathan & Carmichael, 2008; IPCC AR4, 2007)*
  - Minor species
    - Volatile organic compounds (VOCs)

Flow Regimes of Flares

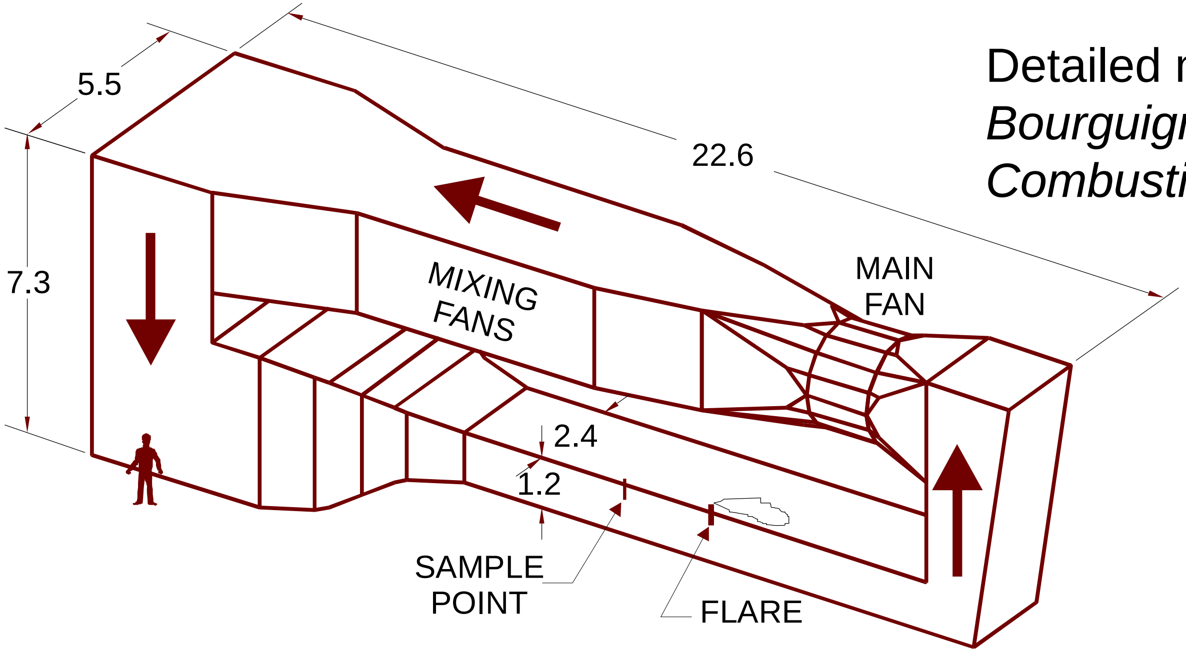
- Two very different regimes ($R = \rho_j V_j^2 / \rho_\infty U_\infty^2$):
  - High R, “lifted jet flames”; Low R, “wake-stabilized flames”
- Primarily have been interested in solution gas flares, low *R*
- Highly variable among installations
- Solution gas flares account for 60-70% of flaring in Alberta

Early Research on Flaring

- Limited scientific understanding of this flow
- Brzustowski (1976) – general description but no consideration of emissions
- Seigel (1980) – Ph.D. thesis looking at single point sampling from industrial size flares with & without steam
- Pohl et al. (1986) – EPA study of emergency scale flares in quiescent conditions
- Limited other studies using single point sampling
- Most previous attempts were focused solely on large scale, high-momentum flares
  - Very limited exploration of crosswind effects
  - No accepted efficiency models

Quantifying Flare Efficiency

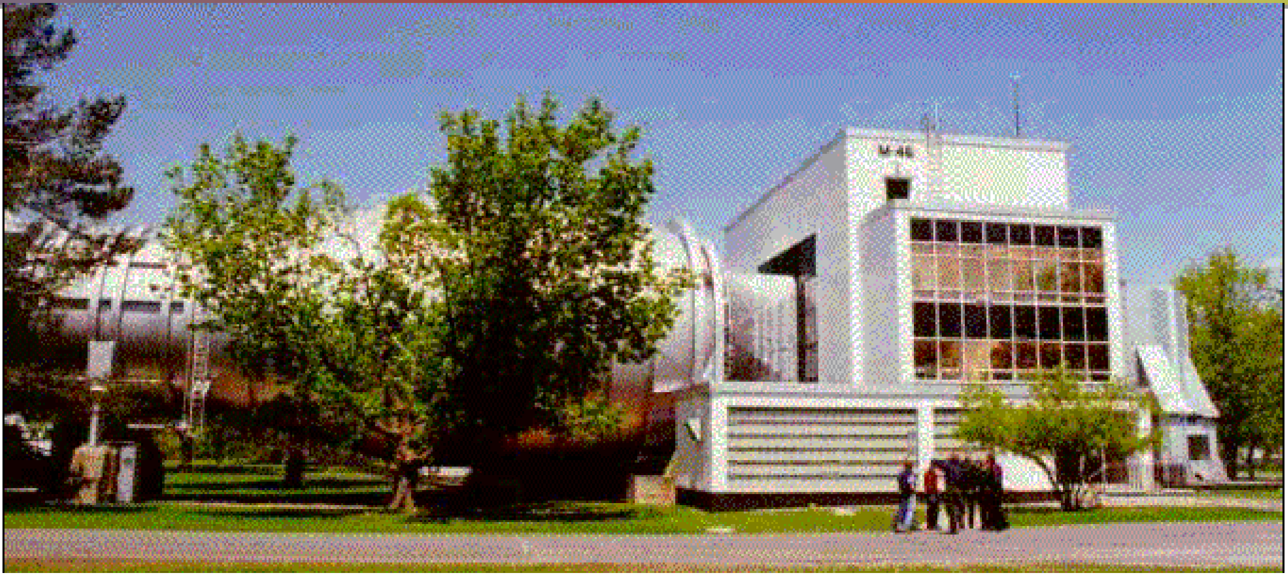
- Accumulate emissions from combusting jets in a closed-loop windtunnel
- Test scaled-down flares (1/8 - 1/2 scale) while varying multiple flow parameters

