

From: Close, David
To: [fracking inquiry](#)
Cc: [REDACTED]
Subject: Origin response to Inquiry questions from 9 August Panel appearance - Complete and Final
Date: Friday, 22 September 2017 12:53:18 PM
Attachments: [image001.png](#)
[170921 Attachment 1 - Response to Panel Questions on 9 Aug 2017 vFinal.pdf](#)
[170921 Attachment 4 - AAPA Certificate\(s\) and Information.pdf](#)

Dear Justice Pepper

We refer to our email communication of Thursday 14 September with regard to our written response(s) to questions put to Origin at our second Panel Hearing appearance in Katherine on 9 August 2017.

As advised at the time, we were in the process of finalising one response, which is now complete and included in the attached final written response (*170921 Attachment 1 – Response to Panel Questions ...*). There is also an additional attachment (*170921 Attachment 4 – AAPA Certificates ...*).

We request that Attachment 4 (*170921 Attachment 4 – AAPA Certificates ...*) remain confidential as the document provides information that is not in the public domain and contains culturally sensitive information.

Regards,
David

David Close Ph.D.

Unconventional Exploration Manager

Origin

[REDACTED]

From: Close, David
Sent: Thursday, 14 September 2017 8:33 PM
To: fracking inquiry (fracking.inquiry@nt.gov.au) <fracking.inquiry@nt.gov.au>
Cc: [REDACTED]
[REDACTED]
[REDACTED] Panel appearance

Dear Justice Pepper.

Please find attached correspondence in relation to Origin's appearance in front of the Inquiry Panel on 9 August in Katherine.

Regards,
David

David Close Ph.D.

Unconventional Exploration Manager

Origin

[REDACTED]



Origin Energy

Response to Inquiry Panel questions from Origin's appearance in Katherine on 9 August 2017

Version	1.0
Submitted	14 September 2017
Presented by	Origin Energy

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1 Year-round operations

Question.

Can Origin outline any specific risks associated with year-round operations and specifically large rainfall events associated with the NT wet season?

Response:

Origin and other operators within Australia and internationally have demonstrated the ability to safely operate in a diverse range of environmental conditions. In Canada, operators have overcome the challenges of operating in Arctic and sub-Arctic muskeg during the spring. In Alaska, the Trans-Alaska Pipeline has been engineered to overcome the challenges caused by permafrost and major earthquakes. In the Bass Strait in Australia, operators are able to operate through major winter storm events and high-seas. These are just a few examples of industry overcoming some of the harshest operating environments.

Origin does not support prescriptive measures that may limit the operating window in the Beetaloo. Any of the challenges of working through the wet season in the Beetaloo can be overcome through engineering solutions. How Origin would overcome the challenges should be reviewed and assessed under an objective or play based framework by the appropriate regulatory bodies.

The first step in assessing the challenges regarding operations in the wet season is to collate available data in order to assess potential hazards. Anti-industry activists have made claims that widespread flooding occurs across the Beetaloo. To assess this claim Origin used the Water Observations from Space database compiled by Geoscience Australia (<http://www.ga.gov.au/scientific-topics/hazards/flood/wofs>). Water Observations from Space (WOFS) is a web service displaying historical surface water observations derived from satellite imagery for all of Australia from 1987 to present day. WOFS aim is to allow better understanding of where water is usually present; where it is seldom observed; and where inundation of the surface has been occasionally observed by satellite. WOFS displays the detected surface water from the Australia-wide Landsat 5 and Landsat 7 satellite imagery archive.

Surface water is detected from satellite images using an automated water mapping algorithm created by Geoscience Australia. The water detected for each location is summed through time and then compared to the number of clear observations of that location (i.e. observations not affected by cloud, shadow or other quality issues). The result is a percentage value of the number of times water was observed at the location. This provides relatively seamless historical water coverage for Australia, as observed by satellite. The colouring of the summary layer indicates how often water was observed in each cell of a 25 metre by 25 metre grid across Australia. Possible floods appear in the low values (red to yellow colours) while consistent water bodies such as lakes and dams have high values (blue to purple colours).

Figure 1 shows the number of clear satellite observations over the period (1987 to present) for each grid cell. Over the Beetaloo area there have been between 400-600 clear observations.

Origin's permits are dominated by two surface drainage basins. To the south east of Daly Waters there is a low-lying region known as the Balmoral Lagoon (Figure 2). In a normal wet season rainfall drains south-west into the Balmoral Lagoon and it remains submerged for a number of months. The other large drainage basin is dominated by Newcastle Creek, which flows into Lake Woods, west of Elliott. Other than the watercourses which contain flowing water in the wet season, the Balmoral Lagoon is the only large area of standing water in the project area. Figure 3 shows the percentage of clear observations on which water was detected. The data clearly show all the aforementioned major surface water features in the area. The data indicate that wet season flooding impacts are small as only 2.5% of Origin's permit area has water detected more than 2% of the time.

At this point it is not known if any development would be located in within the flood prone areas. If it was Origin has a view that there is no technical, safety or environmental reason why construction, drilling, hydraulic fracture stimulation, and operational activities could not be undertaking during the NT wet season period. Possible risk mitigation strategies that Origin would consider on a case by case basis are:

- Minimizing surface footprint in flood prone areas through strategic pad placement. This would entail drilling wells just outside the extent of the flood plain. Figure 4 shows an example of a hypothetical development around the Balmoral Lagoon.
- Phasing of operations to minimize activities in flood plains during the wet season. This strategy is effective if only a portion of the development area is prone to flooding.
- Construction of all-weather infrastructure. Construction techniques, methodologies and equipment are available to allow infrastructure to be both built, operated and maintained during times of rainfall and inundation. Examples of this includes the construction of elevated or raised access roads and lease pads incorporating water flow management such as culverts and causeways to ensure environmental flows are not impacted. The use of technologies such as geofabrics, geonets and pavement stabilisation products to support pavement designs to ensure durability and stability for operations in wet conditions and the correct selection of construction equipment such as tracked machinery are commonplace in the construction industry. In parallel with these techniques, water management methods such as diversion drainage, dewatering and erosion and sedimentation control can be used to compliment these activities.
- Fluid handling practices to prevent loss of containment due to large rain events. These include, but are not limited to, closed systems, freeboard requirements (i.e. applied at Amungee NW-1), high level alarms in conjunction with excess storage capacity and transfer ability.

Working in the wet season also presents the following opportunities:

- Continuity of works for NT contractors: contractors who operate in the NT are in a unique situation where a significant proportion of their works are in the north of the Northern Territory where the wet season is more prolonged and intense. This has an impact on these businesses where they are required to maintain equipment and personnel without income or cashflow. Providing an opportunity for these companies

to minimise or alleviate this downtime period would greatly improve employment opportunities and profitability of many of the local contracting companies.

- Wet season efficiencies: Earthwork construction inherently has a high demand for water to ensure moisture contents are at their optimum for compaction and workability. Having the ability to plan and execute earthworks when soil moisture contents are at their optimum (typically during or shortly after the wet) reduces the demand for the extraction of water from aquifers to achieve compaction and reduces the need for dust suppression. In addition to reduced water demand, operating in the wet season can also reduce the potential bushfire risk which can occur during clearing activities.

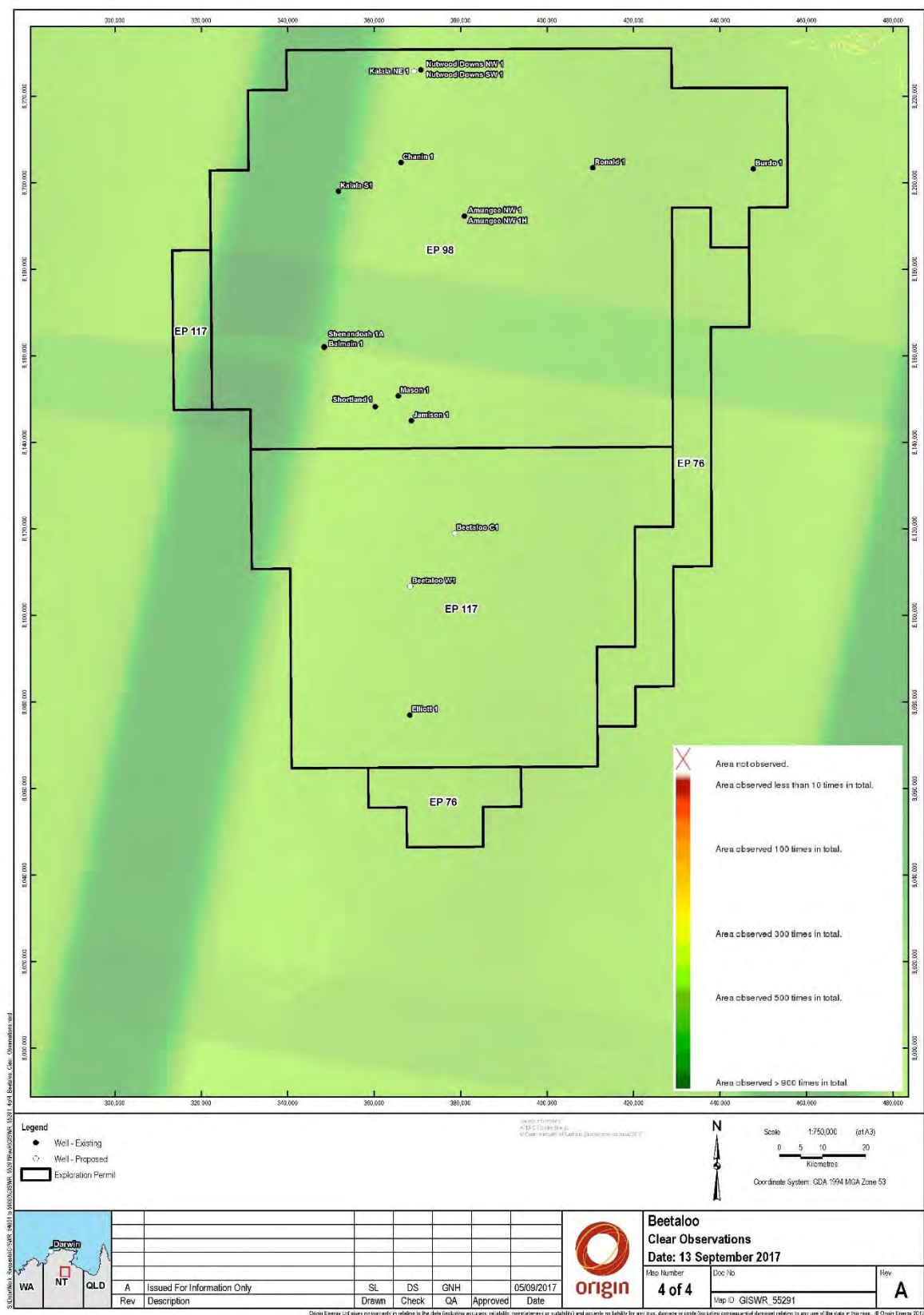


Figure 1 Clear satellite observations reported by Geoscience Australia in their Water Observations from Space database (1987 to present)

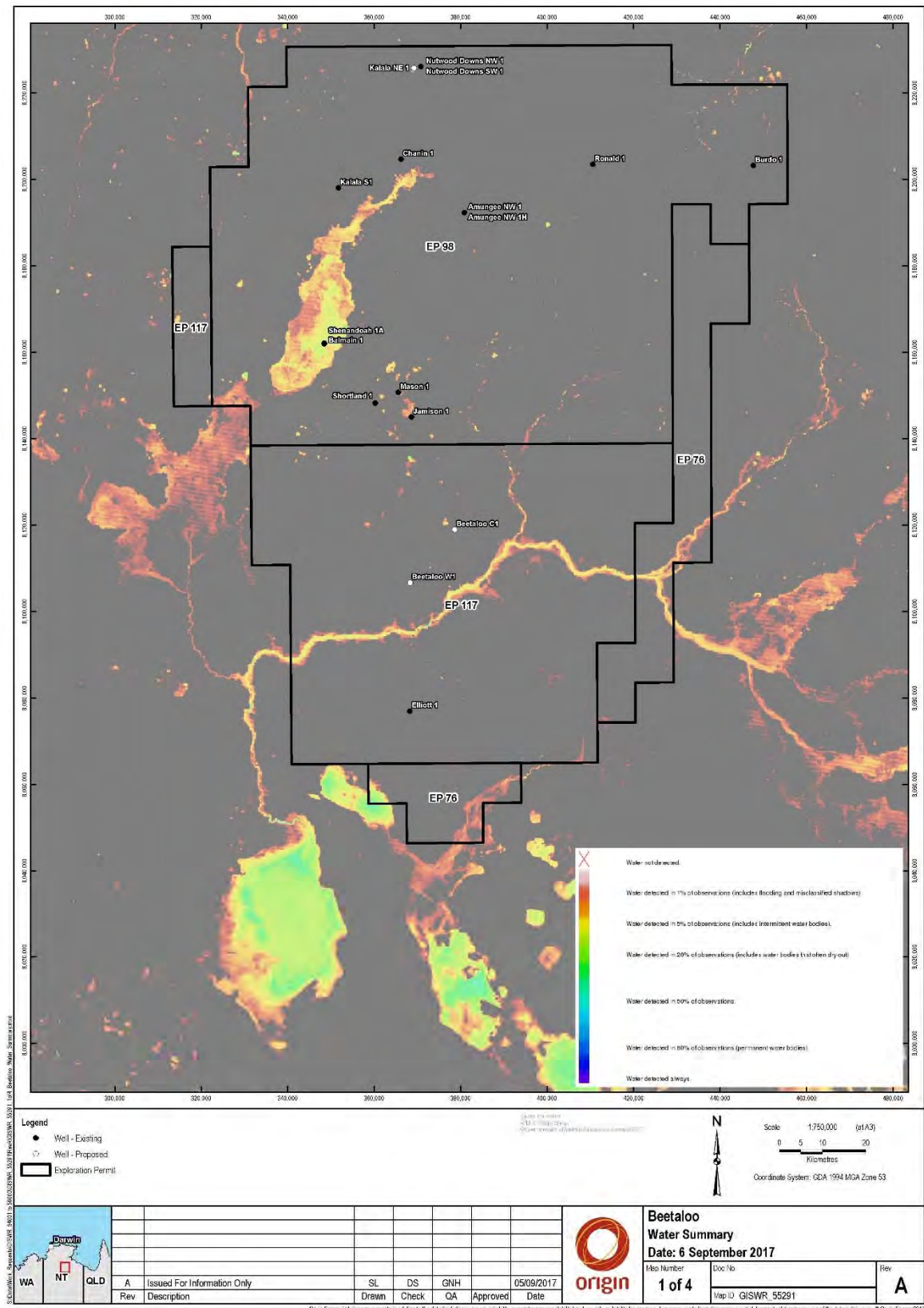


Figure 3 Percentage of clear observations on which water was detected

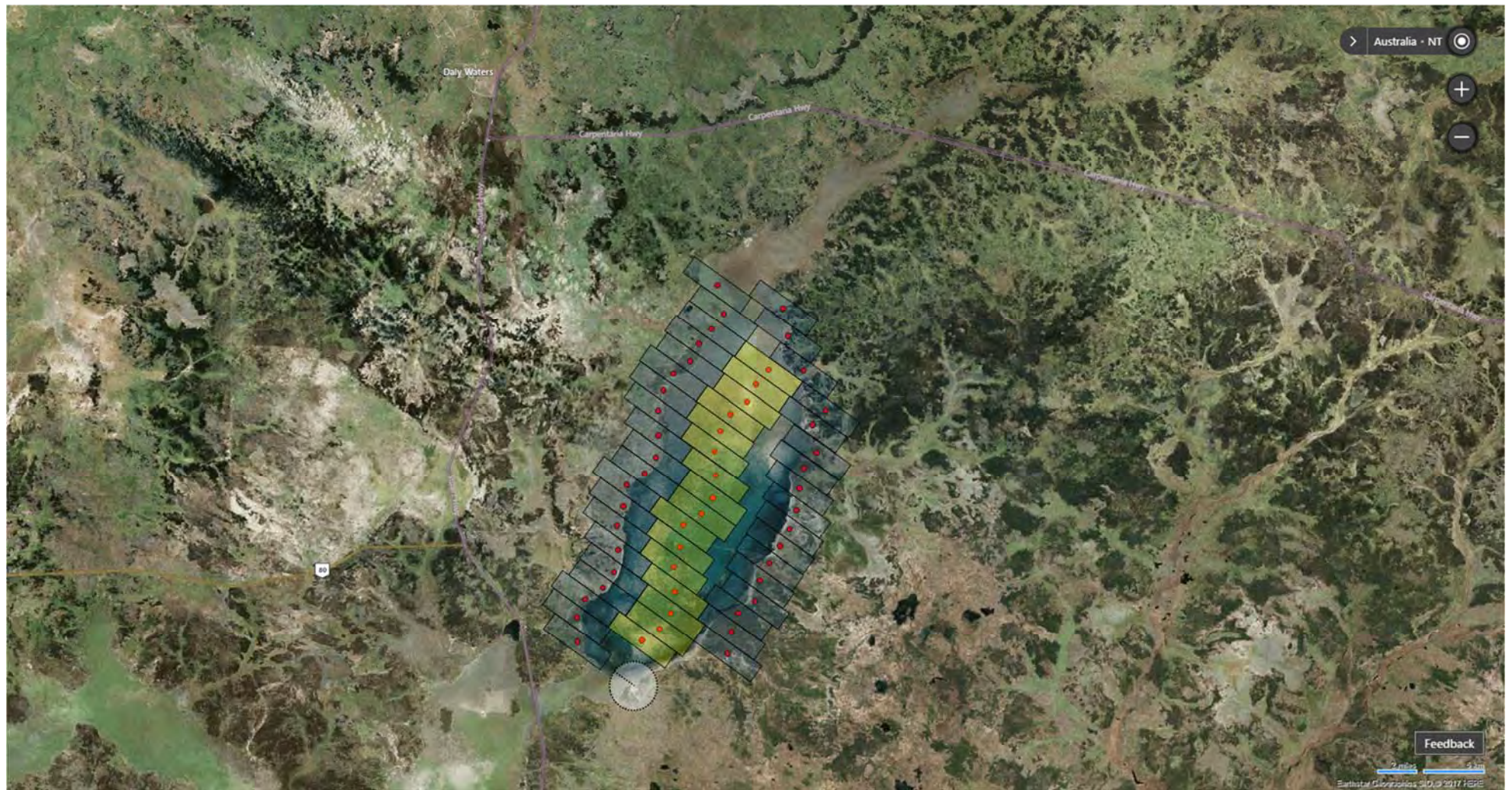


Figure 4 Notional development demonstrating how pad placements can minimize activity within a flood plain.

2 Flaring

Question.

- i) Can Origin outline a likely approach to flaring in NT (location/frequency)?
- ii) What flare efficiency is expected?
- iii) Do you have an air marker that would inform any health risk assessment?

Response:

i) Flaring frequency

Although flaring will be required during the exploration and appraisal phase of any oil and/or gas development in the NT, once in the production phase of a development flaring would be minimised and likely required only occasionally. Flaring or venting is primarily used as a safety mechanism in producing fields and facilities. Production facilities require periodic pressure relief in the system that is triggered by inbuilt safety systems, which can be achieved by either venting or flaring gas. Venting emits methane to the atmosphere, whereas flaring converts methane to carbon dioxide, a less potent greenhouse gas. Emissions from these practices are reported annually in Origin's *National Greenhouse and Energy Report*. As flaring is a wasted resource, all companies seek to minimize the flaring of gas.

NT shale developments would likely differ considerably from QLD CSG fields in relation to flaring. Flaring in Queensland field was primarily the result of the requirements to deal with excess "Ramp up" gas during the transition from full production to full capacity operations at the Gladstone LNG facilities. Ramp up gas that was unable to be utilised in the domestic market or other LNG facilities had to be flared – there are unlikely to be such ramp up pressures in any NT shale gas development as there are unlikely to be greenfield LNG plants linked to shale developments.