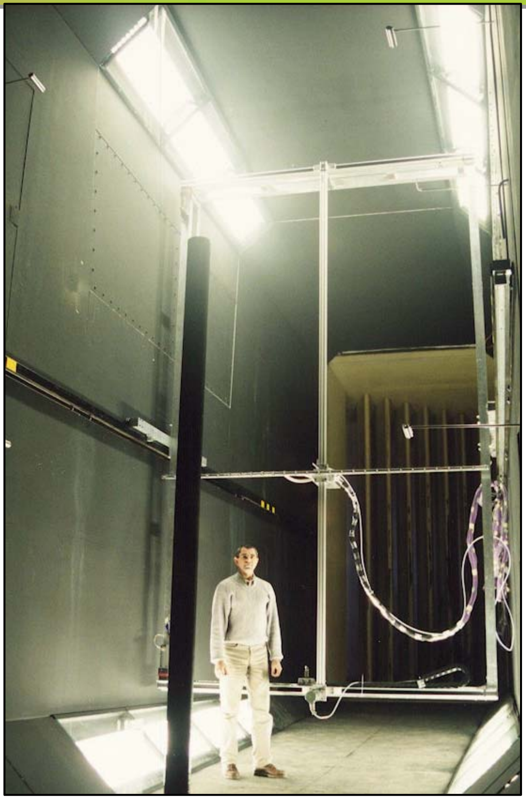


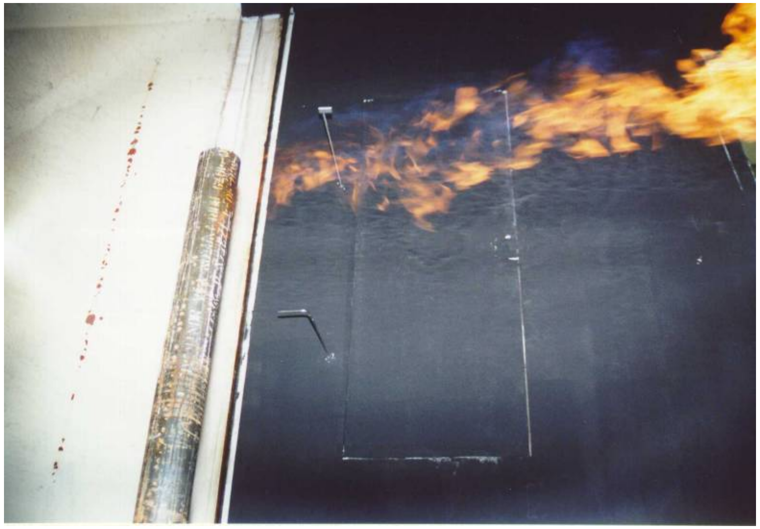
Detailed methodology:
Bourguignon et al., Combustion & Flame, 1998.

Windtunnel Experiments at U of A

Larger scale testing at NRC







- Full-scale solution gas flares
- “Small scale” emergency / production flares

Quantifying Flare Efficiency

Focus was on solution gas flaring

- Low momentum
- Flares typically 3-8” diameter
- Typical volumes of up to ~10^6 m^3 per year (<2000 SLPM)
- Variable composition
- ~60-70% of flaring/venting in Alberta, Canada

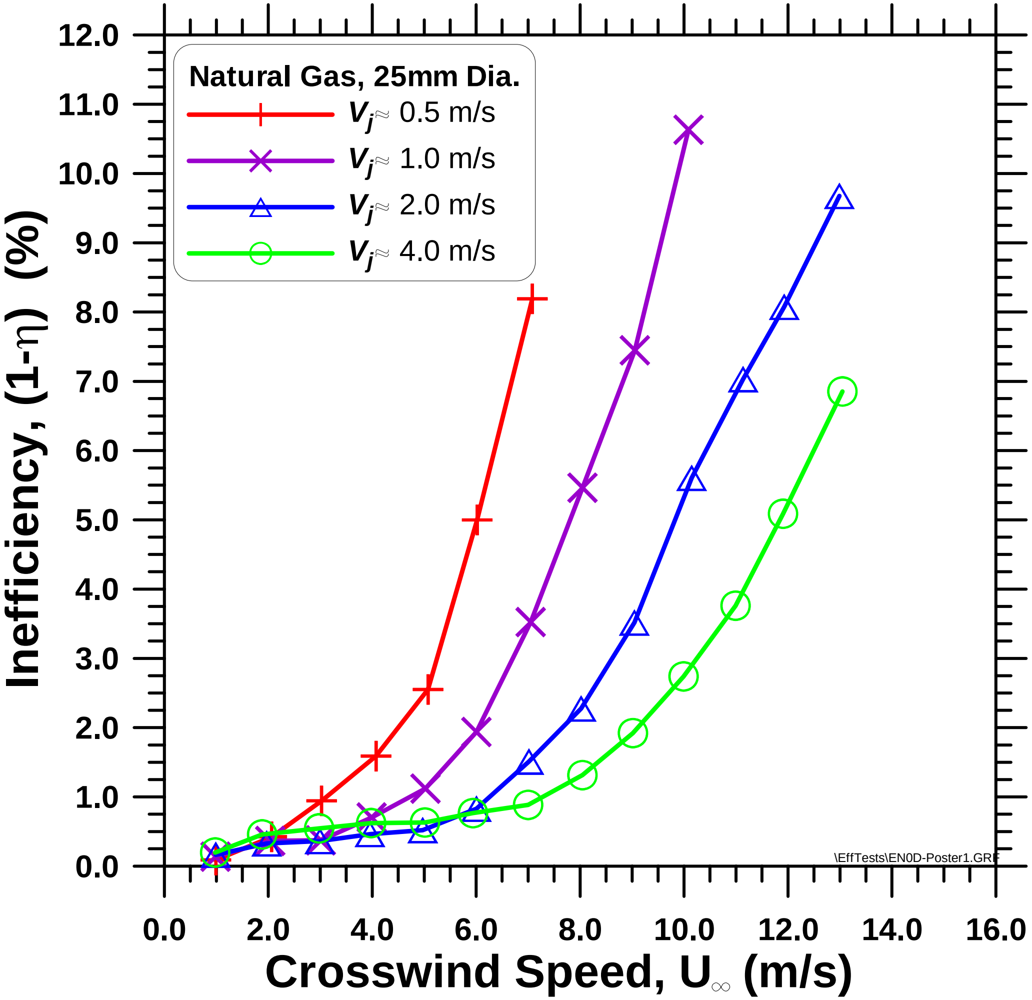
Methodology

- Mass balance on combustion products
- Closed-loop windtunnel testing as well as multipoint sampling in large open-loop windtunnel
- 1” to 4” scale flares

Flare efficiency in a crosswind

Lab-flares burning sales-grade natural gas

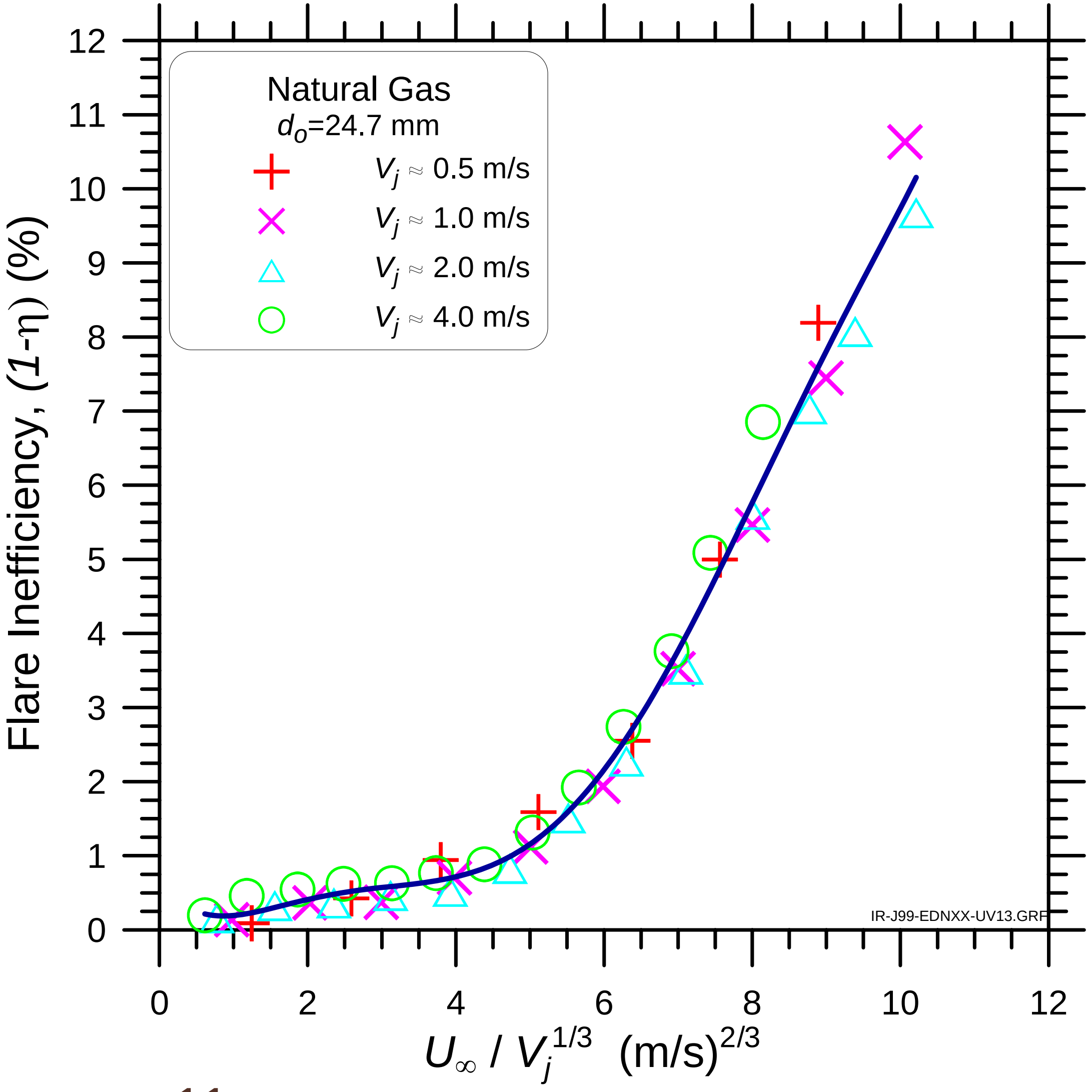
- (In)efficiency is strongly dependent on crosswind speed
- Previous research, Pohl et al. (1986), Seigel (1980), only looked at zero crosswind case
- Analysis shows inefficiencies primarily un-burned fuel + CO



Flare efficiency in a crosswind

Initial Steps toward efficiency models

- Can correlate velocity dependencies with parameter $U_\infty / V_j^{1/3}$
- Parameter can be related to a Richardson number and non-dimensionalized as
  $U_\infty / (g\ V_j\ d)^{1/3}$

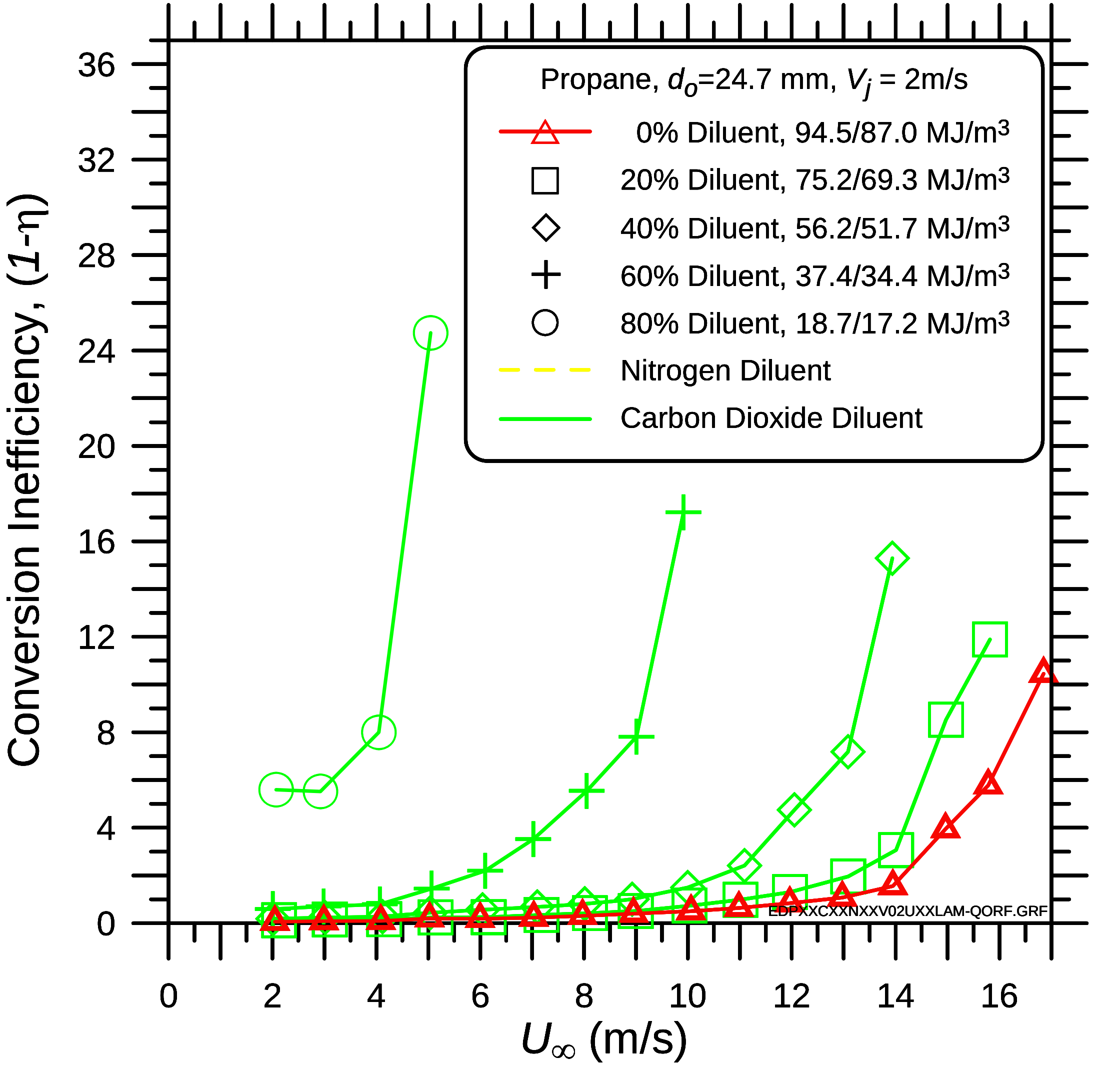


Johnson & Kostiuk, Combustion & Flame 123:189-200 (2000)