Flaring in QLD CSG fields and facilities was mitigated where possible through the shut in of wells during planned and unplanned outages, however, flaring cannot be eliminated from CSG developments as some CSG wells may become unproductive if shut in for extended periods. Such wells are often left producing to avoid costly work over or production declines – this is not expected to be an issue for NT shale gas developments where shut-ins are unlikely to negatively impact a well's productivity.

ii) Flaring efficiency

The University of Alberta Flare Research Project (1994) (UAFRP, 1994; included as Attachment 2 to this submission) provides a comprehensive review of flaring efficiency and related issues. At low crosswinds the UAFRP (1994) reports very high (>99%) flare efficiencies. There are other factors such as flow rates, the cross-sectional area of the flare, gas type (i.e. proportion of methane, ethane, propane, etc.), and natural gas exit velocity that also impact flare efficiency. We estimate that the Amungee NW-1H flare efficiency was >99% based on the following estimates during the flaring period:

- i. Average wind speed at Daly Waters = 6.4 km/h = 1.8 m/s
- ii. Amungee flow rate ~ 1 MMcfd = 28,316 m³/d = 0.33 m³/s
- iii. Cross sectional area of flare = 0.03 m²
- iv. Natural gas exit velocity = 10 m/s.

iii) Health risk assessment

Emissions from Flaring:

- Emissions from the combustion of gas in flares is well studied and are covered under the Commonwealth National Pollutant Inventory (<http://www.npi.gov.au/system/files/resources/4bb4362a-ca3c-01e4-79eb-d288223f2b60/files/eet-manual-oil-and-gas.pdf>)
- The primary emissions are anticipated to be Carbon Monoxide and Oxides of Nitrogen (NO_x), with minor emissions of Volatile Organic Compounds (VOCs)
- Scientifically robust health-based ambient air quality guidelines exist under the National Environmental Protection (Ambient Air Quality) Measure. If commercial shale gas development within the Beetaloo Basin were to proceed, it is anticipated that impacts from flaring (and other activities) on ambient air quality will be assessed against the relevant health based guidelines within an Environmental Impact Assessment. Such an assessment would be undertaken using well established contaminant dispersion models (e.g. AERMOD or CALPUFF). Additional information on the health risk assessments utilised to develop the National Environmental Protection (Ambient Air Quality) Measure can be found at the following link: <http://www.nepc.gov.au/nepms/ambient-air-quality>
- Origin does include information related to flaring in Table 22 of our April 30 submission to the Inquiry

Monitoring example from QLD CSG:

- Real time monitoring of ambient air quality within the Surat Basin is being undertaken by GISERA (<https://gisera.org.au/project/ambient-air-quality-in-the-surat-basin/>)
- This includes the monitoring of three sites adjacent to Gas Processing Facilities (Miles Airport, Hopelands and Condamine), and two background sites (Tara and Burncluith)
- Monitoring of combustion by-products (CO, NO_x, ozone, and particulate matter) is undertaken, as well as speciated VOC's, aldehydes and H₂S
- Data are live streamed to the EHP website and are publicly available (<https://www.qld.gov.au/environment/pollution/monitoring/air-monitoring/swq?>)

- No exceedance of any National Environmental Protection Measures relating to air quality have been attributed to flaring or any other unconventional gas development activities
- GISERA should be contacted directly to discuss the details and results of this program.

3 Radial drilling

Question.

Can radial drilling technology be used as an alternate to hydraulic fracturing in shale gas plays (as reported on at <http://www.unconventionaloilandgas.com.au/the-drilling-technology-significantly-increasing-well-production-and-recovery/>)?

Response:

Radial drilling is almost certainly not going to be applicable in shale gas as it does not create the required contact with the source rocks for gas rates. Industry in the US tests and adopts or rejects applicable technology very rapidly due the high volume of drilling and hydraulic fracturing. To date no operator is using radial drilling technology in lieu of hydraulic fracturing.

4 Groundwater recharge

Question.

The Inquiry are seeking data specific to the Beetaloo area regarding groundwater recharge, age of the water related to recharge, and sustainable yield. Can Origin provide any additional information on these matters? Specifically, are there studies based in the southern extents of the Beetaloo area?

Response:

Origin's most comprehensive review of existing data and publications is included in our previous submissions to the Inquiry (our 30 April submission and the separate submission of the Knapton and Fulton (2015) report commissioned by Origin in 2014).

The scope of work proposed by CSIRO as part of their Beetaloo Basin Groundwater Study includes the evaluation of recharge mechanisms and rates using environmental tracers:

- i) Source of recharge: major ions, stable isotopes of water, ^{87}Sr , noble gases
- ii) Recharge rates by estimating the change in groundwater age along flowpaths: SF_6 , ^{14}C
- iii) Identification of recharge processes: noble gases

The CSIRO study will cover all of Origin and Santos' permit areas, including the southern Beetaloo area, hence further information regarding the Inquiry's request will be available if further exploration and appraisal is able to proceed post this Inquiry process. Origin's ongoing groundwater monitoring program is also covering the south of the Beetaloo area and so information regarding water level and quality across the region is being compiled during exploration and appraisal.

5 Aquifer contamination

Question.

- i) Does Origin have analysis on the flow-path and rate of dispersion in the event of a surface spill? Can or have Origin undertaken modelling of worst-case-scenario events?
- ii) What remediation methods do you have available?

Response:

- i) Flow-path and dispersion of surface spills

Origin commissioned an independent risk assessment (Fulton and Knapton, 2015a) by NT based hydrogeological consultants (Cloud GMS) following the completion of the Beetaloo Basin Hydrogeological Assessment (Fulton and Knapton, 2015b). One of the objectives of an aspect of this risk assessment was to "...constrain the likelihood of short term spills at the surface migrating to the groundwater" using numerical modelling.

Fulton and Knapton (2015a) conclude the following:

"The leakage assessment presented suggests that based on the volumes that can reasonably be expected from a spill/leakage event would be insufficient to mobilise fluid and any potential contaminant to the watertable under the expected site conditions. Based on the following assumptions:

- *the maximum volume of any spill would be less than 0.001 - 0.002 times considered in the leakage assessment (based on 50000 litres maximum load of a B Double trailer); and*
- *the spill would be removed in less than the 60 days of the mud/flare pit operation timeframe considered in the leakage assessment."*

A copy of the Fulton and Knapton (2015a) risk assessment is attached to this submission. Further modelling would be undertaken as part of any detailed project planning with site-specific information relevant to the proposed development area.

Origin's recently submitted Beetaloo Project Hydraulic Fracturing Risk Assessment also provides further details relevant to the potential consequences of such a surface spill.

ii) What remediation methods do you have available?

Origin's April 30 submission to the Inquiry provides detailed information in Chapter 4.3 regarding the risks associated with surface spills and the controls in place to prevent such spills and respond in the event the controls are not ultimately effective. The submission also includes the Beetaloo HSE Management Plan and the Beetaloo Oil Spill Response Plan (appendices 1 and 6 of the April 30 submission). Origin's most recent reply to the Inquiry's 25 July request for information also provides a detailed response to this query in Question 4.

References:

Fulton and Knapton, 2015a, Beetaloo Basin - Groundwater Impact Risk Assessment

Fulton and Knapton, 2015b, Beetaloo Basin Hydrogeological Assessment

6 East coast gas supply

Question.

There are various positions being put to the Inquiry with regards gas supply into the East Coast Market. What is Origin's position on this issue?

Response:

Origin refers the Inquiry to the recent analysis by consulting firm McKinsey (link below), which provides a thorough analysis of the many interrelated and complex factors that are relevant in any discussion regarding the East Coast Gas Market. In summary, McKinsey report that the east coast has abundant gas resources but needs new supply to be developed quickly to meet demand.

<http://www.mckinsey.com/global-themes/asia-pacific/meeting-east-australias-gas-supply-challenge>

7 NLC and AAPA approvals

Question.

NLC approval and AAPA certification for fracture stimulation

Response:

Origin provides, at Attachment 4, a copy of its AAPA Application and AAPA Certificate C2014-184. The application was submitted in June 2014 and certification received in December 2014 for all associated exploration well activities at a number of potential well sites. It can be clearly seen on Certificate 2014-184 that there are no known sacred sites within the authorised area of the Amungee NW-1 (location closest to Carpentaria Highway).

At the commencement of multi-year exploration programs it is not known if the geology of the target zone is able to be fracture stimulated. It is through the process of exploration, including the harvesting of core samples, wire logging and DFIT testing, that data to determine and understand the technical suitability for horizontal drilling and / or hydraulic fracture stimulation.

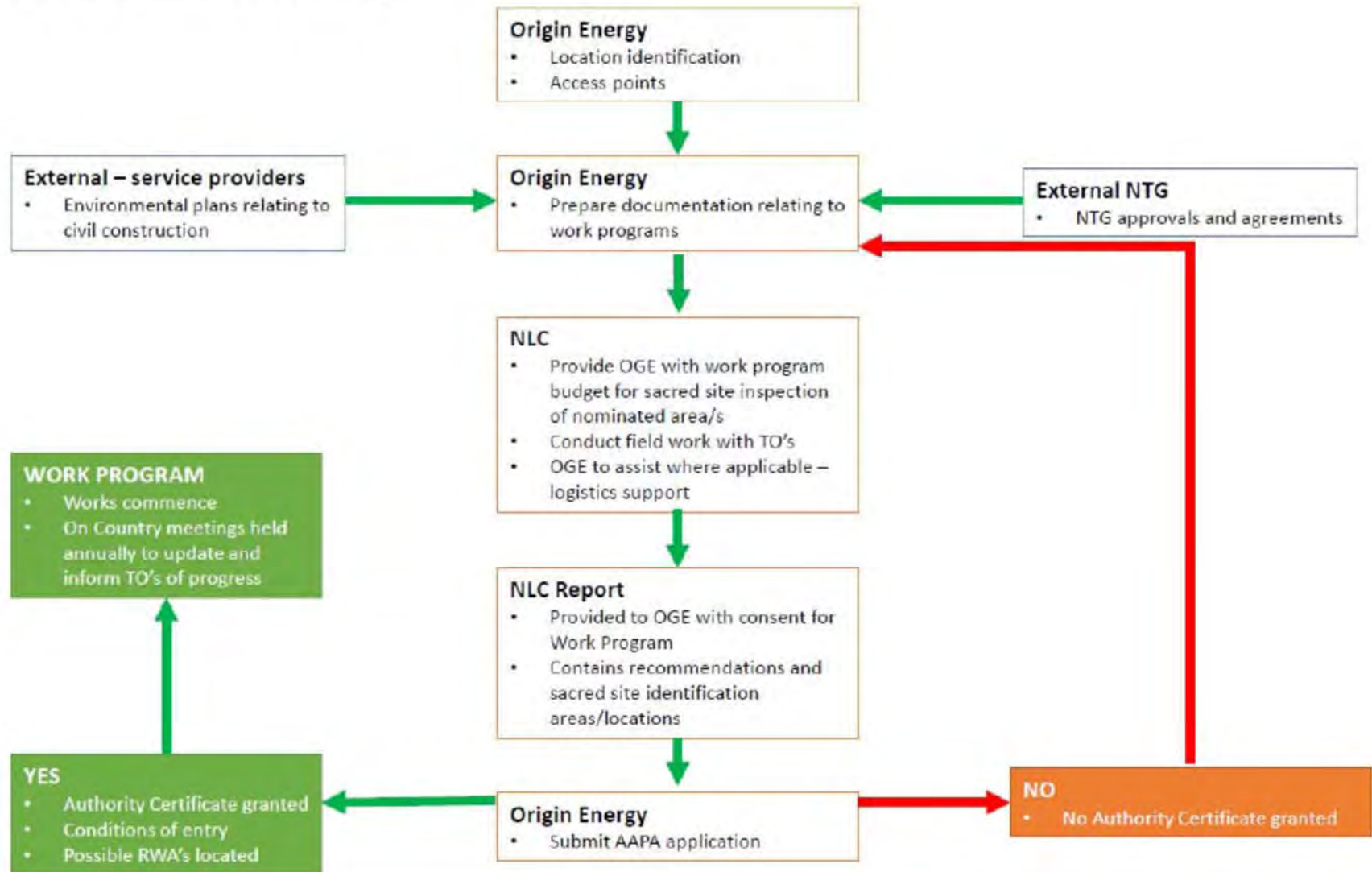
Once the vertical well at Amungee NW-1 was safely and successfully installed, substantial technical work was undertaken in order to make an assessment about the well location's geological compatibility for fracture stimulation. Data collected and studied, returned the results that the location was suitable to safely install a horizontal well and execute a hydraulic fracture stimulation.

Given the absence of sacred sites within the existing AAPA Certificate authorised work area, there was deemed no requirement to seek indemnity by way of an amendment to the existing Certificate (2014-184).

Traditional Owner engagement on the abovementioned activities, and their consent, was sought by working with Traditional Owners and their statutory representative body. Origin received the final endorsement and consent for the horizontal well and hydraulic fracture stimulation at an On-Country meeting held on 20 October 2015 at the Newcastle Waters School. A copy of the NLC minutes from that meeting evidence that at 2.00 pm, Traditional Owners held a private meeting to discuss Origin's request for permission to drill on the cleared sites, and the result returned was a unanimous yes. Origin has not provided a copy of those minutes though recommend the panel seek the support of the Northern Land Council to sight those minutes of meeting.

By way of providing additional commentary on engagement with Traditional Owners with regard to Cultural Heritage clearance work, Origin - together with Traditional Owners engaged with the authority of the NLC - conduct annual survey scouting and cultural heritage work prior to deciding on well locations. Traditional Owner guidance and advice on where activities may or may not be suitable is factored into the decision making process. Below is a simplified flowchart - *Work Program Clearance Road Map* - outlining the ongoing engagement cycle in relation to consultation, engagement and approvals from the Traditional Owners and the Northern Land Council.

Work Program Clearance Road Map



UNIVERSITY OF ALBERTA FLARE RESEARCH PROJECT

**FINAL REPORT
NOVEMBER 1996 – SEPTEMBER 2004**



September 1, 2004



UNIVERSITY OF ALBERTA
FLARE RESEARCH PROJECT

UNIVERSITY OF ALBERTA

FLARE RESEARCH PROJECT

FINAL REPORT SEPTEMBER 2004

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PREFACE

Larry Kostiuk, Matthew Johnson, and Glen Thomas of the University of Alberta Flare Research Project are the principal authors of this report, but its contents are a compilation of the research activities and efforts of many individuals. In a project where open collaboration between individuals was the norm, the task of properly identifying and giving credit to those people for their specific research contributions, while still trying to present combined results, is complex. Many of the results reported here have appeared in other formal publications (e.g., conference proceedings or archival journals) with the appropriate authorship indicated at that time. The objective of this report is to bring together much of that research into a single document where connections between the work can more easily be made and more comprehensive conclusions can be drawn.

The table below lists the individuals who have participated in the Flare Research Project, and the authors would like to thank these members of the Flare Research Group for their intellectual contributions and efforts to this work.

Members of the Flare Research Group (November 1996 – September 2004)

Name	Position	Dates/Status
Larry Kostiuk	Professor, Principal Investigator	11/96 – 09/04
David Wilson	Professor, Co-Investigator	11/96 – 09/04
Mark Ackerman	Faculty Service Officer, Co-Investigator	11/96 – 09/04
David Checkel	Professor, Co-Investigator	11/96 – 09/04
Doug Dale	Professor, Co-Investigator	11/96 – 09/04
Wayne Pittman	Technician	11/96 – 08/99
George Skinner	M.Sc. Student	01/97 – 08/98 Graduated
Matthew Johnson	Project Engineer / Ph.D. Student	03/97 – 08/01 Graduated
Adrian Luhowy	Summer Student	05/97 – 09/97, 05/98– 09/98
Eric Bourguignon	Post Doctoral Fellow	09/97 – 06/98
Pascal Poudenx	Research Associate/ M.Sc. Student	03/98–06/03 Graduated

Adrian Majeski	M.Sc. Student	05/98 – 07/00 Graduated
Kevin Godfrey	Summer Student	05/98 – 09/98
Oleg Zastavniuk	Project Research Associate	09/98 – 10/03
Robert Prybysh	M.Sc. Student	05/99 – 10/01 Graduated
Eric Matheson-Jones	Summer Student	05/99 – 09/99
Chad Larson	Summer Student	05/99 – 09/99
Cedric Lefevre	Visiting Student	06/99 – 08/99
Glen Thomas	Project Manager/Research Associate	03/00 – 09/04
Jason Nichols	Summer Student	05/00 – 09/00
Alison Jack	Summer Student	06/00 – 08/00
M. Arshad	M.Sc. Student	09/00 – 11/03 Graduated
Lindsay Howell	M.Sc. Student	04/01 – 04/04 Graduated
Kyle Nishiyama	Summer Student	07/01–08/01, 07/02–08/02, 05/04–08/04

Also important to this research have been the financial and in-kind contributions that were made by various organizations and agencies. The table below lists these organizations and the authors greatly appreciated their financial support and advice throughout the project.

Participating Organizations and Agencies

Organization or Agency	Form of Support	Individuals
Environment Canada, Ottawa	Financial and In-Kind	Bill Reynen, Michael Layer, and Anne-Marie Thompson
Natural Sciences and Engineering Research Council (NSERC)	Financial	
Canadian Association of Petroleum Producers (CAPP), Calgary	Financial and In-Kind	David Pryce, Rod Brunes, David Lye, Kendall Dilling, and John Squarek
Environmental Science and Technology Alliance Canada, Sarnia, Ontario	Financial and In-Kind	Rob McBrien, Tom Jack, and Al McDowell
Alberta Science and Innovation, Edmonton	Financial and In-Kind	Richard Nelson
Amoco Canada, Calgary	Financial and In-Kind	Rod Brunes, and John Ward

Alberta Energy and Utilities Board (EUB), Calgary	In-Kind	Kim Eastlick, Michael Brown, Hal Knox, Harry Lillo, Jim Spangelo, and Ian Dowsett
Petroleum Technology Alliance Canada (PTAC), Calgary	In-Kind	Eric Lloyd and Tannis Such

EXECUTIVE SUMMARY

Background

The research presented here was the result of a multiyear investigation into the emissions, combustion processes, and fluid mechanics relating to solution gas flares. In 1999, there were approximately 8249 active oil and bitumen battery sites scattered throughout Alberta which produced a total of 59.4 million m³ of conventional oil and 23.7 billion m³ of solution gas. Although most solution gas produced in Alberta is “conserved”, approximately 6 % of these gases were flared or vented at the battery sites. In 1999, 3715 of these battery sites reported volumes of gas flared totalling 0.938 billion m³ while 1346 reported straight venting of gas totalling 0.485 billion m³. In total, there were 4499 oil and bitumen battery sites in Alberta that reported flaring or venting operation during 1999 with a combined gas volume of 1.42 billion m³.¹

There is significant site-to-site variation in the flaring volumes, gas composition, and ambient conditions for solution gas flares. Based on 1999 data, the median volume of gas flared or vented was approximately 60,300 m³/year. While 95% of battery sites flare and vent less than 1,000,000 m³/year, these batteries only consume 43% of the total gas flared and vented at all battery sites. Gas composition data from battery sites are not reported and, as such, an accurate estimation of the volumes of sweet/sour gas being flared or vented is not possible. Limited data from individual well sites suggest that there is also significant variability in the relative concentrations of all the major fuel species contained in the solution gas. Given this variation, the notion of an average composition of solution gas is essentially irrelevant. Hence, solution gas flaring is neither well defined by a single set of operating parameters nor characterized by any single battery site. Solution gas flaring is better thought of as a class of flows that needs to be understood in general and not on a case-by-case basis.

The approach taken in this research project has been to experimentally study generic pipe flares under well-controlled conditions in order to understand the performance of flares in general. To provide control over the wind, this research was conducted in wind tunnels where the wind speed, from a known direction, could be set. Working in a laboratory setting afforded other advantages such as being able to blend together different gases to create a varied, but known, flare stream for testing. The majority of these tests were conducted within the confines of the wind tunnel located at the University of Alberta (U of A). This closed-loop wind tunnel was used to test reduced-scale flares which provided the foundation for subsequent testing and modeling regarding the characterization of flare performance. Experiments were also conducted at the National Research Council (NRC) in Ottawa. This single-pass wind tunnel was used to test full-scale flares which served to verify and extend the experimental work accomplished at the U of A.

The basic objectives of the research were:

- develop accurate methods for measuring the overall combustion efficiency of flares with either gaseous flare streams or flare streams containing liquid droplets within the test facilities;
- measure the overall combustion efficiency as a function of wind speed, exit velocity, flare stack diameter, fuel type and energy density;
- provide insight into the mechanisms that cause lower overall combustion efficiencies;
- develop models to estimate overall combustion efficiencies of flares;
- develop models for the scaling of plumes that disperse the products of combustion from flares as a function of wind speed, exit velocity and flare stack diameter;
- measure and map the local combustion efficiency of flares in a crosswind to help understand the difficulties in interpreting single-point measurements;
- develop methods for measuring the production rates of selected toxic compounds emitted from flares either in vapor phase or bound within the soot;

¹ The 2004 EUB Upstream Petroleum Industry Flaring and Venting Report (published May 2004 based on the year ending December 31, 2003) shows that 843 million m³ of gas was flared or vented in the province of Alberta.

- develop methods for measuring the production rates of particulate emissions from a flare;
- measure the emissions of selected toxic compounds in both the vapor phase and bound to soot emissions per unit mass of fuel burned for flares;
- measure the overall combustion efficiency of flares that contain liquid droplets of either water or hydrocarbon fuel as a function of droplet size, number density, wind speed and exit velocity.

Experimental Facilities

The experimental data that will be presented throughout this report have been collected either at the U of A's Flare Research Facility or the NRC's wind tunnel. The U of A facility consists primarily of the following: a closed-loop wind tunnel used to impose a crosswind on the flare; flare-stream control systems to supply various gases and liquid droplets to the flare; and a range of equipment to monitor and control the experiments. The NRC facility is a single-pass wind tunnel with similar equipment to the facility at the University of Alberta used to control and monitor experiments.