Energy Density & Efficiency

Identification of critical role of heating value on flare efficiency

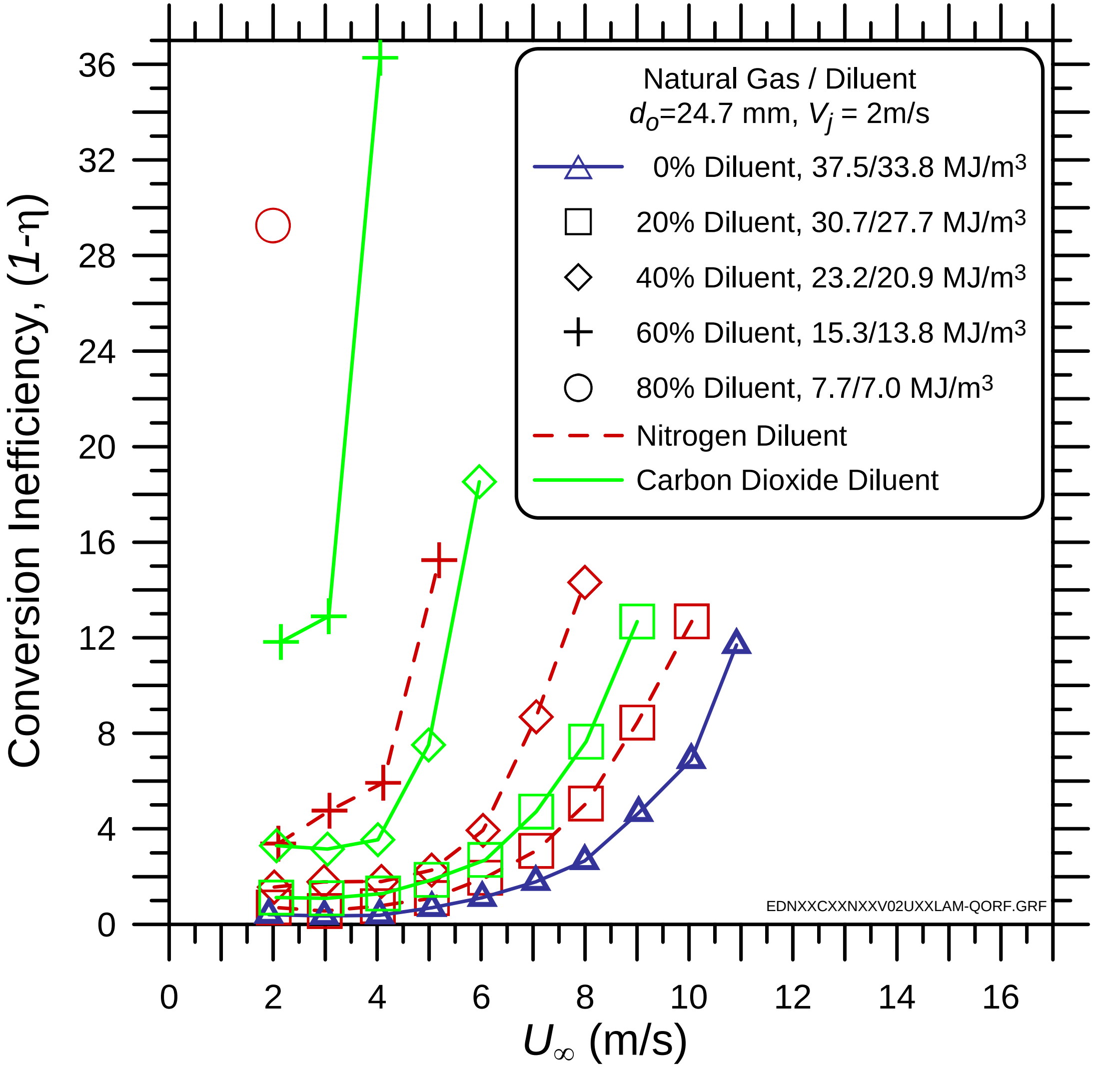
- Blends of propane and CO_2 maintain constant mass density while varying energy density
- Can no longer explain this result in terms of a simple Richardson number



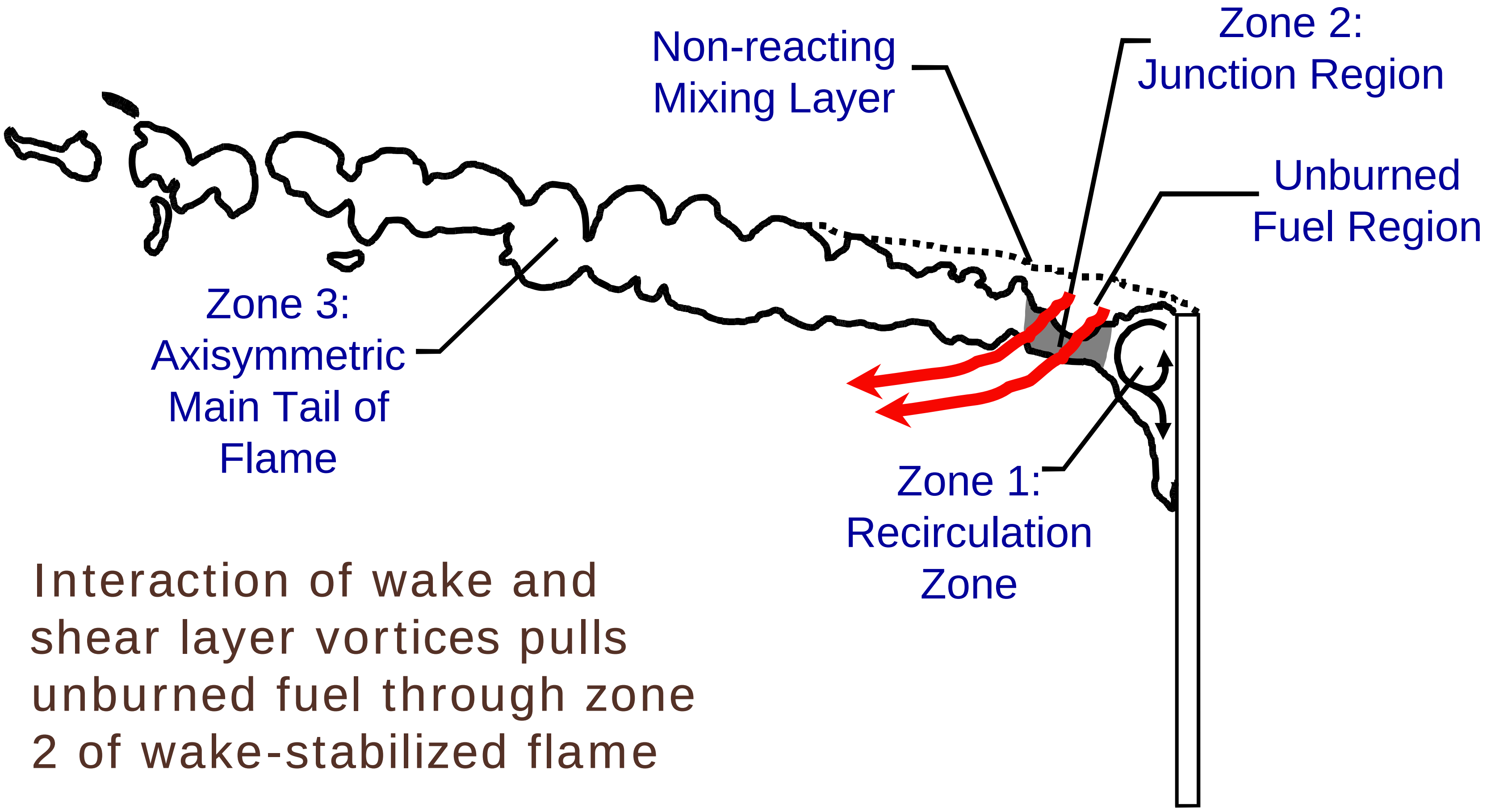
Johnson & Kostiuk, Combustion & Flame 123:189-200 (2000)

Key Outcomes: Directive 60

- Natural gas based flames seem more susceptible to effects of added CO_2
- Curves are displaced upward as well as to the left
- Important result for industry which lead directly to a regulatory change in Alberta via ERCB Directive 60



“Fuel Stripping Mechanism”