The closed-loop wind tunnel, located at the U of A, had an internal volume of approximately 350 m³. A 150-kW-DC motor drove a 3-m-diameter fan that was capable of producing stable crosswinds (U_{∞}) between 1 and 35 m/s in the 2.44-m-wide by 1.22-m-high test section of the tunnel. A three-component, computer-controlled traversing system was available for positioning various probes in the tunnel flow downstream of the flare stack. The flares used in this research were scale-model pipe flares ranging in outer diameter (d_o) from 12.1 to 49.8 mm. The fuel gases supplied to the flare were either sales grade natural gas, technical grade ethane, or commercial grade propane. Other gases added to the flare stream to alter its mass or energy density were carbon dioxide (CO₂) and nitrogen (N₂). All of the gases were supplied from cylinders. The flow rate of each gas type was controlled and measured by one of several mass flow meters. In order to collect soot from flares, a 0.6-m-diameter ducting was installed parallel to the wind tunnel. Once installed, this setup allowed for the extraction of the whole plume and the measurement of soot from flares. The addition of liquid droplets

to the flare stream was done using ultrasonic droplet generators mounted at the base of the flare stack. This system allowed for varying amounts of droplets of different sizes to be added to the flare stream.

The single-pass wind tunnel, located at the NRC in Ottawa, was driven by a 6-m-diameter compressor powered by a 1050-kW-DC motor to produce crosswinds between 1 and 39 m/s. The test section of this wind tunnel was 3-m-wide by 6-m-high and was 13-m-long. The tests conducted at the NRC used pipe flares made of schedule 40 pipe with the following outer diameters: 30.0 mm, 58.8 mm, and 114.3 mm. The largest diameter stack represented a full-scale solution gas flare stack found in the field. Tests were performed using sales grade natural gas where the supply line for the experiments was tied into the main utility gas line. No diluents were used at the NRC.

Overall Combustion Efficiency of Gaseous Flares

For a flare burning a mixture of hydrocarbon fuels, the efficiency was characterized here by the “carbon conversion efficiency”, which is defined as the effectiveness of the flare in converting the carbon in the fuel to carbon in CO₂. Methodologies were developed to determine accurately this overall efficiency for flares where the combustion products are predominantly gaseous. For the natural gas- and ethane-based flares there were no measurable particulates (i.e., soot) emitted. Propane-based flares under some circumstances emitted over 1 % soot by mass, but typical particulate emissions were less than 0.4 %. A discussion of the composition and implications of these particulate emissions is provided later in this summary.

A series of measurements was conducted to determine the overall efficiencies of flares burning gaseous fuels (i.e., natural gas, ethane, and propane). Data on the influence of crosswind speed, flare gas exit velocity, flare diameter, fuel type, and diluent content in the fuel are presented and discussed. Models are presented which describe the trends in the data.

Results show that the crosswind has a strong effect on the efficiency of the combustion with an exponential dependency. At relatively low crosswinds, U_∞ , the efficiencies are very high ($> 99\%$), but as U_∞ is increased the efficiency falls dramatically. Natural gas flames are more susceptible to these crosswind effects than either ethane or propane flares as it takes lower wind speeds to induce comparable levels of inefficiency. The data demonstrate that the efficiency of the combustion also depends on the mean fuel jet exit velocity (V_j). Higher velocity fuel jets are less sensitive to the effects of crosswind. The efficiency characteristics are the same for the different flare diameters tested where the larger diameter flare stacks are more resistant to the effects of increased crosswind speed. The bounds on scaling are provided experimentally up to an outside stack diameter of 114.3 mm, while arguments based on exterior flow regime transitions suggest that this upper bound on scaling may be extended by a factor of four or more depending on the prevailing wind speed.

Models developed to interpret experimental data and to estimate flare efficiency required an understanding of the dominate fluid mechanics around the flare and of the mechanism that leads to combustion inefficiencies. In order to elucidate these processes, a multitude of diagnostic techniques included: two-dimensional cross-stream mapping of mean-temperature and major-species concentrations; gas chromatography of the emitted gases; fast-flame-ionization mapping of hydrocarbons around the flame; and sheet-laser imagery along the flow direction to track the flow of the flare stream. The conclusion of these examinations was that the dominant fluid mechanic forces associated with solution gas flares are the momentum flux of the crosswind and the buoyancy of the combustion products. The inefficiencies result from emissions of either carbon monoxide (i.e., the partial oxidation of the hydrocarbon fuel) or raw fuel being stripped from the flare stream without any participation in the combustion. At low crosswinds these two sources are of the same order of magnitude, but as the wind speed increases the fraction of raw fuel being stripped away rapidly increases and becomes the dominant cause of inefficiency. The pathway that allows the raw fuel to be stripped away from the flame was determined to be driven by a standing vortex on the leeward side of the flare stack. The interaction of this standing vortex with the ring vortices emerging from the stack partitions the flame such that packets or bursts of raw

fuel could be drawn beneath the flame. Once under the flame, these packets of raw fuel were dispersed into the atmosphere and then measured as the main source of inefficiencies.

By considering the ratio of buoyancy flux of the plume to the momentum flux of the wind as the important parameter defining the flow, a simple model was proposed to connect the effects of wind speed (U_∞), exit velocity (V_j), and outside stack diameter (d_o). This model resulted in the parameter $U_\infty / (V_j d_o)^{1/3}$, which was successful in collapsing data for any particular flare stream composition. Unfortunately, this simple model did not capture all of the physics since it was unable to bring together the data from different flare stream compositions and energy densities. The effects of changing energy density were examined in detail and it was found that lowering the energy density of the fuel also had a profound impact on the flare efficiency. The collected efficiency data was used to produce a semi-empirical relationship that can be used to estimate the efficiency of a flare burning in a crosswind. This relationship is:

$$(1 - \eta) \cdot (\text{LHV}_{\text{mass}})^3 = A \cdot \exp\left(B \frac{U_\infty}{(g V_j d_o)^{1/3}}\right)$$

where LHV_{mass} is the lower heating value of the flare stream on a mass basis and g is the gravitational acceleration. The coefficients, A and B , are the following: $A = 133.3 \cdot (\text{MJ/kg})^3$ and $B = 0.317$ for methane base flares; and $A = 32.06 \cdot (\text{MJ/kg})^3$ and $B = 0.272$ for propane and ethane based flares. The lower heating value raised to the third power in this equation results from the high sensitivity observed when lowering the energy density of the flare stream by diluting it with inert compounds. For natural gas-based flare streams, at energy densities below 15 MJ/m^3 significant inefficiencies result at wind speeds as low as 1 m/s . Therefore, based on this model and current data, the recommendation is made to raise the lowest permissible energy density of flare streams to 20 MJ/m^3 .

Local Combustion Efficiency and Plume Structure

Experiments were conducted to determine the mean thermal and compositional structure of the plumes of solution gas flares. The features seen in the plumes of flares provide a framework for scaling the size of these plumes and investigating the origins of inefficiencies with respect to wind speed, exit velocity, and stack diameter. To visualize the thermal plume structures, two-dimensional cross-stream mappings were constructed by taking many mean temperature measurements with an array of thermocouples at selected planes downstream of the flare. The compositional structure of the post-flame gases was determined using single- and multi-point sampling techniques developed as part of the research project.

At low crosswind speeds, the plume had a very distinctive kidney shape, which is located well above the tip of the flare stack. As U_∞ increased, the trajectory of the flame is made more horizontal and the hot products of combustion are moved into a region where they are increasingly influenced by the flow structures created by the stack. As the crosswind was increased further, the amount of gases drawn into the wake of the stack became more pronounced, and a second peak in the mean temperature field appeared below the height of the stack tip.

The observed plume shapes were very similar to those seen in non-reacting buoyant jets issuing into a cross flow. Scaling of the characteristic dimension of the plume (d_p) is based on models developed to predict the size and trajectory of non-reacting plumes. These models are based on the combined forces of the momentum of the crosswind and the buoyancy of the combustion products, and predict that

$$d_p^* \propto g^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3}$$

where x is the downstream distance from the stack and d_i is the inside diameter of the stack. Data fitted to this expression had an average root mean squared (r.m.s.) error of 12%.

The structure of the compositional plume based on CO_2 , CO and unburned hydrocarbons (HC) was measured downstream of the flame. The plume of CO_2 was very similar to the

thermal plume for all tested conditions. This was expected since the formation of CO₂ is associated with combustion, which elevates the temperature of the gases. The plumes of emitted HC and CO were structurally different from the plumes of CO₂ for all wind speeds. The existence of CO and HC in the plume, a consequence of incomplete combustion, in a pattern different from CO₂ showed that the efficiency was not homogeneous over the entire plume. In the case of high wind speeds, the spatial variations in measured combustion efficiency were seen to range from 65 % to near 100 % within a single plume. The integrated efficiency over the entire plume from many single-point measurements showed good agreement with the overall efficiency measurements discussed earlier. These spatial variations in local combustion efficiency highlight the problem of single-point samples. As shown in these experiments, single-point samples, due to the considerable variability in magnitude, are not representative of the overall efficiency of a flare.

Minor Species Emissions

For this part of the research, the focus shifted away from combustion efficiency to considering the minor species emitted from natural gas and propane flares. Despite the fact that these minor species represent only a small mass fraction of the combustion products, they are important because of their potential toxic or carcinogenic properties.

The data collected were for selected compounds and were used to help characterize the potential toxicity of flare emissions. This study was divided into two parts based on the phase (i.e., vapor or solid) in which these species were emitted. Separating the emissions into phases provided an enhanced understanding of the issues of minor emissions. This understanding also helped to direct discussion towards appropriate monitoring and mitigation strategies. The tested vapour-phase compounds were: 17 poly-nuclear aromatic hydrocarbons (PAH); benzene, toluene, ethyl-benzene, and xylene (known collectively as BTEX); and 12 aldehydes. No attempts were made to identify and catalogue the full range of chemical compounds that could exist in the products of combustion from these flares.

For the vapour phase, five samples were analyzed and showed that the amounts of PAH, BTEX and aldehydes emitted by the flares were below the detectable limits for this method. The detectable limits for the PAH were estimated to be in the order of 30 µg/kg of gas flared, while the detectable limits for the other compounds were of the order of 1 mg/kg of gas flared. These emission rates proved to be two orders of magnitude less than those found in the solid phase emissions of propane flares.

As a part of measuring the solid phase emissions from flares, a technique was also developed for mapping the soot plume of a flare using a modified dual-channel fast flame ionization detector. An important observation from these experiments was that the particle plume emitted from flares corresponded to the size and shape of the thermal plume, although the soot particles were emitted at their highest frequency directly behind the flame tip. This last observation regarding the higher frequency of soot particles behind the flame tip suggests that this region of the flow is responsible for a majority of the particulate material emission, regardless of the crosswind speed. As a result of these tests, the particle plume was found to be inhomogeneous and, therefore, excluded the possibility of using single-point sampling to quantify the particle emission rate.

Once the entire particle plume was located, it was characterized in three ways: the mass of the particulate phase emitted from the flare for each unit mass of flare gas burned was calculated; the particles collected on the filter were imaged to provide an estimate of the particle size range emitted from flares; and the material collected on filters were chemically analyzed to determine the composition of the particles.

From the data collected, the amount of particulates emitted from flares burning natural gas and natural gas blended with octane all fell below the detectable limits. The detectable level was conservatively estimated to be 1.7 mg/m³ of air or an average number density of 1 ppb in the plume.

For propane flares, the soot emissions from the flare were shown to decrease slightly as either the crosswind or jet exit velocity was increased. This result was characterized in terms

of a mixing ratio, defined as $U_{\infty} \bullet V_j$. As a result of extensive testing, it was found that the emission of soot decreased as the mixing ratio increased. However, it was found that beyond a mixing ratio of 3 (m/s)^2 the mass fraction of soot emitted remained constant at approximately 0.4% of the fuel burned. This result was not a strong function of stack diameter (d_s). This result suggests that soot emissions at low mixing ratios are more of a concern for larger stacks.

The particles emitted from propane flares were imaged with a scanning electron microscope (SEM) to estimate the size and shape of particles collected on filters. The soot particles consisted of large collections of spherules that combined to produce highly irregular-shaped aggregates that were seldom found outside the range of 100 to 400 nm in size. The individual spherules were approximately 30 nm in diameter and their shape was characteristic of soot particles as described in previously published research.

Mass spectroscopy was used to measure the mass of 21 selected PAH compounds in the solid phase. It was found that the amount of individual PAH emitted varies considerably. These chemical analyses allowed for the detection of numerous compounds in the soot such as naphthalene, acenaphthylene, fluorine, phenanthrene, fluoranthene, and pyrene.

Overall Efficiency of Flares with Liquid Droplets

One of the realities of flaring at solution gas sites is the possibility of liquid droplets as part of the flare stream. The origins of these droplets are attributable to two sources. One possible source is the condensation of saturated hydrocarbon or water vapors in the flare stream. The other possible source is the droplet carry-over from a separation process or a liquid knockout system located upstream of the flare stack.

The effect of droplets on combustion and emissions will depend on their composition, amount, and physical size. For example, if the droplets are composed of water containing salt (i.e., NaCl), the chlorine could act as a chemical inhibitor to combustion, form a strong vapour-phase acid, or be emitted as a chlorinated hydrocarbon.

Very little is known about the composition, size distribution, or amounts of liquid droplets that are part of a typical solution gas flare stream. This concern regarding liquid droplets in flaring gas streams was investigated in a field study and reported separately. These field tests resulted in no liquids being found in gas sampled at the base of seven flare stacks. Consequently, these tests did not provide any direction on the composition of liquids that might occur in the flare stream. Therefore, as a starting point, the experimental results presented here are based on the idealized cases of iso-octane, diesel fuel, and distilled water droplets being added to the flare stream.

These experiments required the flare system to be modified to allow droplets, produced by ultrasonic generators, to be introduced into the flow. With this method of droplet generation, it was possible to add droplets of varying sizes and mass fractions to the flare stream of natural gas. Droplets of water, iso-octane, or diesel were added separately to the flare stream in quantities up to a mass fraction of 30% and exposed to crosswind speeds ranging from 2 to 9 m/s. The exit velocity of the 24.7-mm-diameter flare stacks, used in these tests, was set to either 1 or 2 m/s. The droplet size diameters were measured and characterized as a mass-mean diameter and, depending on the composition of the droplets, this characteristic diameter could be varied from 4 to 200 micrometers.

An enhanced method for measuring the combustion efficiency was developed in Chapter 7 to allow for the emission of non-gaseous hydrocarbons (*e.g.*, soot). This methodology was not used in the presented results since detailed measurements to identify soot emissions showed that there were no particulate emissions from these flares.

It was observed that the addition of droplets in these quantities had no effect on the flame structures or patterns relative to gas-phase-only flares. The luminosity of the flares carrying iso-octane or diesel was significantly increased; the luminosity of those flares carrying water droplets was unaffected. For conditions that produced larger iso-octane and diesel droplets, streaks of light were observed at the flame surface and extended downstream for several centimeters. These streaks of light were most pronounced with larger diesel droplets and

were associated with droplets not fully evaporating before reaching the flame where they were ignited and burned while being carried downstream with the flow.

The results of these experiments showed that water droplets added to the flare stream decreased the combustion efficiency proportionate to the amount of water added. In contrast, the addition of fuel droplets resulted in increased efficiencies where iso-octane had a greater impact than diesel on a per mass basis. The explanation for these results was found in the energy balance and dilution effects associated with the various droplet compositions. Water droplets extract energy from the flow in order for evaporation to take place. The addition of these non-reacting vapors to the flare stream results in a flame that is less robust than a natural gas flare without droplets. Therefore, flares streams with water droplets were more susceptible to the mechanisms that create inefficiencies in a crosswind. For combustible droplets, energy is still required for evaporation but the vapors are a fuel that contribute to the total chemical energy being converted to sensible energy at the flame. The energy associated with the combustion of a fuel far exceeds the energy associated with evaporation. Therefore, fuel droplets in the flare stream enhance the robustness of combustion and result in reduced inefficiencies.

The effect of altering the size of droplets carried out the stack exit was examined in these experiments. These results showed that if most of the liquid phase was converted to the gas phase before the flame, through evaporation, then the original diameter of the droplets had no influence on combustion efficiency. In practice, all of the water and octane droplets tested fully evaporated prior to the flame and, therefore, there was no observed effect of droplet size on the combustion efficiency. For the larger size diesel droplets, a notable portion of these droplets were reaching the flame intact and resulted in a slight increase in the combustion inefficiency. The size of droplet that will be evaporated prior to reaching the flame is highly dependent on the following factors: the size and luminosity of the flame; the travel time of droplet between the stack exit to the flame; and the composition of the droplet. Therefore, no recommendation is made regarding an expectable size of droplet that can be emitted from a flare stack without adversely affecting the combustion efficiency.

Higher Exit Velocity Flares

Experiments were conducted on flares with high gas flow rates in an attempt to simulate well-test flares. This research was restricted to 30 mm outside diameter flares and exit velocities ranging from 10 to 40 m/s. These experimental constraints were the maximum manageable conditions allowed within the larger, single-pass wind tunnel. Tests on these flares showed that simulated well-test flares had efficiencies of 99% +/- 0.2%.

1 INTRODUCTION TO THE FLARE RESEARCH PROJECT

The Flare Research Project at the University of Alberta was a multiyear investigation into the emissions, combustion processes, and fluid mechanics related to flaring. This report focuses on the emissions and efficiencies of flares under operating conditions typical of solution gas flares. Chapter 1 introduces the topic of solution gas flaring and the environmental concerns associated with these flares. Also discussed are the research goals of the project, the approach adopted to conduct the research, and the specific objectives of this report.

1.1 SOLUTION GAS FLARING

Flaring is used extensively in the energy and petrochemical industries to dispose of unwanted combustible gases by burning them in an open flame. The role of flares is to consume gases in a safe, reliable, and efficient manner in order to produce, through oxidation, a more desirable emission to the atmosphere than simply venting the gases. Worldwide, approximately 101.9 billion cubic meters of gas were flared or vented in 1997 [1].

Over the last fifty years many different flare designs and strategies have been developed to meet the widely different purposes and operating conditions that industry requires for flares. For example, flares can be used intermittently in emergency situations to deal with plant upsets or scheduled facility shutdowns for maintenance. These intermittent flares tend to be large in size and are to handle very high flow rates of flare gas at near-sonic exit velocities. Alternately, flares can be used to deal with continuous combustible gas flows that are not economical to recover within a process. Typically, these continuous flares involve relatively low gas flow rates and consequently low exit velocities compared to an emergency type flare. Solution gas flares are an important example of these continuous gas flares used in the upstream oil and gas industry and are the main interest of the study.

The term “solution gas” is used to refer to the collection of gases that come “out of solution” when conventional and heavy oil is extracted from a high pressure reservoir and processed near atmospheric pressure conditions. Once brought to the surface, the oil is separated from

any associated water and solution gas at a facility known as an oil battery. At the battery site, the oil is temporarily stored before further processing at a refinery. The water is re-injected into the reservoir of origin and the gases may either be flared or “conserved”. Within this context, “conserved” means the gases are collected and processed later to sales-grade natural gas. In Alberta, the choice of whether to conserve or flare the solution gas at any particular battery site is part of the flare management framework administered by the Alberta Energy and Utilities Board (EUB) [2].

In 1999, there were approximately 8249 active oil and bitumen battery sites scattered throughout Alberta which produced a total of 59.4 million m³ of conventional oil and 23.7 billion m³ of solution gas [3, 4]². Although most solution gas produced in Alberta is “conserved”, approximately 6 % of these gases was flared or vented at the battery sites. In 1999, 3715 of these battery sites reported volumes of gas flared totaling 0.938 billion m³ while 1346 reported straight venting of gas totaling 0.485 billion m³. It is this number of flare sites and the volumes of gas being flared that make the process of solution gas flaring an environmental concern for the public, oil and gas producers, and regulatory agencies.

1.1.1 Characteristics of Solution Gas Flares

It is extremely difficult to describe solution gas flares in terms of a common set of characteristics. Guide 60, published by the EUB [2], requires flare operators to report total volumes of gas flared at battery sites on a monthly basis, but basic data such as the current composition of gas being flared, flow rates of flare gases representative of current conditions (rather than monthly averages), flare diameter, type of ignition system, type of liquid separation system, and composition of any liquids sent to flare are not reported.

² These references are raw data tables of oil and gas volumes by battery site and gas compositional data from well tests provided by the Alberta Energy and Utilities Board. The numbers and statistics quoted were derived from these tables. It should be noted that these numbers include data from wells classed as experimental and/or confidential which are not included in the publicly available data files distributed by the EUB as part of the ST-60 series. As well, the data reflects additional amendments not available at the time of release of EUB ST-60B in August 2000.

Furthermore, anecdotal evidence suggests that most of these parameters can vary widely from site to site.

Although there is no single set of characteristics that describes or defines these flaring operations, certain common features are believed to exist: flare stack height for solution gas is of the order 10 m high and a common stack size is approximately 10 cm in diameter. Other important parameters such as the volume flow rate and velocity of the solution gas exiting from the flare stack (V_j) can vary widely. Moreover, gas flow rates may not be steady depending on the operation of the oil wells feeding the battery. In addition, fluctuations in flow rate can be further exacerbated if the battery is designed to intermittently use a portion of the solution gas for heating purposes at the site. Variations in the mean wind speed (U_∞) at the site also continually alter the flaring conditions. The ratio of U_∞ / V_j could easily vary from zero to 25, which produces flames that are either upright or bent over horizontally, and can significantly affect the performance of the flare. Furthermore, there is considerable variation in the design of the flare tip in terms of wind shrouds and automated ignition systems (e.g., electric spark or continual pilot) that are mounted around the exit of the flare stack.

Figure 1.1 shows a histogram of the number of oil and bitumen battery sites in Alberta sorted by their total volumes of gas flared and/or vented during 1999. In total, there were 4499 oil and bitumen battery sites in Alberta that report flaring and/or venting operation during that year with a combined gas volume of 1.42 billion m^3 .³ The logarithmic scale on the horizontal axis of the histogram highlights the large variability in flow rates among individual battery sites where the median volume flared or vented was approximately 60,300 m^3 /year. Also shown on Figure 1.1 are the cumulative distributions of both the number of battery sites and the total volumes of gas released sorted by the amount flared or vented at the battery sites. These cumulative distributions give an indication of the estimated

³ The 2004 EUB Upstream Petroleum Industry Flaring and Venting Report (published May 2004 based on the year ending December 31, 2003) shows that 843 million m^3 of gas was flared or vented in the province of Alberta. This corresponds to a conservation rate of 95.4% for the year 2003.

size of the flaring operations at individual battery sites and illustrate the proportion of gas flared at these sites. For example, referring to the dashed line in Figure 1.1, it is apparent that 95% of battery sites flare and vent less than 1,000,000 m³/year. Assuming this amount of gas was consumed in a continuously operating flare, this would equate to an exit velocity of 4 m/s on a 100 mm diameter (4 inch) flare stack. Of course, most of these 95% of battery sites flare amounts less than 1,000,000 m³/year and would be expected to operate intermittently at higher and lower flow rates than their average flow rate. Thus, it is estimated that typical exit velocities for solution gas flares would be less than 6 m/s.

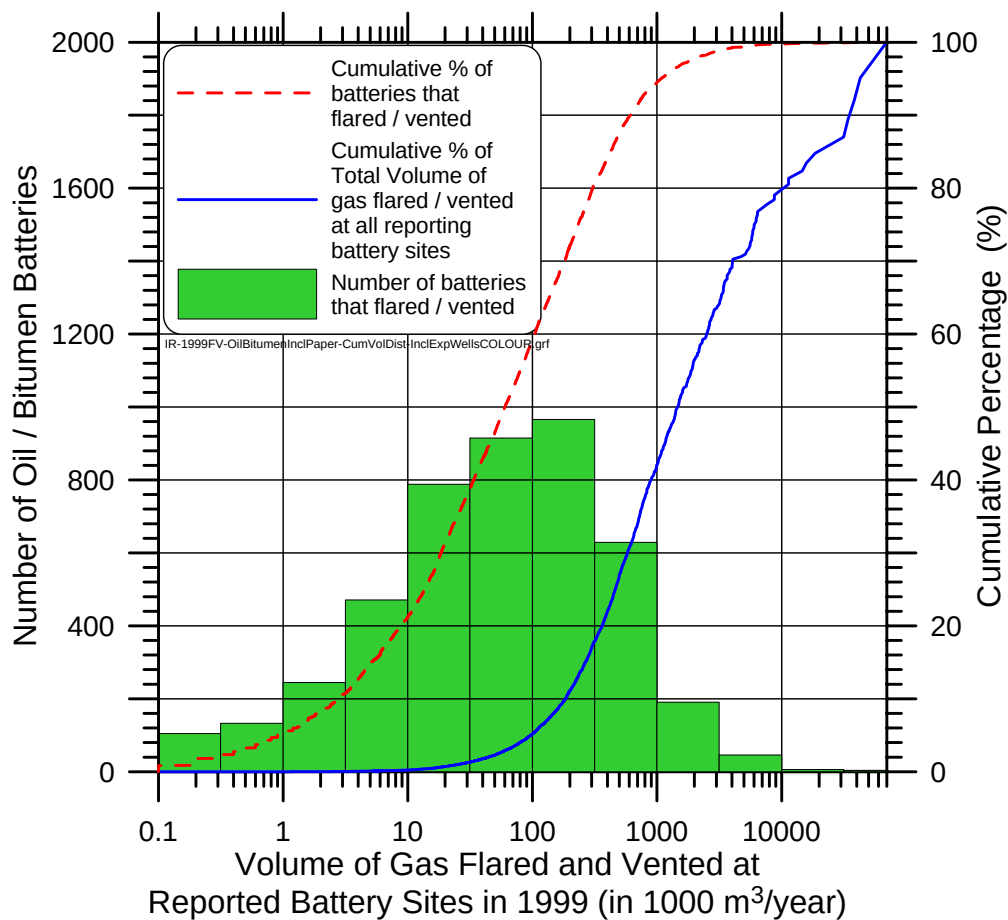


Figure 1.1: Distributions of gas volumes flared and vented at individual battery sites in Alberta in 1999.

Although 95% of battery sites in Alberta flare or vent less than 1,000,000 m³/year, the solid line on Figure 1.1 shows that these 95% of batteries only consume 43% of the total gas flared and vented at all battery sites. Alternatively stated, 5% (or 225) of the battery sites in the

province account for 57% of the gas flared and vented at oil and bitumen batteries in Alberta. At this point, it must be noted that not all of these battery sites represent single sources of solution gas and instead represent a collection of solution gas sources that are reported to the EUB as a single “paper battery”. These paper batteries are concentrated at bitumen sites and represent 23 % of the total gas flared and vented in the province. Despite these complications the distribution of volumes flared and vented presented above can have important implications for the strategies to reduce the total volumes of gas flared and vented in Alberta.

Apart from the physical and environmental differences among battery sites, there are significant variations in the composition of materials being flared. The EUB does maintain a database of well gas analyses (i.e. basic gas phase composition of solution gas at individual oil wells) but these sites are generally removed from the battery sites which often flare a blend of gases from more than one well. Figure 1.2 shows a plot of the mean and maximum concentrations of major components found in solution gas at these individual well sites. The data are derived from a file of 5614 solution gas analyses from well sites throughout the Alberta [4]. The most important observation to be made from this data is that there is significant variability in the relative concentrations of each of the major species contained in the solution gas. The notion of an average composition of solution gas is essentially irrelevant. Even methane (C1 hydrocarbons), which dominate the average concentration of the gas analyses at nearly 70 %, can vary greatly at individual wells. These variations are significant in terms of the potential uses for the solution gas and for the ability of the gas to be combusted in a flare in a safe manner. Both the mass density (kg/m^3) and the energy density (MJ/m^3) of the flare stream are dramatically affected by the observed variations. The inert compounds such as carbon dioxide (CO_2) and nitrogen (N_2), which have mean concentrations around 4%, can make up significant portions of the solution gas and, as will be shown in Chapter 3, this variation has a strong effect on the overall efficiency of the flare.

A main distinction in gas compositions is the amount of hydrogen sulfide (H_2S) present in the solution gas. Although different definitions are used in different situations, gas streams at batteries that contain measurable amounts of H_2S (typically greater than 10 ppm) are referred

to as “sour”. Batteries with less than this amount of H_2S are referred to as “sweet”. As shown in Figure 1.2, the amount of H_2S measured at well sites varies widely from its mean concentration of 2.7 % from 0 % to as much as 76.6 %. Currently, gas composition data from battery sites is not reported and, as such, an accurate estimation of the volumes of sweet/sour gas being flared or vented is not possible. Our current estimate is that approximately 32 % of the gas flared and vented in the province is sour.

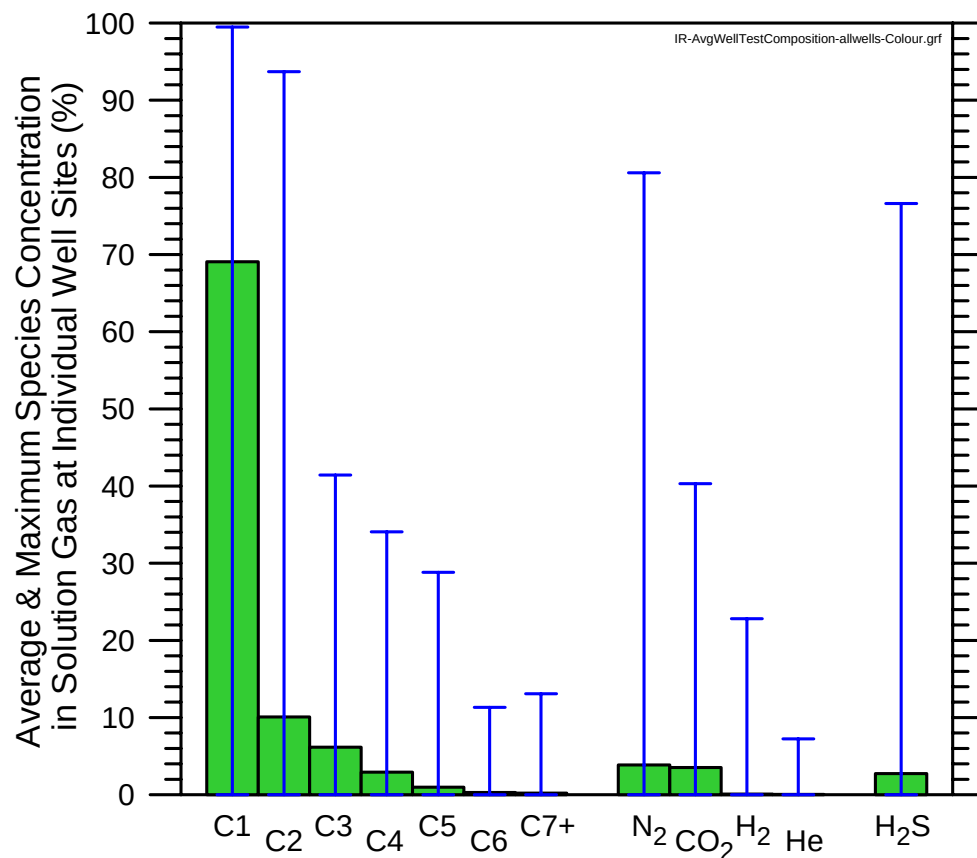


Figure 1.2: Analyses of solution gas at individual oil well sites in Alberta

Previous field work on solution gas flares suggested that the flare stream was considerably more complex because of the inclusion of liquids [5]. That study also suggested that the performance of flares could be profoundly affected by the presence of liquid thus limiting the usefulness of efficiency models based a on gas-phase-only perspective. A recent report presents the results of a preliminary field study to characterize the nature and relative quantities of gases and liquids being flared at battery sites in the Western Canadian Sedimentary Basin [6]. This latest field study found no liquids in flare gases sampled at flare

stacks after the liquid knock-out system. Consequently, the concern of liquid droplet carryover in solution gas flaring is greatly reduced.

It is clear that solution gas flaring is neither well defined by a single set of operating parameters nor characterized by any single battery site. Solution gas flaring is better thought of as a class of flows that needs to be understood in general and not on a case-by-case basis. The challenges associated with studying a device with as many variations as solution gas flares are discussed in Section 1.4 as part of describing the approach taken for this research.

1.1.2 Other Types of Flares Used in Upstream Oil & Gas

The main focus of the research presented in this report is on solution gas flaring, but its connection and relevance to other types of flares is worth discussing. Emergency flaring at plants and refineries typically occurs at exit velocities in the range of Mach 0.2 to Mach 1 and often employs systems to inject water, steam, or air into the base of the flame to reduce the formation and emission of soot. Under these conditions, the mechanism of flame stabilization is significantly different from solution gas flares and therefore results presented here cannot be extended to those situations. Similarly, flaring associated with natural gas well tests occur at very high flow rates and are not relevant to the results presented in this report. On the other hand, continuous flaring of acid gas at natural gas sweetening facilities has a number of similar flow characteristics to solution gas flaring. Therefore, the behavior acid gas flares can potentially be described by the research presented here, though caution is advised since the composition of the acid gas is distinctly different from solution gas.

1.2 ENVIRONMENTAL ISSUES OF FLARING

The environmental issues of gas flaring are generally described in terms of efficiency and emissions. As described previously, the goal of a flare is to consume gases safely, reliably, and efficiently and, through oxidation, produce a more desirable emission to the atmosphere than simply venting the gases. The flare efficiency is a measure of the effectiveness of the

combustion process in fully oxidizing the fuel. (A formal definition of flare efficiency is presented in Section 3.1.) When inefficiencies occur, unburned fuel, carbon monoxide, and other products of incomplete combustion (e.g., soot, volatile organic compounds, etc.) are emitted into the atmosphere. If the flare stream contains methane, the unburned fuel represents an increase in greenhouse gas emissions. In the case of sour gas flares, any unburned fuel emissions are potentially toxic. The emissions of the products of incomplete combustion can also raise health concerns for animals and people.

Most previous research on flares has supported the general observations that flare efficiencies were high (>95%) as long as the flames were stable [7-11]. The most prominent of these studies was sponsored by the United States Environmental Protection Agency (EPA) and involved the testing of flares ranging in nominal size from 3.8 to 30 cm burning bottled gases over a range of flow rates [7-9]. The tests were conducted in such a manner that the wind speed impinging on the flare was low (<5km/hr) and a collection hood placed above the flame collected all the products of combustion. The products of combustion were then sampled and the overall combustion efficiency of the flare was calculated. The main conclusion of the EPA study was that flares had efficiencies greater than 98% for the gas mixtures tested as long as the flame remained stable. Consequently, the problem of maintaining high-efficiency combustion from flares was shifted to understanding the set of operating parameters (e.g., flare gas exit velocity, energy density of the fuel, etc.) that would ensure stable combustion. The results of this EPA study are the foundations of current U.S. federal regulations on flaring [12], but have had little impact on the recommended practice guidelines of the American Petroleum Institute [13].

In 1996, the Alberta Research Council (ARC) released a report describing a multi-year experimentally-based study that culminated in field tests of one sweet and one sour solution gas flare [5]. In this work, a single-point, aspirating probe placed nominally in the center of the plume of the products of combustion was used to measure the emissions from the flares. Standard techniques were used to collect, concentrate and analyze the important carbon-containing compounds present in the plume. The tests were conducted at the normal operating conditions of the chosen battery sites and the prevailing wind conditions at the time

of the tests were reported. The results of this work were in stark contrast to other research since the measured efficiencies of the solution gas flares were as low as 62%. However, the most important difference between the ARC work and that of other researchers was that measurements were performed to look specifically for toxic compounds in the flare emissions. These measurements showed the existence of more than 150 volatile organic compounds (VOC) and poly-nuclear aromatic hydrocarbons (PAH) in the plume of combustion products.

1.3 PROJECT GOALS

The contrast that exists in the conclusions between the ARC and EPA studies was essentially the starting point for the University of Alberta Flare Research Project. Given the differences in the test conditions there was no reason to consider one of these studies correct and the other in error, but it was important to develop a better understanding of how flares could produce such varied outcomes. Therefore, the main goal of the University of Alberta Flare Research Project was to bridge the gap between the ARC and EPA studies by helping understand the potential origins and causes of undesirable emissions from flares. It is believed that a greater understanding of flares in general would lead to developing strategies for solving problems that might exist as they pertain to solution gas flares.

1.4 RESEARCH APPROACH

The approach taken in this research project has been to experimentally study generic pipe flares under well-controlled conditions. The need to have control of the experimental conditions was paramount in order to systematically investigate the many parameters that could affect the emissions from flares. For example, to investigate the effects of changing the flow rate of flare gas it is important to be able to accurately vary the gas flow rate but it is equally important to keep other conditions (e.g., wind speed) the same. Having control of the experimental conditions allows the emissions results to be repeatable and attributable to a well-defined set of conditions and, in turn, estimates regarding the uncertainty in the results can be made. To provide this level of control over the wind, this research was conducted in

wind tunnels where the wind speed from a known direction could be set and the level of turbulence could be prescribed through placing obstructions in the flow upstream of the flare. Working in a laboratory setting affords other advantages such as being able to blend together different gases to create a variety of flare streams with known compositions for testing. Furthermore, if the effects of adding droplets to the flare streams were being examined, the amount, size range, and composition of droplets can be varied and measured quantitatively with relative ease compared to field-testing.

As with all approaches to research, there are restrictions and limitations. By working in wind tunnels it is inevitable that there will be a practical limit on the size of flare that can be tested. These limitations arise as a result of the physical size of the flame and the wind tunnel and the need to avoid flame impingement onto any of the walls. The most common size of flare that was tested was 24.7 mm in diameter but under some conditions flares as big as 114.3 mm in diameter were used, which is full scale of the most common solution gas flare.

Other concerns that arise in using this wind tunnel approach are that the gases being burned are not “real” solution gases and that “real” flare tips are not being tested. As previously discussed, there is no such thing as a typical flare tip design for solution gas flares or a typical solution gas composition. It would be completely impractical to examine the multitude of variations in tip design or gas composition that exist in solution gas flare sites.

It was therefore decided to create an understanding of the performance of flares based on a simple pipe flare, which represents the most generic flare design. This decision recognizes the fact that much of the overall behavior of flares is dominated by large-scale flow features such as:

- a fuel jet issuing into a cross flowing stream of atmospheric air;
- the bending over of the fuel jet and plume by the wind through the entrainment of air into the jet;
- the turbulent mixing process between the air and fuel over the length of the flame;
- the wake-vortices being shed from the leeward side of the flare stack; and
- the buoyancy of the hot combustion products relative to atmospheric air.

Since all of these flow features occur in both pipe flares and the simple unassisted flares used to burn solution gas, the results of pipe flares would be expected to be representative, in general, of solution gas flares. Results on any specific flare designs may vary from the pipe flare results, but the expectation is that the measured trends in emissions and efficiency will be captured with a pipe flare as long as the flow occurs within the same flow regime (see Section 2.1.2).

Since solution gas flaring truly represents a class of fluid dynamic flows, it was decided to burn gases that are representative of the range of flare gas in the field with respect to their mass and energy densities. To achieve this result, the wind tunnel experiments used sales-grade natural gas and commercial-grade propane that could be blended with inert compounds like carbon dioxide or nitrogen. Furthermore, droplets of water or hydrocarbon fuels could be added to the flare stream.

1.5 SPECIFIC RESEARCH OBJECTIVES

The strengths of the approach adopted for this research project permitted several specific research objectives to be investigated. These objectives were:

- develop methods for measuring the overall combustion efficiency of flares with either gaseous flare streams or those containing liquid droplets;
- measure the overall combustion efficiency as a function of wind speed, exit velocity, flare stack diameter, fuel type and energy density;
- contribute to the development of models to predict the overall combustion efficiency of flares operating in the field;
- contribute to the understanding of the mechanism that cause the inefficiencies in flares;
- develop models for the scaling of plumes that disperse the products of combustion from flares as a function of wind speed, exit velocity and flare stack diameter;
- measure and map the local combustion efficiency of flares in a crosswind to help understand the difficulties in interpreting single point measurements and provide insight into the mechanisms that cause lower overall combustion efficiencies;

- develop methods for measuring the production rates of selected toxic compounds emitted from flares in either the vapor phase or bound within the soot;
- develop methods for measuring the production rates of particulate emissions from a flare;
- measure the emissions of selected toxic compounds in both the vapor phase and bound up in any soot emissions per unit mass of fuel burned;
- measure the overall combustion efficiency of flares that contain liquid droplets of either water or hydrocarbon fuel as a function of droplet size, number density, wind speed and exit velocity; and
- develop a correlation to predict the overall combustion efficiencies of flares.

1.6 REPORT STRUCTURE

Chapter 2 provides a detailed description of the facilities and diagnostic equipment used at the University of Alberta Flare Research Facility and the secondary research facility at the National Research Council (NRC) in Ottawa. Chapter 3 deals with the overall combustion efficiency of natural gas and propane flares and how their efficiency is affected by changes in wind speed, exit velocity of the flare gas, stack diameter, and composition of the flare gas including the effects of reduced energy density. The methodology for estimating the overall efficiency is described and the uncertainties expected from this approach are presented. Chapter 3 also provides a detail discussion of the origins of the inefficiencies of flares and a model for predicting the efficiency of these flares. Chapter 4 deals with some of the scaling issues when using model flares. The plumes of the model flares are shown to scale in the same manner as full-scale flares, which contribute to building confidence that other scale-model results are applicable to full-scale. Chapter 5 describes a method for single point sampling in the near plume of the flare to give an estimate of local flare efficiency which is also used in Chapter 8. A multi-point extension of this methodology is presented and used to create a two-dimensional mapping of local efficiency that shows spatial variations in efficiency. Discussion is also given in this chapter to the problem of single-point sampling in the field. In Chapter 6, the problem of minor but toxic emissions from flares is examined when burning natural gas and propane flares. These emissions are examined separately in

their vapor and particulate forms. Chapter 7 considers the added complexity of having droplets of water or hydrocarbon fuels being entrained in a flare stream of natural gas and estimates are made of the overall efficiency. Finally, in Chapter 8, research done for larger scale flares is described. These results correspond to the testing of full-scale flares which are then integrated into the efficiency model. Chapter 8 also presents results of higher-exit-velocity flares.