Non-reacting Mixing Layer

Zone 2: Junction Region

Unburned Fuel Region

Zone 3: Axisymmetric Main Tail of Flame

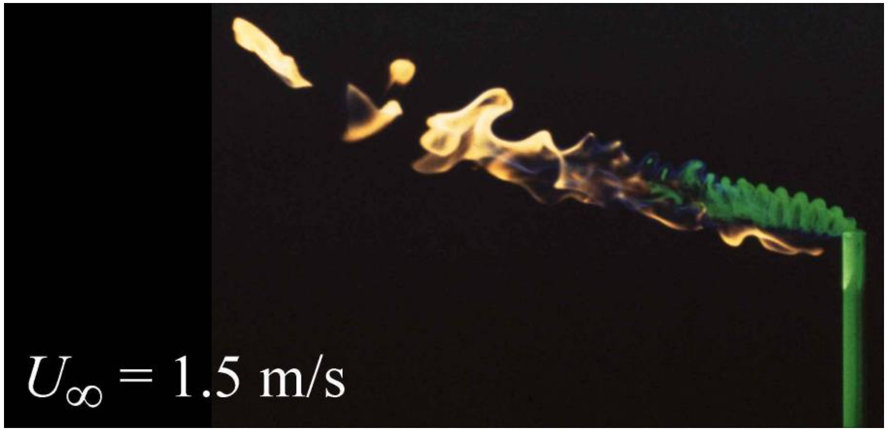
Zone 1: Recirculation Zone

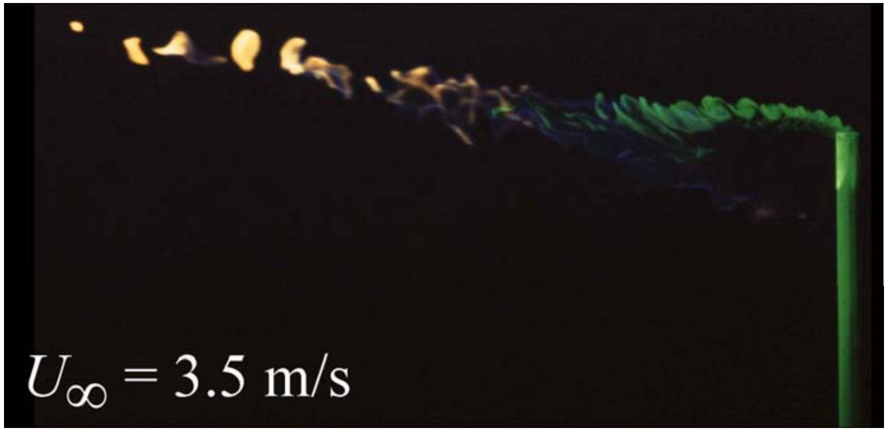
- Interaction of wake and shear layer vortices pulls unburned fuel through zone 2 of wake-stabilized flame

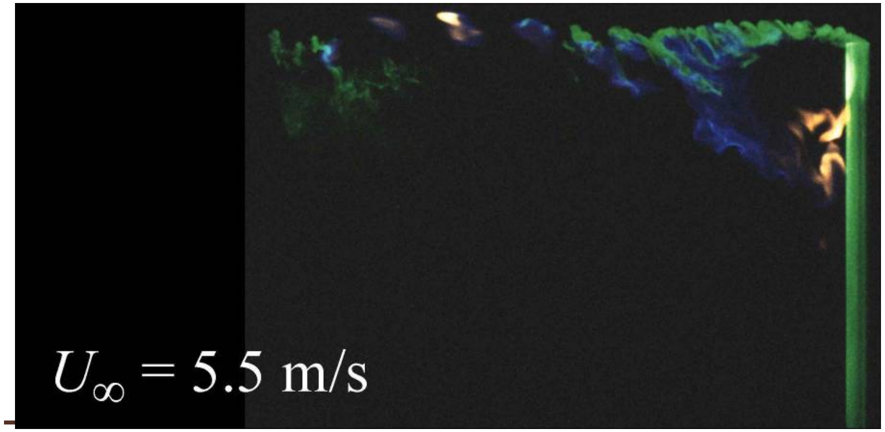
Johnson et al., Comb. Sci. Tech 169:155-174 (2002)

Laser Sheet Imaging

- Fuel jet is seeded with fine oil mist (~5 µm mass mean dia.)
- Mie scattering of laser sheet illuminates unburned fuel (green)
- Unburned fuel is drawn through “Zone 2” and ejected from the flame



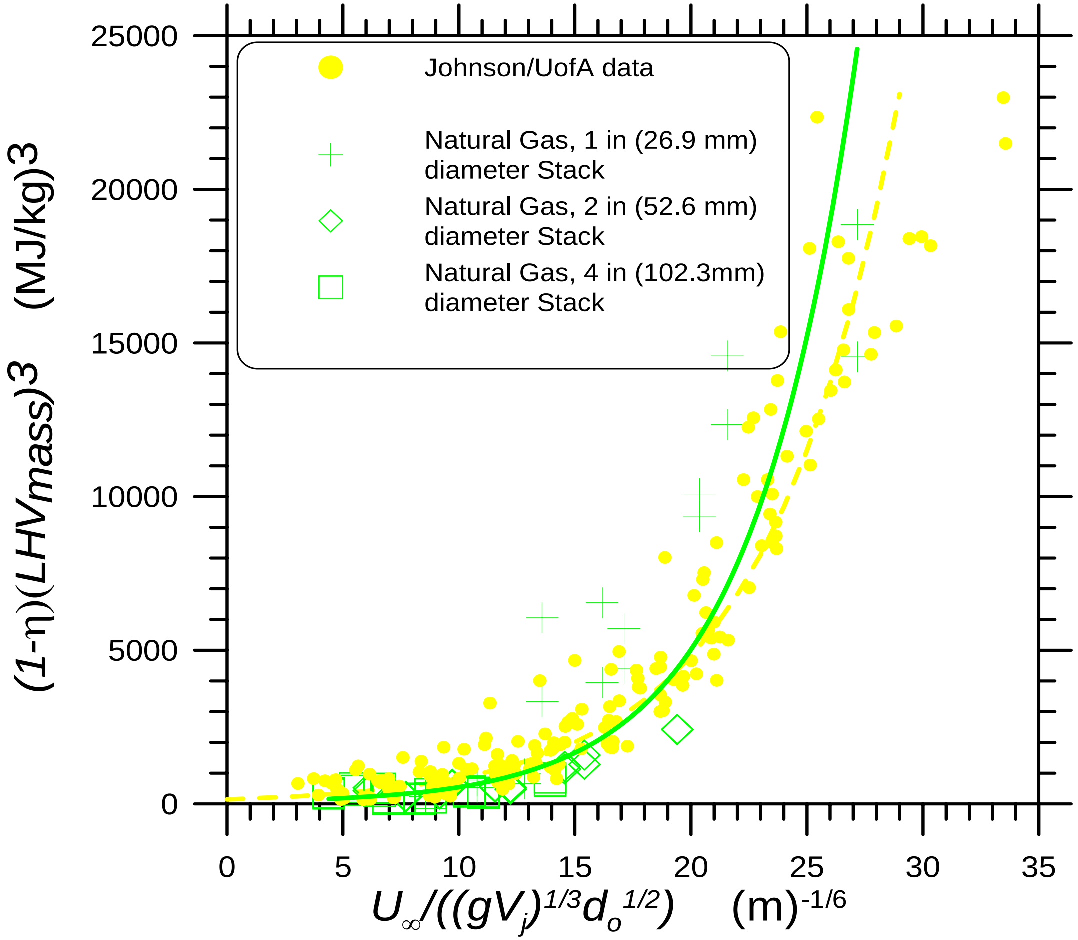




Modelling Efficiency

- Model seems to hold for data at over factor of 8 scaling
- Natural gas correlates better with $d_o^{1/2}$, but strange units
- C_3H_8 varies with $d_o^{1/3}$

- Major result for ***simple fuels*** and efficiency
- Key questions remain for extending results to GHG emissions factors



Johnson & Kostiuk, P. Comb. Inst. 29:1943-1950 (2002)

“Yearly Averaged Efficiency”

- Useful to convert instantaneous efficiency at one wind-speed to meaningful “average” value
- Concept of “Yearly Averaged Efficiency” and “Yearly Averaged GHG Equivalent Emission”
  - Statistically weighted average of efficiency taking into account widely varying wind conditions
  - Calculate using parametric data set and models