1.7 CONCLUDING REMARKS

Conflicting research results on the emissions from flares have helped draw attention to the common practice of solution gas flaring as an important environmental issue within Alberta. Previous research on flares has described them as either very efficient or very inefficient, and in the inefficient case the emissions include a multitude of toxic compounds. The goal of this research was to reconcile these conflicting results through a better scientific understanding of flaring.

An important feature of solution gas flares is the wide site-to-site variation in gas composition, presence of liquids in the gas stream, gas flow rates, and flare design. These site variations combined with variations in environmental conditions, such as ambient temperature, wind speed, and wind direction, make understanding and predicting the emissions from solution gas flares very complex. The few features that are common to solution gas flares include stacks in the order of 100 mm in diameter and gas exit velocities in the order of the mean wind speed.

The approach taken in this research was to study pipe flares of various sizes in the well-controlled conditions of a wind tunnel. Within this wind tunnel environment, the defining parameters of a flaring operation (i.e., wind speed, flare stream flow rate, stack size, flare stream composition, etc.) could be specified and varied independently to elucidate the important physical processes occurring around the flare that impact emissions.

Given the current form of available data, it is difficult to develop a comprehensive statistical understanding of solution gas flaring operations. In order to determine the performance of a flare, the actual composition of the flare gas is needed along with the flow rate and size of flare being used. At a minimum, it is recommended that basic gas composition analysis (mole fractions of C1 to C7+, H₂S, N₂, CO₂ in solution gas) be collected from individual battery sites. It would be necessary to ensure that this data remained accurate as operations at the battery site changed. As well, it is recommended that operators of paper batteries be required to report flare and vent volumes for each physical site separately. This data would be extremely valuable to researchers, technology developers, battery operators, and regulators in assisting in the quest to improve performance of flares and develop economic alternatives to flaring.

2 FLARE RESEARCH FACILITIES

The experimental data that will be presented throughout Chapters 3 to 8 have been collected at the University of Alberta and the National Research Council's (NRC). The University of Alberta (U of A) facility consists primarily of a closed-loop wind tunnel used to impose a crosswind on the flare. Complementary to this facility are systems to supply various gases and liquid droplets to the flare and a range of equipment to monitor and control the experiments. The NRC facility consists of a single-pass wind tunnel equipped with control and analysis systems similar to those found at the U of A. The bulk of the foundational experiments were done at the U of A's facility on sub-scale flares while the NRC facility allowed data to be collected for full-scale flares. This methodology meant that theory, based on sub-scale models, was validated by full-scale experiments. This chapter provides an overview of the physical structure of these two wind tunnels. In addition to the specifications of the facilities, this chapter includes the collected data used to characterize the fluid dynamics associated with the test sections of the wind tunnels and the exits of the flares.

2.1 U OF A FLARE RESEARCH FACILITY

2.1.1 Closed-Loop Wind Tunnel

Figure 2.1 shows a schematic of the closed-loop wind tunnel. This facility had an internal volume of approximately 350 m³ and a 150 kW DC motor that drove a 3 m diameter fan. This configuration was capable of producing stable crosswinds between 1 and 35 m/s in the test section of the tunnel. The integrity of the mean flow was achieved through arrays of turning vanes employed at each of the four bends in the tunnel eliminating the formation of any recirculation zones or secondary flows at the corners. In addition to the turning vanes, a series of three fine-mesh screens and a 6.3:1-area-ratio convergent nozzle produced a near-uniform plug flow in the 2.44 m wide by 1.22 m high test section that followed the contraction section.

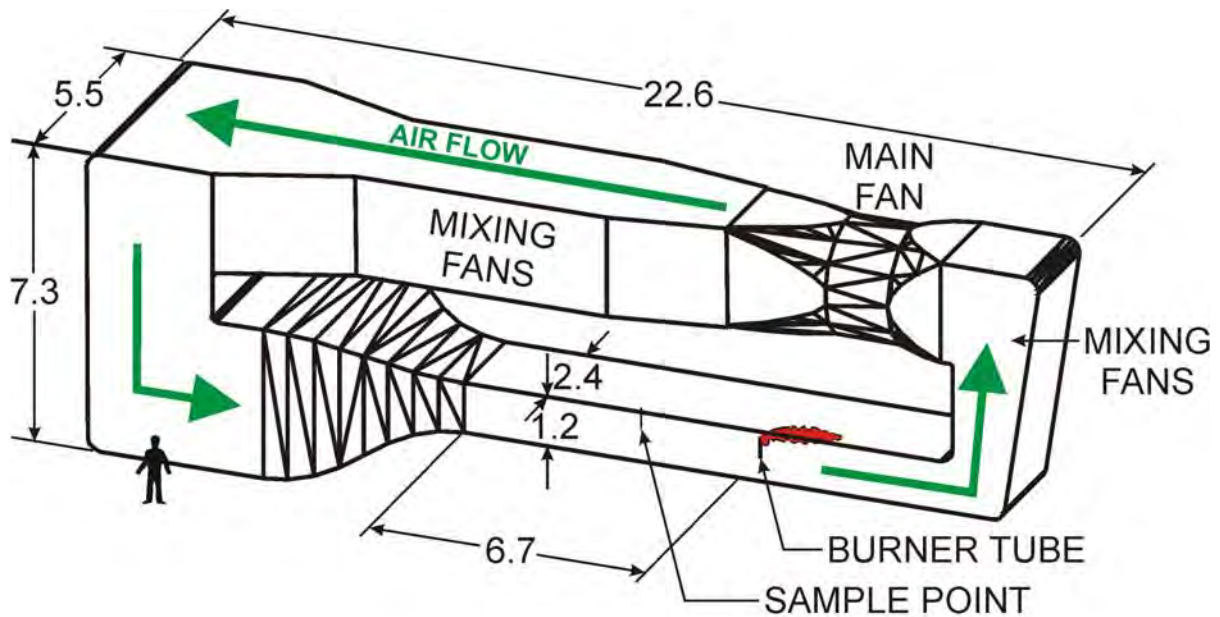


Figure 2.1: Schematic of the closed-loop combustion wind tunnel facility (all dimensions are in metres)

The test section of the tunnel is approximately 11.8 m long and flare stacks were mounted 6.7 m from the leading edge of the test section. By placing the flares well downstream in the test section, grids or arrays of obstacles could be placed upstream of the flare to introduce turbulence into the flow that would be fully developed by the time it reached the flare. The floor of the wind tunnel was constructed with 19 mm thick plywood, which downstream of the flare was covered with 30-gauge-aluminum sheeting to protect it from possible direct flame impingement. The walls along the test section were primarily Plexiglas and provided good visual access to the tunnel for observing the flares. To provide better quality optical access for flame visualization, a 2.1 m x 0.9 m section of the Plexiglas at the stream-wise location of the flame was replaced with tempered glass. The ceiling upstream of the flare was constructed with 19 mm thick plywood, but downstream of the flare the ceiling was made of 19 mm thick ceramic panels that could safely resist the accidental impingement of the flame or hot combustion products.

The wind tunnel also had two sets of dampers and their locations are indicated in Figure 2.1. These dampers allowed the tunnel air to be purged of combustion products and replenished with fresh ambient air between flaring tests. To assist the purging process, two auxiliary fans

were mounted just inside the intake dampers upstream of the main tunnel fan. The purging process took approximately 5 minutes to complete.

2.1.1.1 Auxiliary Equipment

Mounted in the vertical section of the wind tunnel following the test section were three mixing fans. A second set of three of fans was located after the main tunnel fan. Each of these 0.6 m diameter fans was powered by a 0.56 kW motor that drove the redistribution of large volumes of tunnel air ($3.24 \text{ m}^3/\text{s}$ at 11.5 m/s) and dispersed the plume of combustion products across the cross-section of the tunnel. The mixing of combustion products into the tunnel air was important for two reasons. Firstly, to minimize the impact of using a closed-loop wind tunnel, the combustion products could not return to the flare in any coherent form to affect the combustion processes. Secondly, to calculate the combustion efficiency it was necessary to measure the total accumulation rate of various chemical species in the tunnel. If the measurements were to be made by a single-point sample (whose location is shown in Figure 2.1), the flow in the tunnel had to be compositionally uniform so that the sample was representative of the entire flow. The number, size, and orientation of the fans were decided by a trial-and-error process to achieve uniformity in tunnel gas composition and are discussed further in Section 2.1.5.3 on characterization of the tunnel flow.

The ignition system used for the flares was a retractable hydrogen jet diffusion flame that is shown schematically in Figure 2.2. A manual high-voltage spark system, based on an automotive ignition system, was used to light the hydrogen fuel jet issuing from a 6 mm diameter pipe. This pipe could be raised vertically to the appropriate height so that the ignitor flame passed directly over the flare exit. Once the hydrogen flame was correctly positioned, the flow of flare gas was easily ignited. After the flare was ignited the flow of hydrogen was turned off and the pipe was lowered back to the floor level so it did not affect the flow around the flare stack.

In order to measure the mean velocity in the tunnel, a Pitot-static tube was installed in the test section at the same downstream location as the flare stack. A series of three pressure

transducers with different ranges were required to measure the mean dynamic pressure from the Pitot-static tube over all the potential wind speeds. The resulting wind speed ranges for the different transducers were $1 \leq U_{\infty} \leq 6$, $6 < U_{\infty} \leq 14$, and $14 < U_{\infty} \leq 35$ m/s. The gas temperature in the tunnel was measured with a semi-conductor (AD590) transducer. A mercury barometer was used to record the room pressure outside the tunnel. A differential pressure transducer and static pressure taps corrected the measured barometric pressure to tunnel conditions. The temperature and pressure of the gases within the tunnel were needed to estimate the gas density in order to convert the Pitot-static pressure measurements into wind velocity.

A three-component traversing system was available for positioning various probes in the tunnel flow downstream of the flare stack. Movements in the vertical and cross-stream directions were computer-controlled through stepper motors in increments of less than 1 mm. The movement in the stream-wise direction was done manually on tracks in increments of 10 cm over a length of 4 m.

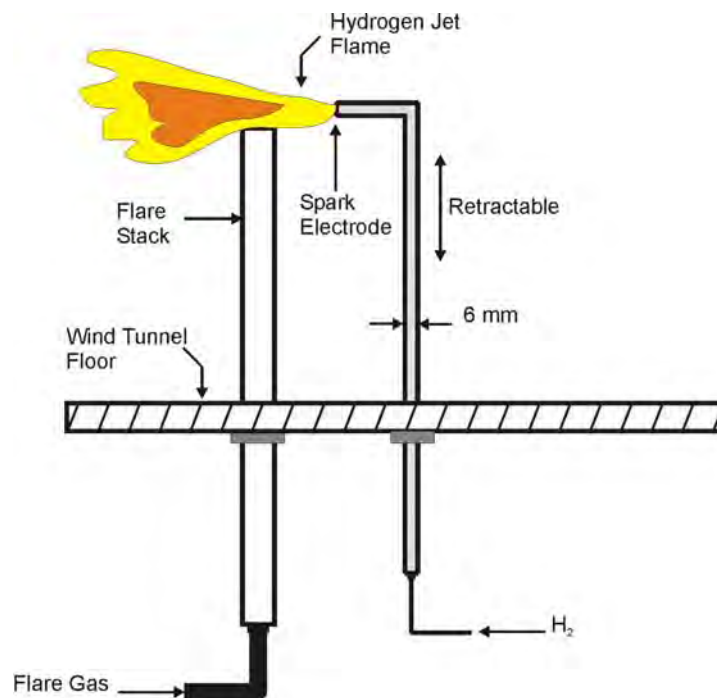


Figure 2.2: Flare ignition system. A retractable spark ignited hydrogen flame was used to ignite the flare.

2.1.1.2 Safety Features

Besides having a ceramic ceiling and a metal-sheeted floor downstream of the flare to protect against high temperature gas, there were other important safety-based concerns that needed to be considered when introducing gaseous fuels into a closed facility. The main concern was the accidental accumulation of gaseous hydrocarbon fuels in or around the wind tunnel. To monitor the accumulation of these gases, a multi-head gas detection and alarm system was installed. The detector heads were placed at floor and ceiling levels at locations inside and outside the tunnel. Besides sounding alarms at preset levels of hydrocarbon concentration relative to the lower explosive limits, the gas monitor also automatically shut off fuel supplies at the source, opened the tunnel dampers, and engaged the non-sparking auxiliary purge fans to help disperse any accumulated fuel gases.

2.1.2 Model Flares

The flares used in this research were scale-model pipe flares. Typical flare stacks used for solution gas flaring at battery sites in Alberta are constructed from nominal four-inch, schedule-40 pipe. This size of flare is referred to in this report as either a “full-scale” or “full-size” flare. The inner diameter (d_i) and outer diameter (d_o) of this full-scale flare are 102.3 mm and 114.3 mm, respectively. To maintain geometric similarity for scaled-down flares the ratio d_i/d_o was held constant by machining the outside of commercially-available pipe to an appropriate wall thickness. Table 2.1 lists the inner and outer diameters of the model flares that were used in this study.

**Table 2.1: Dimensions of Typical Solution Gas Flares and Model Flares
Used at the U of A**

Nominal Scaling to Full-Scale	Inner Diameter d_i , (mm)	Outer Diameter d_o , (mm)	d_i/d_o	H_s/d_o Exposed to Wind	Equivalent Full-Scale Stack Length Exposed to Wind, (m)
1	102.3	114.3	0.9	87.5	10.0
1/2	44.6	49.8	0.9	18.1	2.1
1/3	33.3	37.2	0.9	24.2	2.8
1/4	26.8	29.9	0.9	28.4	3.2
1/4	22.1	24.7	0.9	36.4	4.2
1/6	16.7	18.6	0.9	48.4	5.5
1/10	10.8	12.1	0.9	74.4	8.5

The heights of “typical” solution gas flares (H_s) used in the field are approximately 10 m. Even though the experiments conducted in the wind tunnel use scaled-down flares, the equivalent length of stack exposed to the wind in the tunnel only represents the top portion of a full-size flare. Listed in Table 2.1 is the maximum height-wise scaling available in the wind tunnel when the stacks were raised to their maximum height, which was approximately $\frac{3}{4}$ of the tunnel height. These stack heights were acceptable in high wind conditions when the flames were bent over horizontally. To help interpret this height-wise scale, the last column in Table 2.1 lists the equivalent length of full-scale stack that would be exposed to the wind if the tunnel experiments were scaled up.

When altering the scale of flares it is important to keep the same flow regime between the full scale and the model scale (i.e., avoid changing from turbulent to laminar flow regimes by going to smaller flares). In the case of flares, one must be concerned with both the internal and external flow regimes of the stack.

2.1.2.1 Internal Flow

Typically, the internal flow inside full-scale flares will be turbulent for gas velocities and compositions relevant to solution gas flaring. For example, a full size ($d_i = 102.3\text{mm}$) natural gas flare operating at 20°C with a characteristic velocity of $V_j = 2\text{ m/s}$ has a Reynolds

Number (i.e., $Re_i = V_j d_i / \nu$, where ν is the kinematic viscosity) of 13,140, a value which will produce a turbulent flow. To keep the kinematics of the flow the same between scales it would be appropriate to test scaled-down flares in the tunnel at the same exit velocity as full-scale flares. If, for example, this 2 m/s gas velocity were maintained for the scaled-down flares, the internal flow would be laminar. By changing the internal flow from turbulent to laminar there would be significant changes in the profiles of local mean gas velocity and momentum flux (momentum flux = ρV^2 , where ρ is density). As well, the turbulent mixing properties of the flare gases would be lost and there would be a large change in the total momentum flux of the flare stream.

To compensate for this change in flow regime, turbulence-generating plugs were inserted into the flare stacks. These plugs were designed to introduce turbulence into the flow and redistribute the mean flow to conditions more typical of turbulent pipe flow. The introduction of this turbulence needs to be made near the flare exit so the flow does not relaminarize before exiting the model stacks.

Two styles of turbulence plugs were used in these experiments as shown in Figure 2.3. The more common turbulence generator used was a perforated plug, which has holes 13.5% of d_i in a staggered pattern that creates 65% blockage. The other turbulence generator used a single orifice. The basic dimensions and placement of these plugs within the stack are shown in Figure 2.3. The style of turbulence plug used depended on the size of the stack being tested. The exit velocity characteristics of the stacks are reported in Section 2.1.5.2.

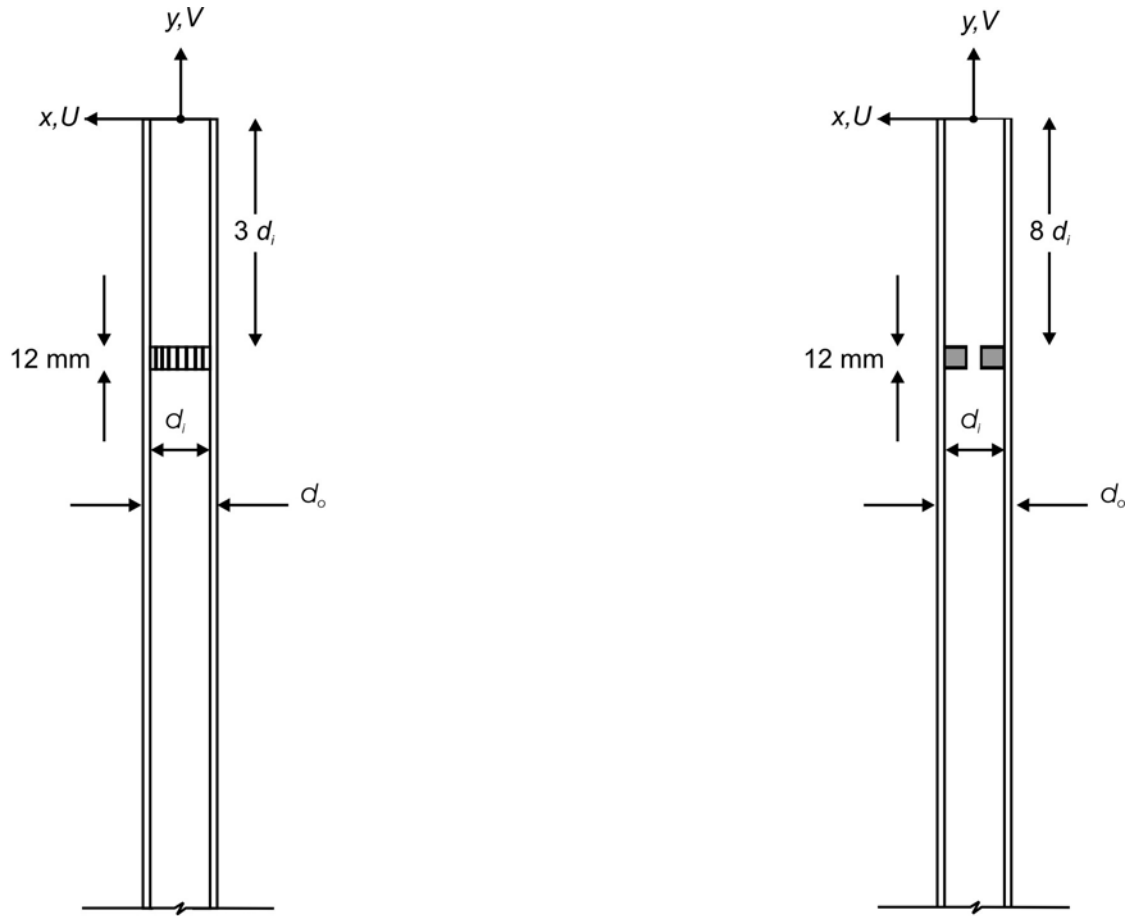


Figure 2.3: Model flare stacks used in this research: (a) internal multi-hole plug turbulence generator (b) internal orifice plug turbulence generator

2.1.2.2 External Flow

The flow regime on the outside of the pipe flare can be characterized by being either a laminar or turbulent boundary layer separation. The transition between these boundary layer separations occurs in the region of a critical external Reynolds Number (i.e., $Re_o = U_\infty d_o / \nu$), which for cylindrical pipes with little roughness is at $Re_o \sim 500000$ [14]. For a typical solution gas flare stack ($d_o = 114.3$ mm) operating at 20°C , the external flow transition would occur at $U_\infty \sim 66$ m/s (238 km/hr). Hence, all flares of interest (either full or model scale) are expected to be in the regime of having a laminar boundary layer separation.

To confirm this flow regime, flares ranging in size from $12.1 < d_o < 114.3$ mm (full scale) were tested by introducing a small flow rate of fuel gas into their wakes to observe the deposition pattern of the soot onto the stack once the gases were ignited. In all cases, the

soot was deposited throughout the wake region of the stack with a very sharp transition occurring to no soot at the angular position of approximately ± 90 degrees from the leading stagnation point of the stack. Having the recirculation zone of the wake extend to this location is characteristic of a laminar boundary separation, where a turbulent separation would occur at approximately ± 140 degrees from the leading stagnation point of the stack [15].

Also shown in Figures 2.3 is the coordinate system used in describing the experimental results. The origin of the coordinate system is located at the center of the exit plane of the flare. The stream-wise direction is $+x$, the upward vertical direction is $+y$, and the transverse direction that creates a right-hand coordinate system is $+z$. The characteristic velocity of the jet of flare gases exiting from the stack (V_j) is the volume flow rate of flare gases calculated at ambient pressure and temperature divided by the inside cross-sectional area of the flare stack.

2.1.3 Flare Gas Supply System

The fuel gases supplied to the flare were either sales-grade natural gas or commercial-grade propane. The compositions of these fuels were analyzed periodically throughout the project by gas chromatography. The average composition of the natural gas and propane are listed in Table 2.2 along with the maximum deviations from the mean found in any one sample. Also listed in Table 2.2 is the energy density of the mean fuel composition. This energy density reported here is the higher heating value of the fuel at 1 atmosphere pressure and 15°C.

Table 2.2: Fuel Gas Composition

Component	Sales-Grade Natural Gas (%)		Commercial-Grade Propane (%)	
	Mean	Max. Deviation	Mean	Max. Deviation
C ₁	94.96	1.30	0.18	0.24
C ₂	2.40	1.25	1.75	0.84
C ₃	0.06	0.01	97.66	1.07
C ₄	0	0.01	0.17	0.43
C ₅ ⁺	0	0	0	0
CO ₂	0.81	0.04	0	0.01
N ₂	1.74	0.07	0.06	0.06
H ₂	0	0	0.01	0.01
He	0.04	0	0	0
Energy Density (MJ/m ³)	37.52	0.33	94.46	0.37

Other gases added to the flare stream to alter its mass or energy density were carbon dioxide (CO₂) and nitrogen (N₂). A schematic of the gas supply system is shown in Figure 2.4. All of the gases were supplied from cylinders and their pressures were regulated to approximately 446 kPa (absolute) delivery pressure by two-stage regulators. The gases were piped separately by Teflon tubing from the regulators to metal coils of tubing placed in a constant temperature water bath before going through mass flow controllers that set the flow rates of the various gases. Once metered, the flare gases were piped to the flare. If more than one gas were being used, these gases would mix within the piping system upstream of the base of the flare.

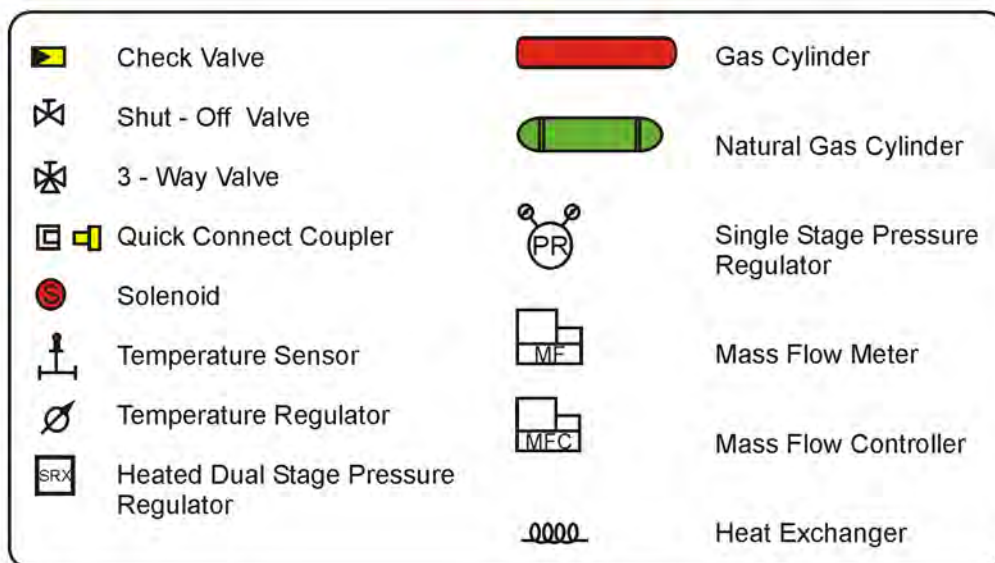
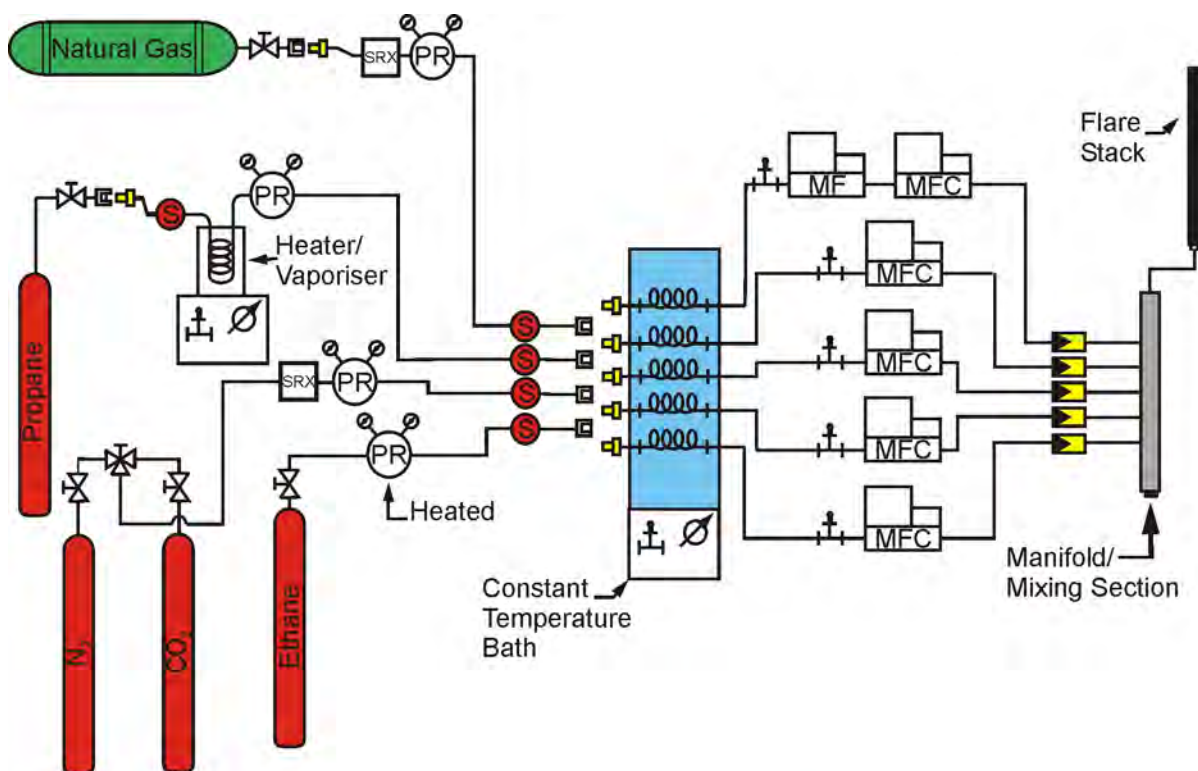


Figure 2.4: Schematic of the flare gas supply system

The constant temperature water bath in the fuel supply system was necessary because the mass flow controllers used were based on measuring the temperature rise of the metered gas when a small but fixed amount of energy is added to the stream. This type of meter requires that the specific heat capacity of the gas being metered remain constant. When gases are

extracted from high-pressure cylinders and the pressure is reduced, their temperature will also be reduced. Without a water bath, the gas temperature and its specific heat capacity at the meter becomes dependent on cylinder pressure and gas flow rate.

The flow rate of each gas type being controlled could be measured by one of several mass flow meters that had different ranges to provide an accurate measure of flow over a large dynamic range. It is important to note that all of the mass flow meters were calibrated for the gas type they were using through a gravimetric technique. The method used here for calibration resulted in an uncertainty in mass flow rate of approximately $\pm 1\%$ of full scale. Factory calibrations based on nitrogen flows that then applied correction factors for different gas compositions were found to be unacceptably inaccurate.

2.1.4 Diagnostic Equipment

Another important component to the University of Alberta Flare Research Facility was the diagnostic equipment used to measure various gas concentrations, gas velocities, and droplet sizes. Described here is only the general equipment that was used in the flare research project. Other equipment that was used for specific measurements that were applicable to only one aspect of the research is described within the chapter of interest.

2.1.4.1 Gas Analysis System

In order to measure combustion efficiency for either the whole flare or just locally within the plume of combustion products, the concentrations of the major carbon containing species expected from hydrocarbon combustion needs to be measured. The components that were measured were unburned hydrocarbons (HC), carbon dioxide (CO_2), and carbon monoxide (CO). The oxygen (O_2) concentration was also measured as part of determining the local combustion efficiency and to monitor the depletion of O_2 in the closed-loop wind tunnel during flaring tests.

The analyzers used were from the Rosemount Instruments NGA2000 series of analyzers. The HC concentration was measured using a flame ionization detector (FID). The

concentrations of CO₂ and CO were measured by a non-dispersive infrared (NDIR) technique, and O₂ was measured with a paramagnetic device.

The combined uncertainties of repeatability and linearity quoted by the manufacturer for all these devices were +/-1% of full scale. To avoid problems of analyzer drift, which is a particular problem for the NDIR units, calibrations were performed twice daily. The span gases used for calibration were Primary Master grade and had an uncertainty in concentration of +/-1%. The meter's linearity was checked with the same grade of mid-span gases. A schematic of the sampling and conditioning system used for measuring the concentration of HC, CO₂, CO and O₂ is shown in Figure 2.5.

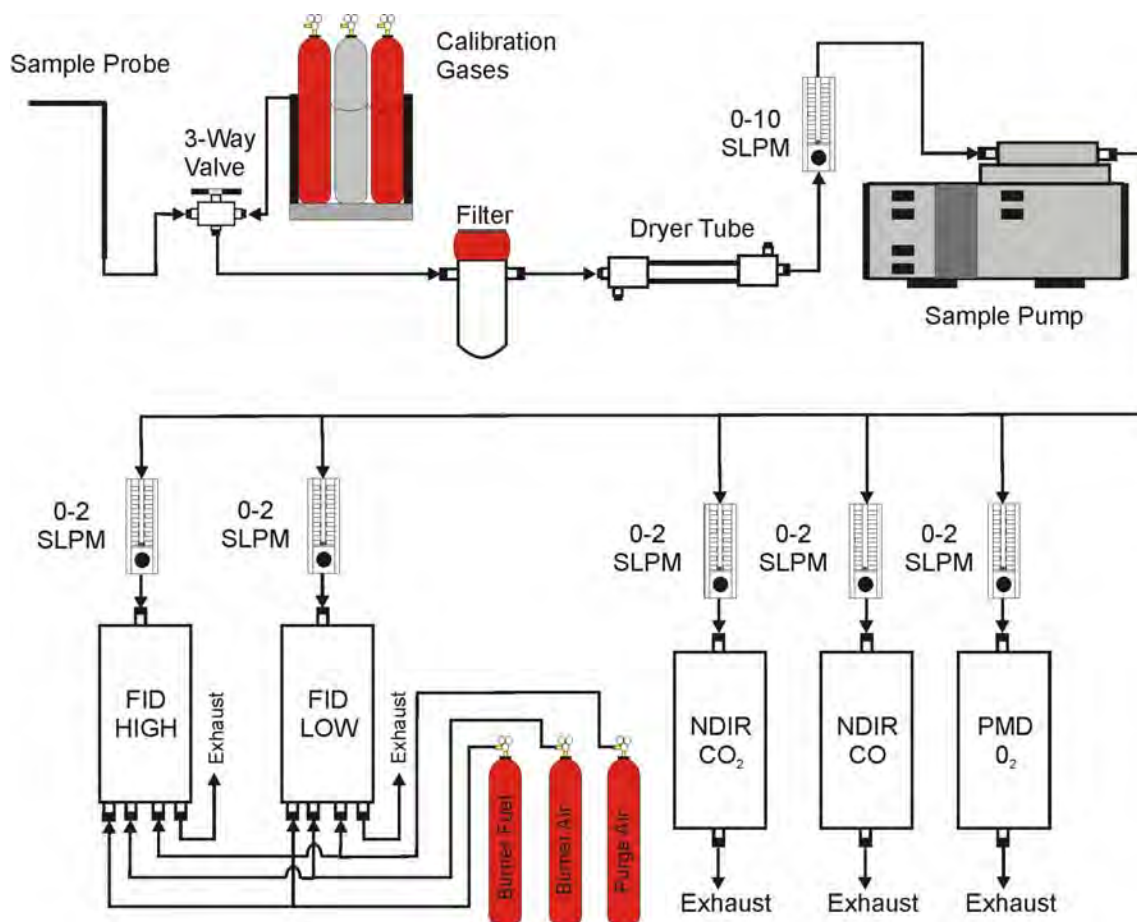


Figure 2.5: Schematic of the gas sampling system for measuring concentrations of major carbon containing species in the wind tunnel

The method of sampling and location of the sampling probes in the wind tunnel depends on the type of experiment being conducted. The process of sampling the products of

combustion after they have been fully mixed with the tunnel air in order to estimate the overall combustion efficiency of flares is discussed in Chapter 3. The sampling of the near plume of the flare to determine local combustion efficiency is described in detail in Chapter 5.

2.1.4.2 Velocity Measurement

Laser Doppler Velocimetry (LDV) and Hot-Wire Anemometry (HWA) systems manufactured by TSI Inc (IFA650 correlator/9230 receiver and Flowpoint 1500, respectively) were used for measuring the velocity of gas flows. Since HWA does not require the flow to be seeded, it was used to measure the mean velocity and the turbulence in the test section of the wind tunnel. The measurement element of the hot-wire probe was 3 mm long and 0.004 mm in diameter, and could measure velocity fluctuations of the order of 3000 Hz. The flow exiting from the flare stacks was measured with the LDV system to measure the mean and fluctuating (turbulent) velocities of the flare stream. The probe size for the LDV system is estimated to be 1.3 mm long and 0.09 mm in diameter. The particles needed for the LDV were formed using light cooking oil and a blast atomizer and had a mass-mean diameter of approximately 4 μm . Droplets of this size range and density allowed the LDV to measure velocity fluctuations in the order of 5000Hz.

2.1.5 Flow Characteristics of the Tunnel and Flares

2.1.5.1 Crosswind Flow

One of the principle objectives of this research was to quantify the influence of the wind on the performance and emissions of flares. Winds in the atmosphere are highly variable in direction, speed, turbulence intensity, and the scale of turbulence. These characteristics are also a function of height within the atmospheric boundary layer and, as a result, it is difficult to duplicate all the features of the atmosphere in a wind tunnel facility. The pragmatic approach adopted in this research was to create only the important features of the wind.

Toward this goal, it is important to note that the upper portion of flare stacks and flames reside in a small horizontal slice in the atmospheric boundary layer. Within this slice of the atmosphere, the mean wind speed and its turbulence properties are essentially constant in the vertical direction. Therefore, the wind that the upper portion of the flares in the wind tunnel (see Table 2.1) were subjected to was made as uniform as possible, which also allowed them to be characterized by a single mean wind speed and turbulence properties.

Figure 2.6 shows representative mean velocity profiles along the two axes of symmetry of the test section at the stack location for a crosswind speed of 8 m/s with no turbulence generating devices in the tunnel. The mean velocity is essentially uniform between the boundary layers, which are approximately 12 cm thick at this position. The r.m.s. turbulent velocity fluctuation in the core flow of the tunnel without any turbulence generators (shown in Figure 2.6) was found to be consistently less than 0.4 % except at low wind speeds (<2 m/s) where this intensity rises to about 1.8%. Filtering the measured velocity time signal showed that this increase in turbulence at low wind speeds was a result of small, low frequency (<0.2 Hz) oscillations of the mean wind speed. These oscillations in wind speeds were associated with the control circuitry of the wind tunnel fan to maintain a fixed speed and were not turbulence.

Uniform grids of different size obstructions and blockage ratios could be placed upstream of the flare stack to create a uniform turbulent environment for testing the flares. The distance between the turbulence grid and flare stack could also be varied to alter the scale and intensity of the turbulence as seen by the flare. Flows created in this manner remain uniform over the core of the tunnel flow and could be characterized by a mean velocity, turbulence intensity, and turbulence length scale.

Turbulence scales larger than the flames were not considered as part of this study. These larger flow structures act on the flame as a whole and are unable to interact effectively with the reacting part of the flow. The time scales of these larger turbulent structures are much longer than the time scales associated with the combustion, and the expectation is that the flame sees them as a quasi-steady change in mean velocity. In contrast, the smaller scales of

turbulence are able to participate in the combustion by wrinkling the flame surface and augmenting the mixing of air into the flame. Also, since the flares tested were pipe flares with directional symmetry, no attempts were made to include varying wind direction in this study.

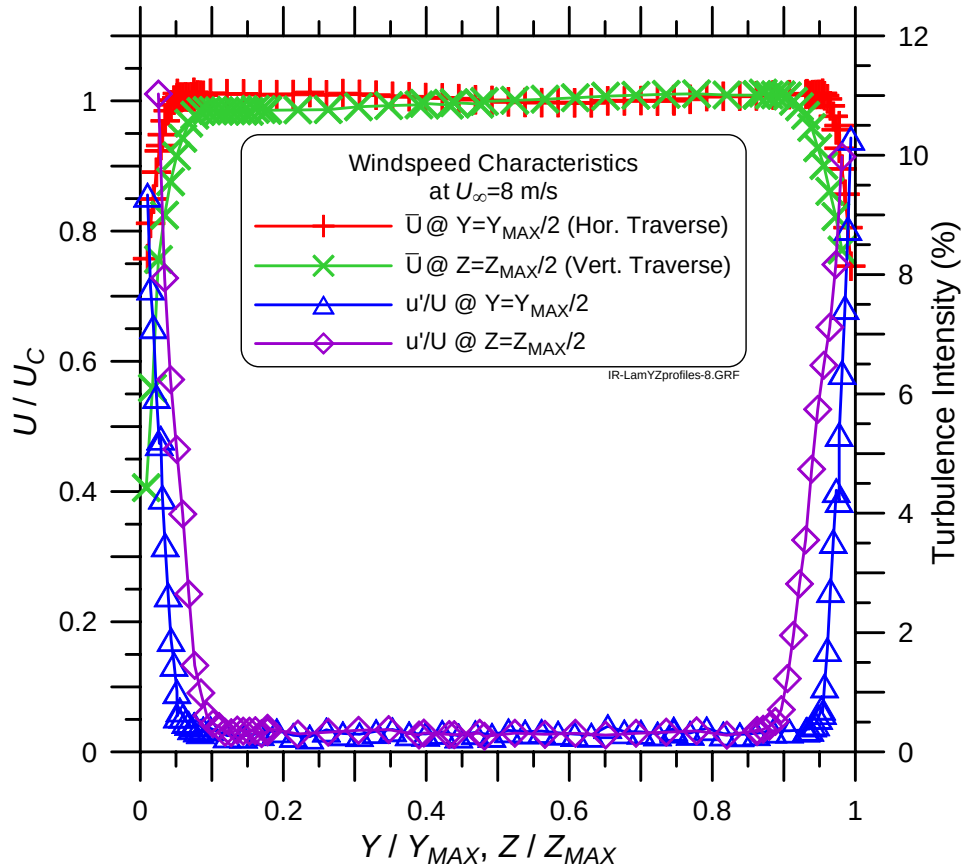


Figure 2.6: Horizontal and vertical velocity and turbulence intensity profiles across the test section of the wind tunnel at the location of the flare

2.1.5.2 Flare Gas Flow

Laser Doppler velocimetry was used to characterize the exit flow conditions of the flare stacks. Figure 2.7 shows profiles of the mean velocity and turbulence intensity 5 mm above the exit of the 24.7 mm diameter (d_o) flare and the perforated plug turbulence generator for a mean jet velocity (V_j) of 2 and 4 m/s. The characteristic velocity (V_j) is defined as the volume flow rate of flare stream at ambient conditions divided by the inside area of the burner tube. Also shown in Figure 2.6 is the mean velocity profile for high Reynolds number pipe flow [15]. This particular turbulence plug produced a mean velocity profile similar to

fully-developed turbulent pipe flow for Reynolds numbers as low as 2500 with a turbulence intensity of 10-15%.