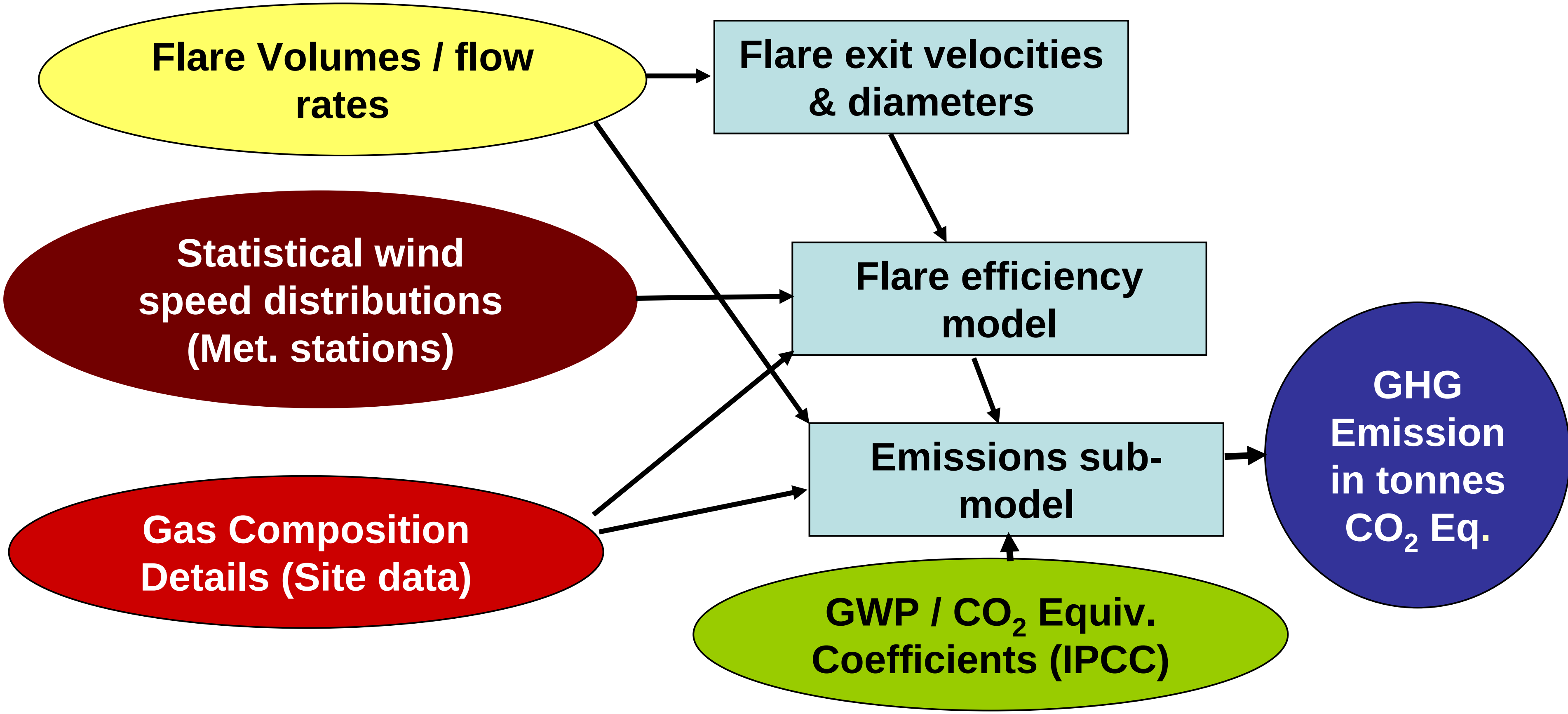
$$\overline{\eta} = \int_0^\infty P(U_\infty)\eta(U_\infty, V_j, D, HV)dU_\infty$$

where $P(U_\infty)$ = probability dist. function of wind speed, U_∞

$\eta(U_\infty, D, V_j, HV_,)$ = efficiency of flare as function of wind speed and operating parameters

Concept for GHG Quantification

- Required data inputs:



Flare Volumes / flow rates

Flare exit velocities & diameters

Statistical wind speed distributions (Met. stations)

Flare efficiency model

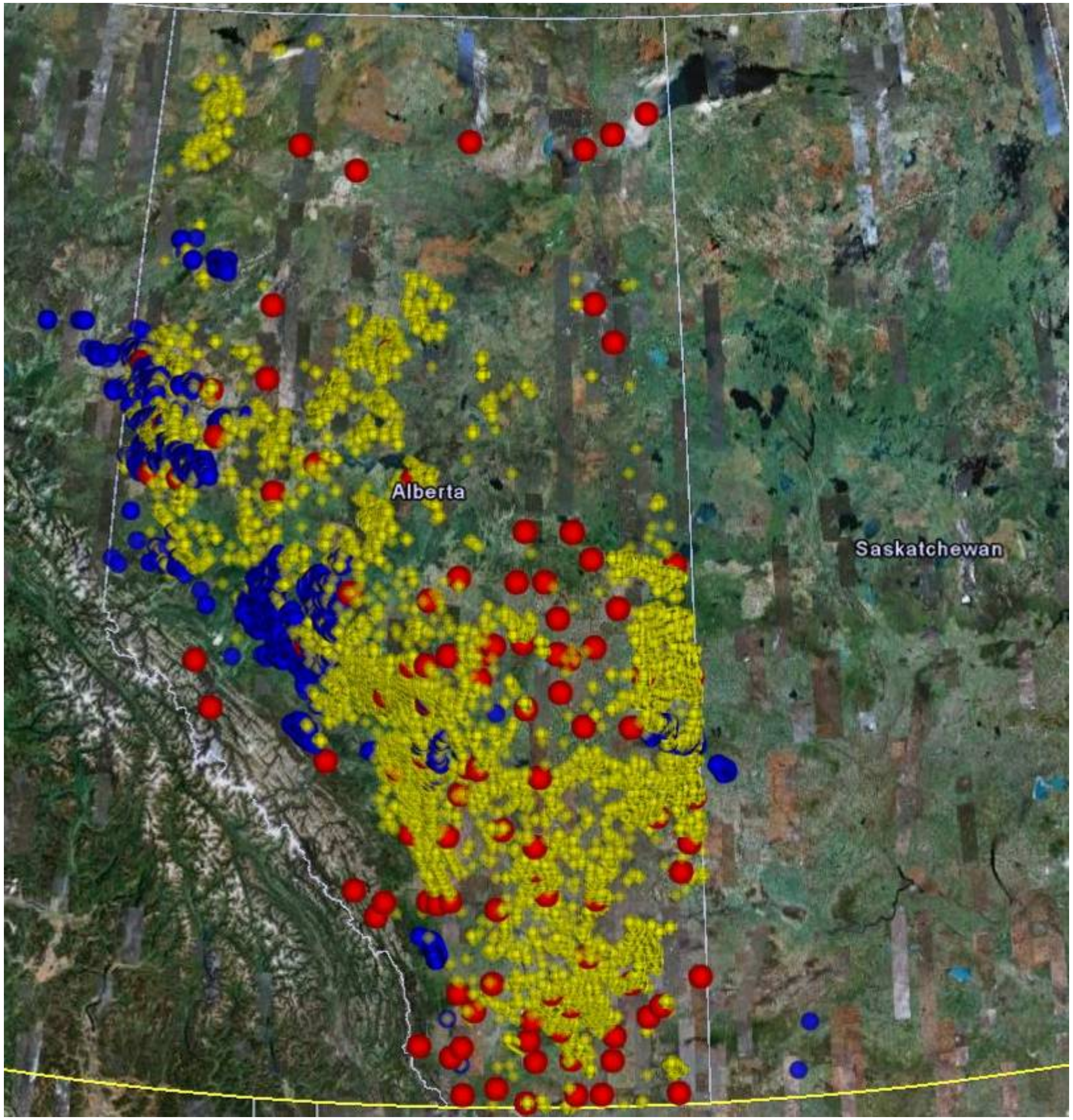
Gas Composition Details (Site data)

Emissions sub-model

GHG Emission in tonnes CO_2 Eq.