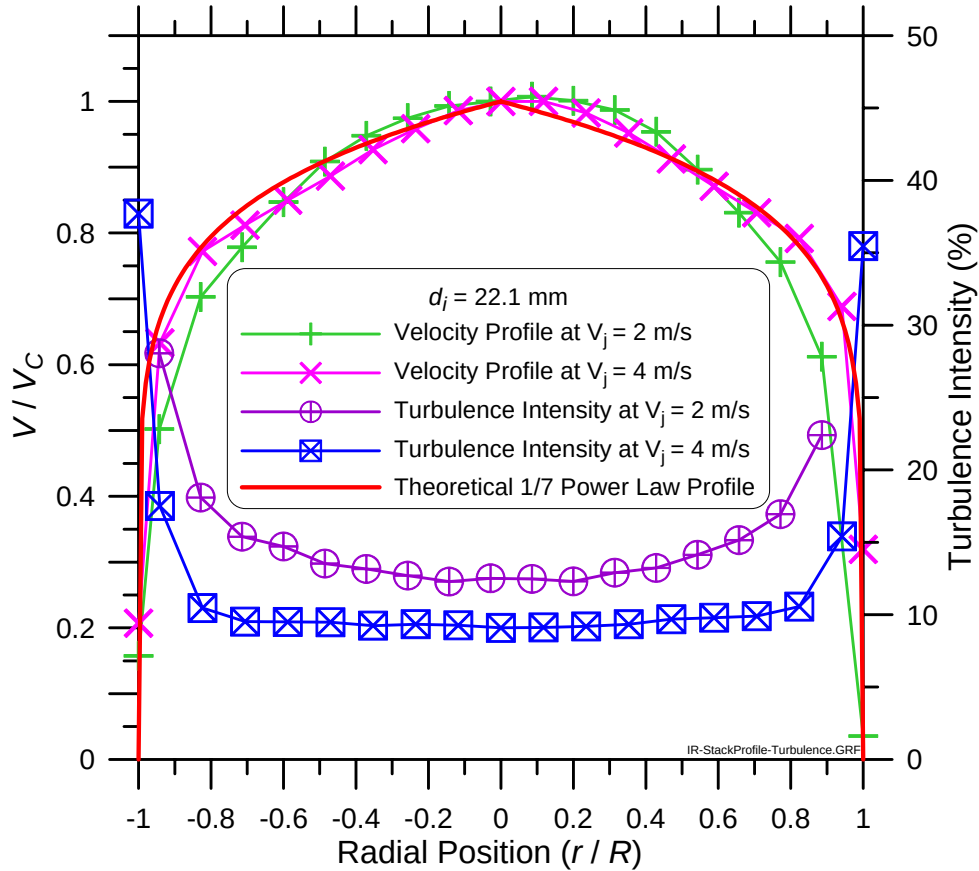


Figure 2.7: Internal velocity and turbulence intensity profiles for the 1-inch-nominal flare stack

2.1.5.3 Uniformity of Tunnel Gas Composition

As discussed previously, several auxiliary mixing fans were placed within the tunnel on either side of the main tunnel fan. The purpose of these auxiliary fans was to fully mix the plume of combustion products emitted from the flame into the bulk of the tunnel air. To determine the effectiveness of these fans, the uniformity of the tunnel gas composition was measured when tracer gases were introduced into the tunnel. The tracer gases were introduced at the stream-wise plane of the flare stack and measured at the stream-wise plane of the sample probe. The positions of both the sampling probe and flare are shown in Figure 2.1.

Several tests were conducted to test the uniformity of the tunnel gases. Fixed flows of heavier-than-air carbon dioxide (CO_2) and lighter-than-air methane (CH_4) were introduced into the tunnel from separate injectors. These gases were injected at ceiling or floor levels, and either in the center or off to the side of the tunnel. Tests were conducted at wind speeds ranging from 1 to 14 m/s, and the sample probe was moved both horizontally and vertical across the sampling plane of the tunnel. Using the ratio of the concentration of CO_2 to the concentration of CH_4 within any sample as a measure of the degree of mixing, the sample probe was moved to several locations to determine the spatial homogeneity in composition. In the worst case, the spatial variation in this degree of mixing was $\pm 0.3\%$ from the mean concentration ratio.

2.2 NRC FLARE RESEARCH FACILITY

The flaring research facility described below was located at the National Research Council in Ottawa, Ontario. The facility, part of the Institute for Aerospace Research, was originally designed and constructed in the 1960s for research related to aeronautics. In 2000, the U of A Flare Research Project modified this tunnel so that combustion experiments could be conducted within its test section. The sub-sections below describe the physical facilities of the tunnel employed as part of flare testing. As with the U of A facility, only the general equipment of the NRC facility is described in this section. The more specific equipment used for the particular components of the research will be described in Chapter 8 which covers the research conducted in this larger wind tunnel.

2.2.1 Single-Pass Wind Tunnel

The flaring facility at NRC Ottawa is shown schematically in Figures 2.8, 2.9, and 2.10. This facility was a single-pass wind tunnel such that ambient air was drawn into the tunnel, passed through the test section, and then discharged from the wind tunnel at the outlet. Unlike the closed-loop facility, fresh air was continuously brought into the wind tunnel and passed only once through the test section. The air was drawn into the wind tunnel by a 6 m diameter compressor section located very near the inlet to the tunnel. This air was passed to a plenum

that was 12 m in diameter and 26 m long. The combination of this size of plenum and the sections of screen placed at its discharge end attenuated the turbulence created by the compressor section. A contraction section with an area ratio of 4:1 accelerated the flow into the test section to create a near-uniform (see Section 2.2.5 for measurements of flow uniformity) crosswind that the flares were exposed to during testing. After passing through the test section the air was discharged at right angles to the inlet to avoid excessive ambient wind-driven flows in the tunnel. The driving force of the compressor was a 1050 kW DC motor capable of producing crosswinds of 39 m/s in the test section.

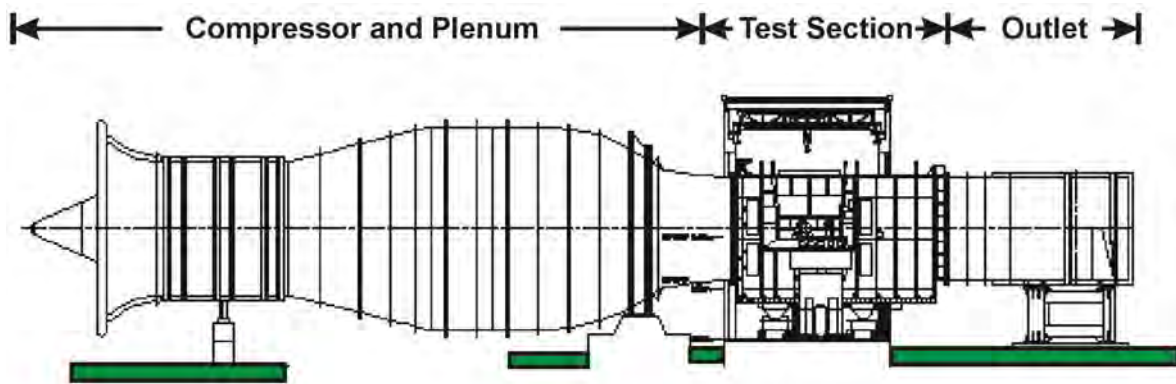


Figure 2.8: NRC Wind Tunnel - Side View

As shown in Figure 2.9, the wind tunnel test section was equipped with an overhead crane to remove the roof section and allow equipment to be installed in the test section. The observation windows were used to monitor tests and to photograph the flame.

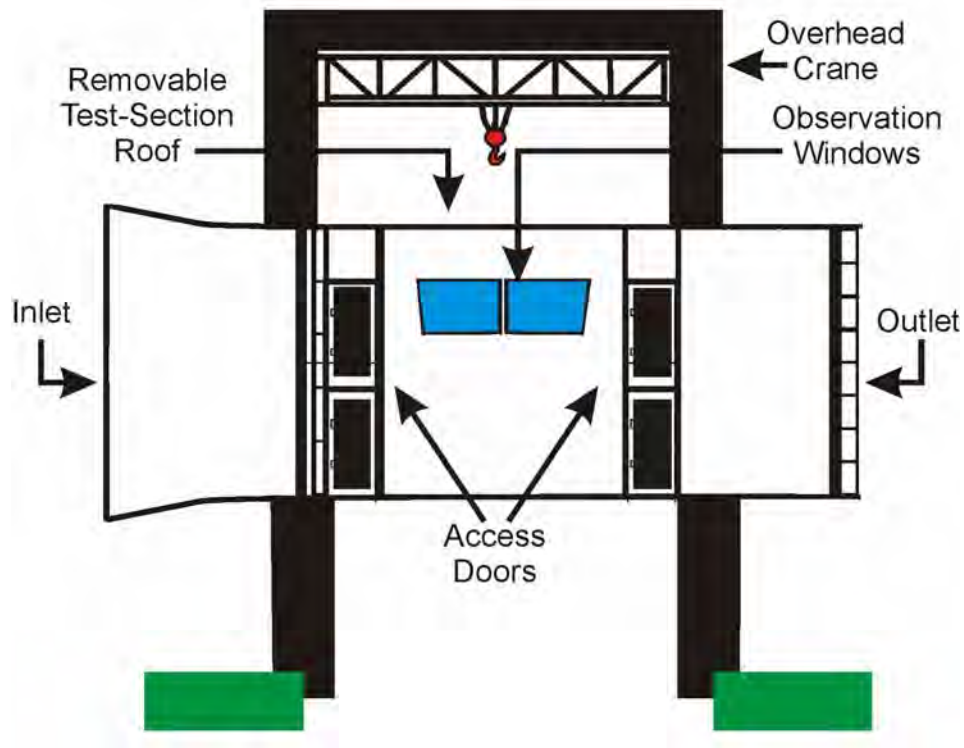


Figure 2.9: NRC Wind Tunnel Test-Section Exterior – Side View

The interior of the test section of the wind tunnel measured 3.05 m wide by 6.10 m high with a length of 13.0 m. As shown in Figure 2.10, the wind tunnel contained aerodynamic fairings in the corners. These fairings decreased in size from the front of the test section to the back of the test section in order to account for the boundary layer growth along the walls, ceiling, and floor. This configuration of fairings insured a constant mean velocity along the length of the test section.

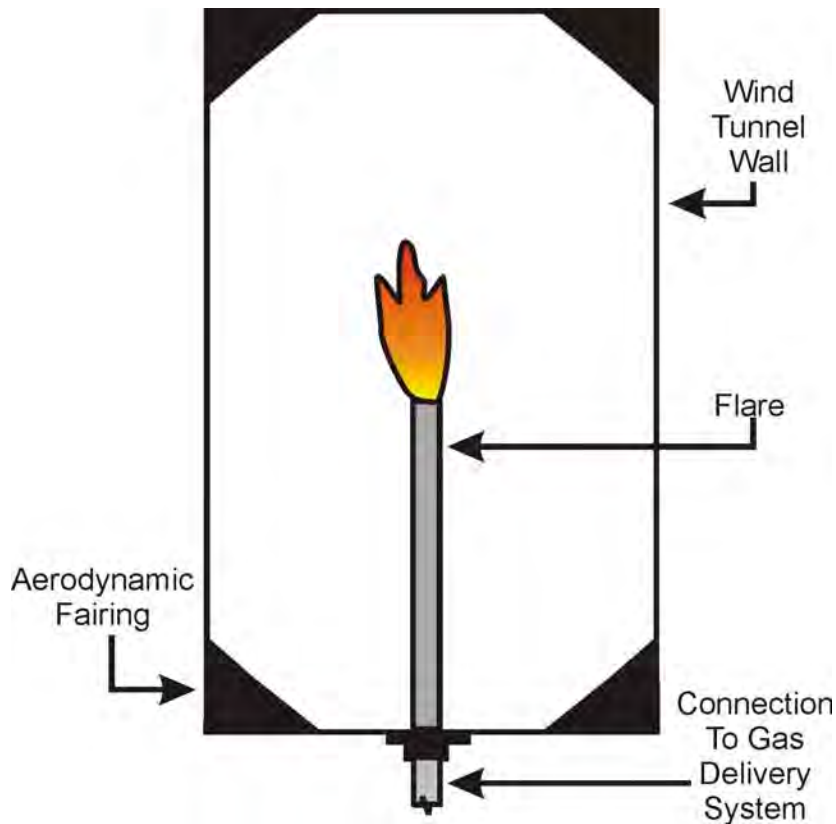


Figure 2.10: NRC Wind Tunnel Test-Section Interior – Stream-Wise View

2.2.1.1 Auxiliary Equipment

A retractable hydrogen flame ignitor, similar to the one explained in Section 2.1.1.1, was used to light the flare as shown in Figure 2.12 as part of the flare gas supply schematic. The system consisted of a fuel source of compressed commercial-grade hydrogen connected by flexible Teflon tubing to a 6 mm diameter rigid steel tube. This steel tube could be manually extended and retracted into the wind tunnel through an access port in the wind tunnel wall such that its tip could be placed immediately above the exit of the flare stacks for ignition purposes. The hydrogen flame itself was ignited by a manually operated high-voltage sparking system. The ignition spark took place between the tip of the steel tube and an internally mounted electrode with an insulated connecting wire led back through the steel tube to a standard automotive sparking system. In order to ignite the flare, the steel tube was extended above the flare stack tip, the hydrogen fuel was turned on, and the ignition system was activated. It is only after the ignition of the hydrogen flame that the relatively large

volume flow rate of flare gases was allowed into the wind tunnel. Once the flare was ignited, the hydrogen flame was extinguished by shutting off its fuel supply and the steel tube was retracted back to the wind tunnel wall so that it would not cause any flow disturbances near the flare stack tip.

Wind speed was measured at the inlet of the test section with two Pitot-static tubes that were mounted on both wind tunnel walls and protruded into the airflow. The tubes were connected to independent pressure transducers that were monitored by two separate computers. One of these computers was the master-control computer operated by researchers managing flare tests and collecting data. The other computer was operated by an NRC technical officer as part of monitoring and setting the desired wind speed. The wind speed was set manually by using a pair of analog potentiometers (for coarse and fine adjustments) to control the current delivered to the wind tunnel's 1050 kW DC motor.

Figure 2.11 displays the three-dimensional traverse installed in the test section downstream of the flare stack. The traverse was computer-controlled in the vertical and cross-stream directions. Positioning in the stream-wise direction was done manually on a set of rails installed in the wind tunnel. The traverse could be programmed to follow a predetermined two-dimensional grid pattern behind the flare stack to acquire data. Servomotors facilitated movement of the traverse probe in the horizontal and vertical directions, respectively, with a spatial accuracy of ± 5 mm in both directions. Either a single-point gas sampling probe or the multi-point thermocouple system (the thermocouple "rake") could be attached to the traverse probe mount plate — both systems will be described later in Chapter 8.

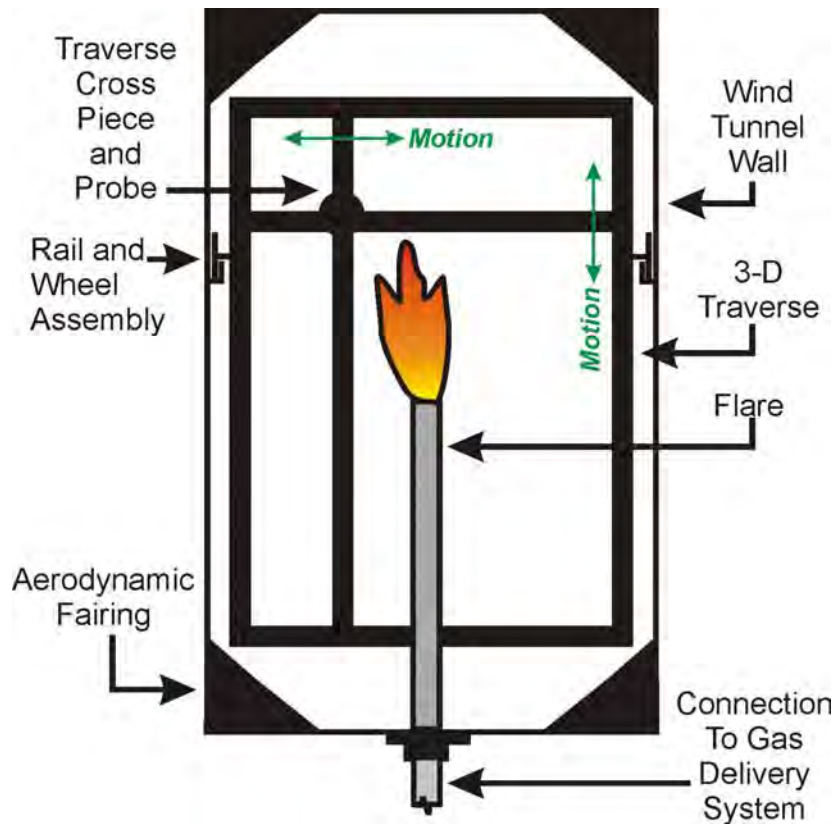


Figure 2.11: Interior of NRC Wind Tunnel with Traverse – Stream-Wise View

The traverse system was equipped with a wheel on either side as shown in Figure 2.11. These wheels were set in rails mounted on the wind tunnel walls in order to position the traverse in the stream-wise direction. The traverse could be positioned up to 8 m downstream of the flare stack. The traverse was locked in position using four hydraulic pistons mounted at each corner of the traverse.

2.2.1.2 Safety Features

The wind tunnel at the NRC was renovated extensively to incorporate the latest fire and safety equipment as required by Ontario provincial regulations. These renovations included gas detectors mounted outside the test section to monitor hydrocarbon and carbon monoxide concentrations. This system was fully integrated with the campus-wide fire and safety monitoring system at the NRC. In addition, much of the electrical wiring was replaced and brought up to current code specifications.

2.2.2 Flare Stacks

As mentioned previously, typical flare stacks operating in Alberta as solution gas flares were constructed from standard four-inch schedule 40 pipe. At the NRC facility it was possible to test flares of this size, but, in order to provide continuity with the sub-scale flares tested at the U of A facility, some sub-scale flares were also tested at the NRC facility. This continuity was important in order to show that the data from both facilities were consistent with each other and that any scaling relationship developed would be equally consistent. As with the closed-loop tests, these tests used smaller flares that were machined to maintain the same d_i/d_o ratio characteristic of four-inch pipe. The flares used at the NRC facility are listed in Table 2.3.

Table 2.3: Dimensions of Solution Gas Flares Used at NRC

Nominal Scaling to Full-Scale	Inner Diameter d_i, (mm)	Outer Diameter d_o, (mm)	d_i/d_o	H/d_o Exposed to Wind	Equivalent Full-Scale Stack Length Exposed to Wind, (m)
1	102.3	114.3	0.9	26.7	3.05
1/2	52.6	58.8	0.9	51.9	5.93
1/4	26.9	30	0.9	101.7	11.6

2.2.3 Flare Gas Supply System

The flare gas supply system was designed so that the flare could burn sales-grade natural gas as depicted in Figure 2.12. This gas was introduced into the wind tunnel building through a 50 mm diameter pipe with a gauge delivery pressure of 350 kPa. Once in the building, the gas encountered a series of manual safety valves and computer-controlled shutoff valves before passing through a constant-temperature water bath. The gas traveled through metal coils immersed in this water bath in order to stabilize the gas temperature at approximately $293\text{ K} \pm 1\text{ K}$. This constant temperature was needed since the mass flow controllers (MFC) are sensitive to gas temperature and were calibrated to measure the gases at this specific inlet

temperature. The fuel then passed through one of these seven computer-controlled MFCs. Each MFC was calibrated for a specific flow rate range. This collection of MFCs could deliver flow rates of gas between 0 and 30, 100, 500, 1000, or 3000 slpm. The MFCs had an accuracy of $\pm 1.0\%$ of their individual full-scale and were calibrated by the manufacturer for natural gas. The gas temperature was measured with a solid-state analog temperature sensor before being sent to the flare stack to ensure the water bath was maintaining its set point.