GWP / CO_2 Equiv. Coefficients (IPCC)

Integration of Data & Model



- Relational database
- 9767 Battery sites that reported flaring and/or venting during Jan. 2002- Dec.2005
- Composition data from 2908 distinct locations
- Detailed statistical wind speed data from 107 Environment Canada meteorological stations

Quantification of GHG Emissions

- Major Results:

Year	# of Active Btys	# flaring or venting	Gas. Flared (1000m³)	Gas Vented (1000m³)	Tot. F+V (1000m³)	Yearly-averaged efficiency (%)	GHG from flaring (tonnes)	GHG from venting (tonnes)	Total GHG (tonnes CO_2 eq.)
2002	9427	6025	508349	500990	1009339	**95.1**	1091382	7877467	**8968849**
2003	9699	6255	412937	378157	791094	**95.1**	821666	5933247	**6754913**
2004	9864	6079	372903	355969.3	728872	**94.9**	766745	5553294	**6320039**
2005	9716	5531	375518	291137	666655	**95.1**	627978	4548395	**5176373**

- Total GHG emissions of 5.2 million tonnes of CO_2 equivalent from flaring and venting at Alberta conventional oil batteries in 2005 (does not include well testing, gas plants etc.)

Summary of Flare Efficiency Research

Key Outcomes to Date

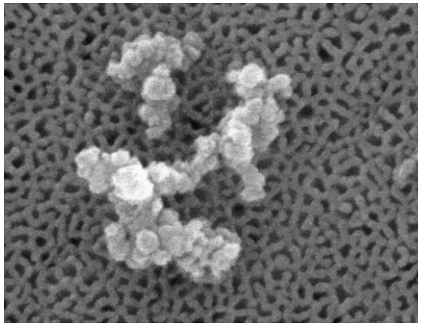
- Implementation of regulatory limits in ERCB Directive 60 (Alberta, Canada)
  - Adoption/adaptation of ERCB Directive results into World Bank Voluntary Standard for GGFR partnership
- Identification of fuel stripping mechanism as primary cause for flare inefficiency
- Development of semi-empirical model to predict efficiency in low heating value flares
- Preliminary development of models to predict gas-phase GHG equivalent emissions

Summary of Flare Efficiency Research

Some Challenges Ahead

- Desire quantitative models based on realistic (e.g. multi-component) flare gas composition data
  - If national and international entities (World Bank & Methane to Markets) are to put a price on carbon / enable cap and trade, we need sufficiently accurate GHG models for flares
- Soot (PM) and Volatile Organic Compounds (VOCs) have not been quantified
- High momentum flares (relevant to well test flaring, offshore flaring, etc.) largely unexplored

Brief Notes on Soot / PM Emissions



- Accurately quantifying PM emissions from combustion is a significant engineering challenge
- Formation exceedingly complex; entails:
  - Chemical composition of fuel
  - Turbulent mixing & diffusion of air and fuel species
  - Rate of heat transfer from flame
  - Residence time / temperature history through flame
- No existing practical approaches for quantifying PM in plumes of flares

Current Research Initiatives

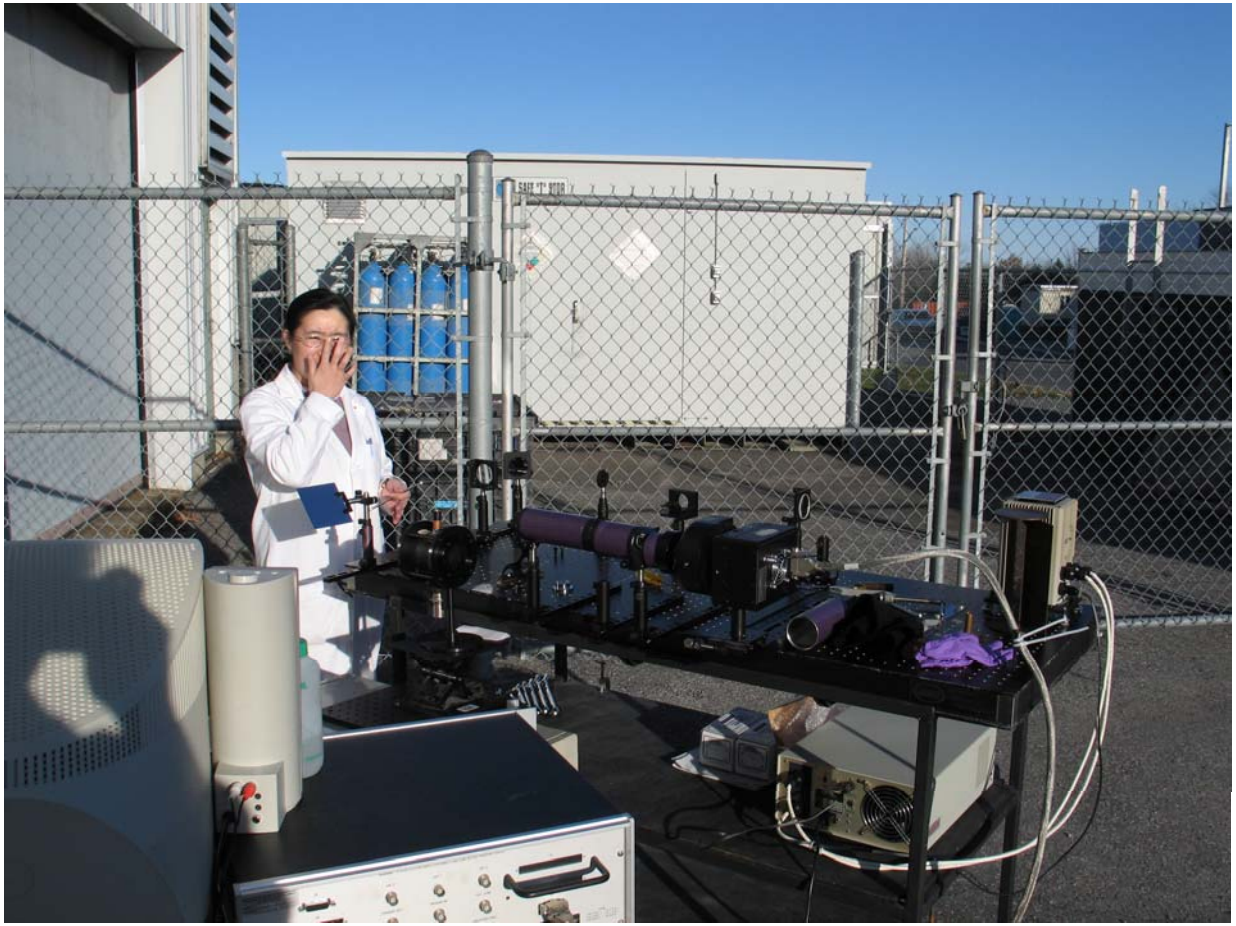
Four interrelated projects:

1. Fundamental study of sooting propensity of binary fuel mixtures
2. Directly measure soot emissions from flares in controlled lab setting
    - Protocol development, fundamental investigation
3. Measure optical properties
    - Necessary to support quantitative measurements
4. Develop diagnostic to measure soot from flares in the field
    - Desire simple tool to improve upon qualitative “opacity”

2. Quantifying Soot Emissions

Sampling enclosure housed at NRC

4. Field Diagnostic for Soot Plumes



Chen Yang, M.A.Sc. 2008

- Initial outdoor experiments using sky-scattered solar radiation to measure transmissivity of test samples

(Thomson et al., Applied Optics, 2008)

Novel soot diagnostic: principle

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- Mathematical basis:

$$\dot{m}_{\text{soot}} = \frac{-\boxed{u}\,\rho_{\text{soot}}\,\lambda}{6\pi\,\boxed{E(m)_{\lambda}(1+\rho_{\text{sa}})}}\boxed{\int \ln(\tau_{\lambda}(y))\,dy}$$

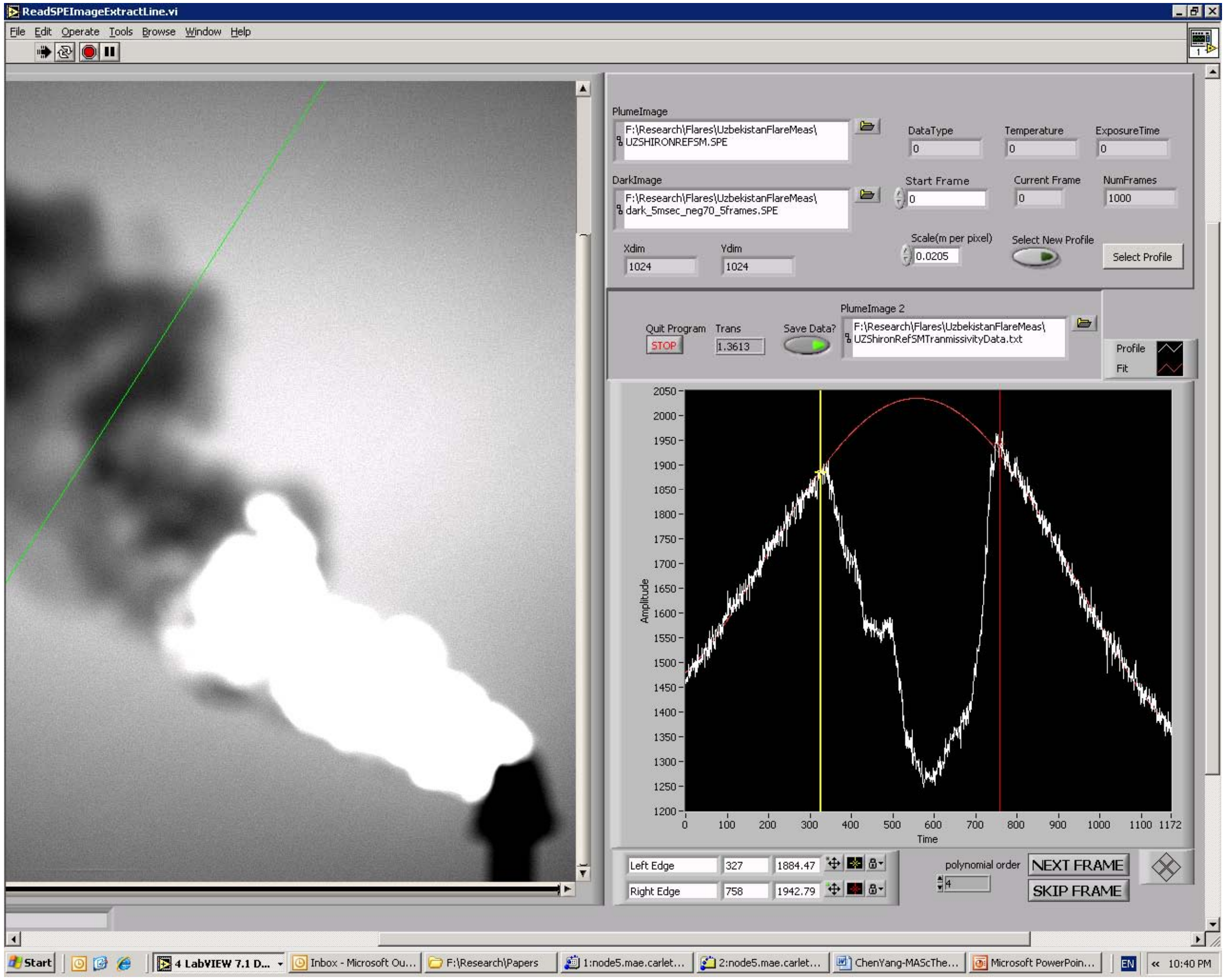
- Basic Idea: If we can develop a quantitative system to measure transmissivity, we can make field measurements of soot plumes
  - –Useful on its own and to compare with lab work
- Requires knowledge of optical properties of soot aggregates ($E(m)_{\lambda}$, ρ_{sa})
  - –Focus of sub-project in collaboration with National Research Council Canada

Field testing of new soot diagnostic

- Field measurements performed in Uzbekistan, July 2008, as part of separate project to estimate flare volumes with Dave Picard (Clearstone Eng.) and World Bank
- Field system consists of scientific grade, thermoelectrically cooled CCD camera, optical filter, and commercial lens controlled with custom software

Field testing of new soot diagnostic

- Detailed post-processing and data analysis conducted offline
- Custom image analysis software in LabVIEW



PlumeImage: F:\Research\Flares\UzbekistanFlareMeas\UZSHIRONREFSM.SPE

DarkImage: F:\Research\Flares\UzbekistanFlareMeas\dark_5msec_neg70_5frames.SPE

DataType: 0

Temperature: 0

ExposureTime: 0

Start Frame: 0

Current Frame: 0

NumFrames: 1000

Xdim: 1024

Ydim: 1024

Scale(m per pixel): 0.0205

Select New Profile

Quit Program

Trans: 1.3613

Save Data?

PlumeImage 2: F:\Research\Flares\UzbekistanFlareMeas\UZShironRefSMTranmissivityData.txt

Left Edge 327 1884.47

Right Edge 758 1942.79

polynomial order: 4

Preliminary Results: First test of new Sky-LOSA diagnostic

- Analysis of 100 independent measurements of transmissivity
  - Plume velocity estimated from high-speed video
- Soot flux measured at 5.0 kg/hour
  - Approximately equivalent to 540 trillion particles per second
  - ~100-1800 old or new buses

Summary

- Quantifying flare emissions is very challenging, but significant progress in recent years
- Conversion efficiency now understood to be strongly influenced by crosswind and fuel composition
- Preliminary work suggests quantitative predicting of GHG emissions for creditting etc. could be possible with new experimental data for realistic fuel compositions
- Work currently underway to better quantify soot (PM) emissions
- Preliminary demonstration of field measurement technique shows promise for estimating soot flux in strongly sooting flares

Research Team

Principle Investigators:

- Matthew Johnson, Carleton University
- Michael Layer, Natural Resources Canada
- Kevin Thomson, National Research Council
- David Wilson, University of Alberta
- Larry Kostiuk, University of Alberta
- Greg Smallwood, National Research Council
- Dave Snelling, National Research Council

Graduate Students / Research Engineers

- Carol Brereton, M.A.Sc. candidate
- Pervez Canteenwalla, M.A.Sc. 2007
- Adam Coderre, M.A.Sc. candidate
- Brian Crosland, Ph.D. candidate
- James McEwen, M.A.Sc. candidate
- Stephen Schoonbaert, M.A.Sc. candidate
- Stephanie Trottier, M.A.Sc. 2005
- Patrizio Vena, M.A.Sc. candidate
- Chen Yang, M.A.Sc. 2008
- Eric Bourguignon, Post. Doc., 1998
- Lindsay Howell, M.A.Sc. 2002
- Adrian Majeski, M.A.Sc. 2000
- Pascal Poudenx, M.A.Sc. 2002
- Rob Prybysh, M.A.Sc. 2001
- George Skinner, M.A.Sc. 1999
- Glen Thomas, Research Engineer
- Oleg Zatavniuk, Research Engineer

Project Partners

Natural Resources Canada

National Research Council Canada
NRC · CNRC

CAPP
CANADIAN ASSOCIATION OF PETROLEUM PRODUCERS

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

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Questions?