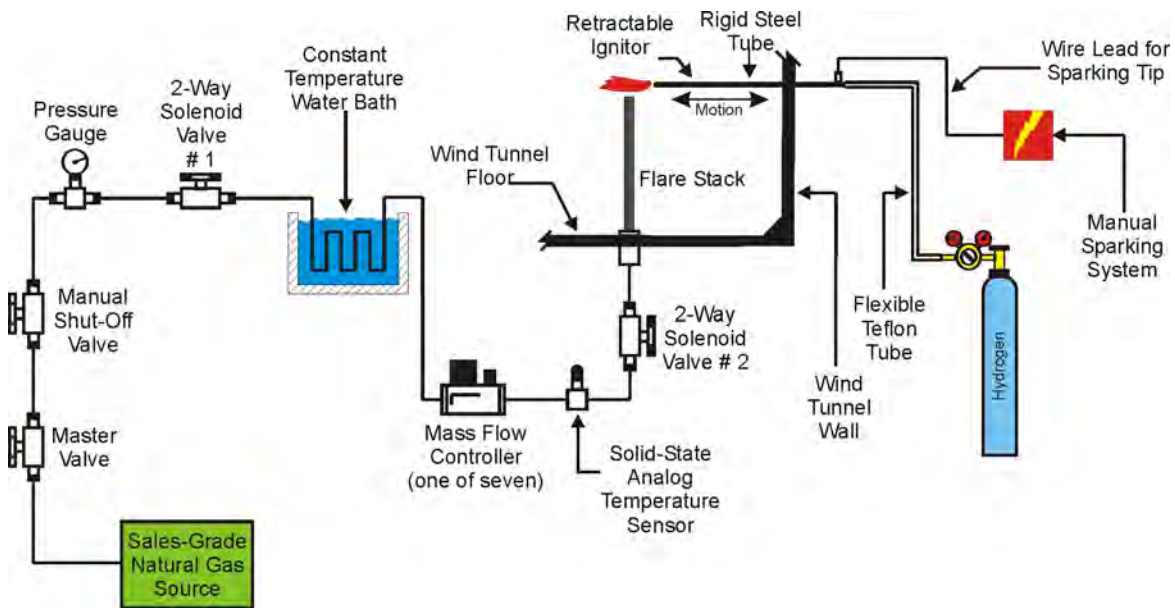


Figure 2.12: Gas Supply System at NRC

2.2.4 Gas Analysis System

Figure 2.13 provides an overview of the gas analysis system. The flow path of the sampled gases from the sampling probe (described in detail in Chapter 8) to the analyzers involved a few processes. After leaving the tunnel the sample was carried in a heated sample line that maintained the gas sample at 333 K to avoid any condensation at that stage. The sample was then passed through a thermo-electric cooler set to 268 K to remove the water vapor in the sample at that corresponding saturation pressure and thereby avoid any accumulation of damaging water in the analyzers. Following the condenser, any particles larger than 3 micrometers were removed by a fiber filter. The flow was then passed through calibrated rotameters to ensure that the correct flow of gases was passed through each of the analyzers.

The flow in the sample lines was driven by vacuum pumps that were located either upstream or downstream of the analyzers depending on whether the analyzer worked either at positive or negative pressure relative to ambient conditions. After the gases were analyzed they were exhausted back into the tunnel downstream of the flare. A series of valves existed in the sampling system to allow samples of ambient air to be drawn from upstream of the flare or to pass calibration gases through the analyzers. Also included in the gas sampling system were cylinders of reference gases and fuels for the normal operation of the gas analysis equipment.

The sampling system could measure concentrations of CO₂, CO, CH₄, and O₂ in the sampled gases. The analyzers used consisted of a Siemens Ultramat 6E (CO₂ and CO), a Siemens Oxymat 6E (O₂), and a Horiba FIA-510 (CH₄). The flow rate of sampled gas delivered to the analyzers was approximately 0.5 l/min for the CH₄ analyzers and 1.0 l/min for the CO₂, CO, and O₂ analyzers. Given a total sampling rate of 3.5 l/min and the total length of 15 m of 6 mm sample lines, the system incurred a sampling delay of approximately 15 s. This sampling delay was incorporated into the data acquisition system and the data were recorded at 2 Hz and time-averaged over 30 s periods to capture an accurate mean concentration of measured components in the gas sampled. Each analyzer was calibrated at the beginning of each day of experiments. Gravimetrically-prepared primary master calibration gases balanced with nitrogen were used. Table 2.4 lists the calibration gases used along with the reported accuracies.

Table 2.4: Specifications of Calibration Gases

Calibration Gas	Concentration	Accuracy
CO ₂	500 ppm	± 25 ppm
CO ₂	1500 ppm	± 75 ppm
CO	10 ppm	± 0.5 ppm
CO	40 ppm	± 2 ppm
CH ₄	10 ppm	± 0.5 ppm
CH ₄	100 ppm	± 5 ppm
O ₂	20.9%	± 0.4 %

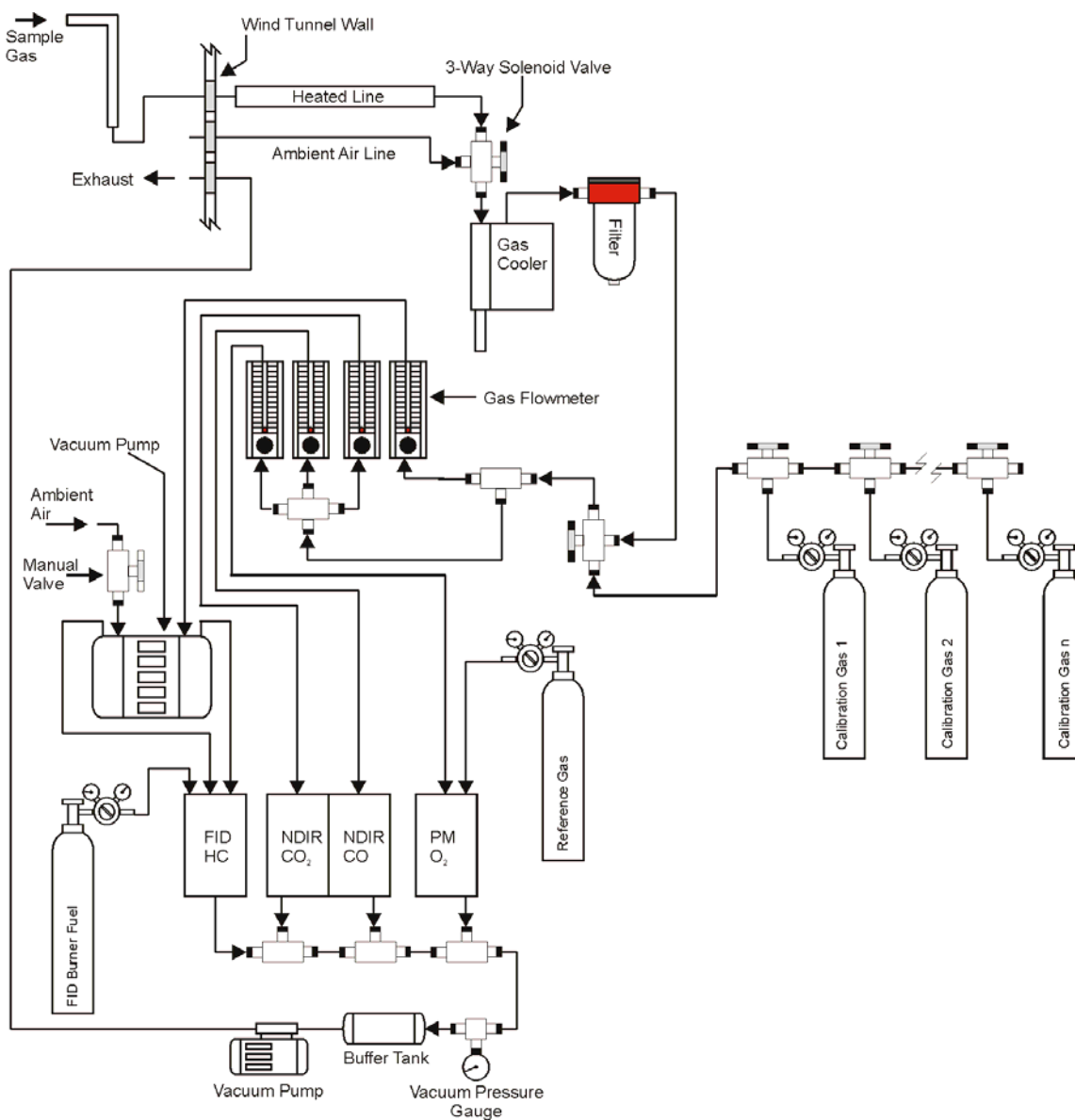


Figure 2.13: Gas Analysis System at NRC

The Siemens Ultramat 6E uses two separate non-dispersive infrared (NDIR) detectors that measure concentrations of CO₂ and CO. In each analyzer, an infrared beam was focused through two separate test cells, one housing a reference gas and the other housing the gas sample to be analyzed. After the beams exited the two test cells, they were compared for the difference in energy intensity. This energy difference between the two beams was caused by

absorption of the beam by the gas sample and was used to generate an electric signal proportional to the concentration of CO₂ or CO.

The Siemens Oxymat 6E was a paramagnetic detector. This detector used of the paramagnetic properties of O₂ for detection purposes. O₂ molecules from the gas sample were placed in an inhomogeneous magnetic field that attracted the molecules in the direction of increased field strength. This process induced a pressure differential across a test cell that produced an electrical signal proportional to the pressure differential. The concentration of O₂ was then calculated based on this signal.

The Horiba FIA-510 is a flame ionization detector (FID). Within the unit a hydrogen flame was used to combust the gas sample, causing carbon atoms in the sample to emit ions. This process produces a trace ionization current across two electrodes near the flame, which was directly proportional to the number of carbon atoms as hydrocarbons burned in the sample.

The NDIR and paramagnetic detectors produced outputs of 0-20 mA, which were converted to 0-10 V DC signals using a resistor. The FID produced a 0-10 V DC output. All outputs were relayed to data acquisition cards installed in the master-control computer (discussed later). The specifications of the individual analyzers are listed in Table 2.5.

Table 2.5: Specifications of Gas Analyzers Used at NRC

Detector		Range	Drift	Repeatability	Uncertainty
Name	Type				
Ultramat 6E	CO ₂	0-10 ⁴ ppm	< ±1% of range / week	< 1% of range	100 ppm
Ultramat 6E	CO	0-200 ppm	< ±1% of range / week	< 1% of range	2 ppm
FIA-510	CH ₄	0-500 ppm	< ±1% of range / day	< 0.5% of range	2.5 ppm
Oxymat 6E	O ₂	0-25 %	< ±0.5% of range / 3 months	< 1% of range	0.25%

Three computers controlled all aspects of experimentation and data acquisition at the NRC facility. Slave computer # 1 was dedicated to receive data from the mass flow controllers

and was connected to all valves in the fuel delivery system. Slave computer # 2 was devoted to acquire data from the temperature measurement apparatus. The third computer acted as the master-control computer. This master computer controlled all aspects of the fuel delivery system and the motorized traverse, and monitored the tunnel wind speed, ambient temperature, and ambient pressure. It collected data from the plume sampling system and all the experimental data acquired by the two slave computers for the purposes of processing and storage.

All three computers operated on Windows 2000/NT platforms and were connected via a local area network (LAN). Data acquisition and control software was developed exclusively with LabVIEW (National Instruments) computer code. The master computer generated a file for each test that contained important parameters such as ambient temperature, ambient pressure, tunnel wind speed (set and actual), fuel flow rates, and gas analyzer readings.

2.2.5 Flow Characteristics of the Tunnel

As mentioned previously, this wind tunnel was capable of attaining crosswinds of 39 m/s. During the course of testing, however, the facility was used for lower crosswind speeds in the order of 2 to 14 m/s. The wind tunnel velocity profile was tested for stability and uniformity over the speed range required for the experiments. In this context, flow stability refers to the ability of maintaining a steady mean flow over a period of time comparable to the duration of an experiment (approximately one hour). Since the wind tunnel was open to the atmosphere this stability could be affected by changes in ambient wind conditions. In order to measure this velocity stability, a Pitot-static tube was positioned in the centre of the test section at what would be the flare stack tip location if a 3.05 m stack were installed. The probe was maintained at this position for several hours while crosswind speed was sampled at 5 Hz. While at this position, the wind speed was set nominally to three different wind speeds (2, 5, and 8 m/s). The mean crosswind speed and speed fluctuations were found for each data set as shown in Table 2.6. The fluctuating component (u_{∞}^*) of speed is the first standard deviation of the recorded velocities.

Table 2.6: NRC Crosswind Characterization

Set Crosswind Speed, U_{∞} (m/s)	Measured Mean Crosswind Speed (m/s)	Fluctuations, u_{∞}^* (m/s)	Fluctuations Intensity, $u_{\infty}^* / U_{\infty} \times 100\%$ (%)
2	2.39	0.23	9.6
5	5.13	0.21	4.2
8	8.23	0.15	1.8

The speed fluctuations for tests conducted with wind speeds of 5 m/s or greater in the wind tunnel were deemed to be within an acceptable range (less than 5%). As wind speeds were reduced below 5 m/s and approached 2 m/s, crosswind speed fluctuations became large and potentially problematic. For tests conducted when the wind speeds were less than 5 m/s care was taken to choose days when the atmospheric conditions were stable. Mean cross-sectional thermal and compositional mappings were generated at wind speeds as low as 2 m/s. However, when interpreting these data, the issue of flow stability should be considered.

Figure 2.14 displays a typical three-dimensional velocity mapping of the test section of the wind tunnel that was made with a single Pitot-static tube. These measurements were only made in the core of the tunnel (2.5 by 4 m) because of the mounting system used to connect the Pitot-static tube to the traverse. Over that portion of the test section, the mean velocity was approximately 8 m/s and the single-point deviation from that mean ranged from 7.8 to 8.35 m/s. Given that mapping these velocities took several hours with a single probe, it would be expected that a component of these deviations would result from the temporal stability of the wind tunnel discussed previously. In fact, two standard deviations in the temporal mean velocity was ± 0.32 m/s (i.e., the expected uncertainty associated with 90 % of the measurements 19 times of 20), which could account for essentially all of the perceived spatial variation shown in Figure 2.14. Therefore, the uniformity of the wind speed in the test section was judged to be acceptable for this research

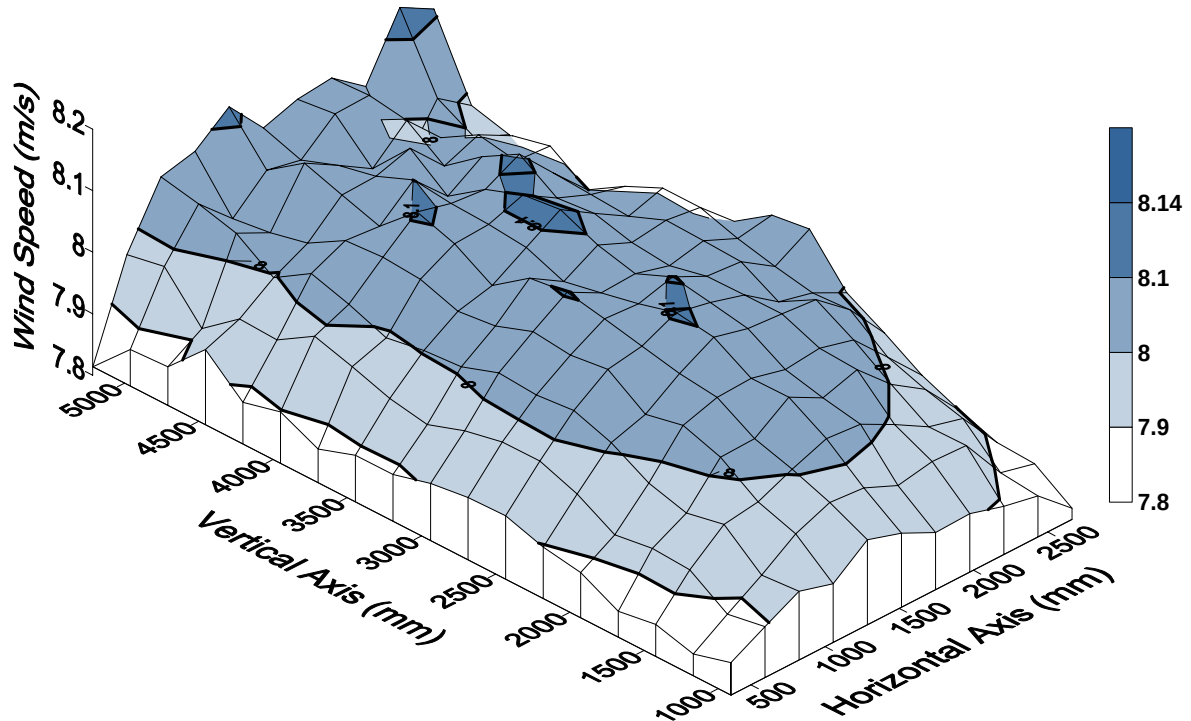


Figure 2.14: Typical velocity profile at stack-tip height in NRC wind tunnel for $U_{\infty} = 8$ m/s using a Pitot-static tube. Horizontal and vertical axes, in millimetres, relative to wind tunnel floor and wall, respectively

2.3 CONCLUDING REMARKS

The University of Alberta Flare Research Facility and the flaring research facility at the National Research Council of Canada were developed to study the emissions, efficiency, and the related fluid mechanics of flares in a crosswind.

The centerpiece of the University of Alberta facility was a closed-loop wind tunnel that was capable of testing flares up to 49.8 mm in diameter at wind speeds of up to 35 m/s. The test section of the facility was 1.22 m high and 2.44 m wide. The crosswind flow within the facility was characterized in terms of mean and turbulence profiles across the test section. These measurements showed that the velocity profile, outside the boundary layers of the walls, in the test section of the tunnel was essentially uniform. The turbulence in the test section was also uniform and could have intensities as low as 0.4 %, but could be increased by adding an obstruction upwind of the flare.

The flares at the University of Alberta facility could be supplied with mixtures of natural gas, propane, ethane, carbon dioxide, nitrogen, and liquid droplets of various sizes that were composed of either water or hydrocarbon fuels. The flares used in the facility were shown to have similar velocity profiles to those expected from solution gas flares in the field. The diagnostic equipment used to make measurements included a suite of on-line gas analyzers, a laser Doppler velocimeter, a hot-wire anemometer, and a particle size analyzer.

The centerpiece of the National Research Council of Canada facility was a single-pass wind tunnel that was capable of testing flares up to 114.3 mm in diameter at wind speeds of up to 39 m/s. The test section of the facility was 6.1 m high and 3.05 m wide. The crosswind flow within the facility was characterized in terms of stability in the mean and uniformity across the test section. For wind speeds above 5 m/s the stability and uniformity were less than 5 % of the mean, while below that velocity care needed to be taken to conduct experiments on days that had stable atmospheric conditions. Turbulence measurements were not conducted on this facility. The flares at the National Research Council could be supplied with natural gas. The diagnostic equipment used to make measurements included a suite of on-line gas analyzers similar to those found at the U of A facility.

3 EFFICIENCY OF NATURAL GAS AND PROPANE FLARES

This chapter provides a substantial investigation into the efficiency of natural gas and propane flares. The chapter begins with the formal definition of flare efficiency used in this research, to quantify the ability of a flare to convert carbon in the fuel stream to carbon dioxide. The methodology is then presented that was used to accurately determine the efficiencies of flares experimentally when the combustion products are predominantly gaseous. Before presenting results of efficiency measurements, details of an exploration into the origins of the inefficiencies are provided. In order to discover the origins of the inefficiencies, the products of combustion were analyzed chemically and two independent techniques were applied to identify their temporal nature and spatial beginnings. Once the issue of the origins and nature of the efficiency has been dealt with, the focus of the research will return to the results of measuring the efficiency of natural gas and propane flares. The approach taken in presenting the results was to consider the relatively simple case of a single flare gas composition of either natural gas or propane. Data is then presented to show the independent influences of crosswind speed, flare gas exit velocity and flare diameter. At this point, a preliminary phenomenological model is presented which is based on the relative magnitude of momentum and buoyancy fluxes. This preliminary model solidifies the functional dependencies of the basic fluid mechanics involved in flaring in a crosswind before introducing the complexities of altering the flare stream composition. Data from widely varying amounts of inert compounds being added to the flare stream are then presented and a semi-empirical model is used to collapse them to a single modeled curve for each fuel type.

This research and the accompanying models were developed at the University of Alberta (U of A) Flare Research Facility on sub-scale flares. This work was subsequently supported by experiments done using larger-scale flares at the National Research Council of Canada Flare Research Facility. This latter work will be presented in Chapter 8 along with a comparison of the results presented here.

3.1 DEFINITION OF FLARE EFFICIENCY

In characterizing the performance of a flare, it is convenient to define a term called the “efficiency” of the flare. Several similar definitions of efficiency have been proposed and used previously [16]. The most rigorous and useful definition of these is properly termed a “conversion efficiency” which quantifies the effectiveness of a flare to fully oxidize a fuel. For a flare burning a mixture of hydrocarbon fuels, the relevant parameter is the “carbon conversion efficiency” which is defined in terms of a rate as follows:

$$\eta = \frac{\text{Mass Rate of Carbon in the Form of CO}_2 \text{ Produced by the Flame}}{\text{Mass Rate of Carbon in the Form of Hydrocarbon Fuel Exiting the Flare}} \quad (\text{Eq. 3.1})$$

This mass-based definition is indicative of the mass conservation equations that are used in its calculation as described in the next section. Although properly called the “carbon conversion efficiency”, this term is often referred to as the “combustion efficiency”. Throughout this report, the terms “efficiency”, “flare efficiency”, and “combustion efficiency” will be used as synonyms for the carbon conversion efficiency, η , and will be reported as a percentage.

Finally, it is worth noting that for flares containing sulphur-based fuels (e.g., H_2S), a second efficiency parameter is required to characterize the performance of the flare – the sulphur conversion efficiency, η_s .

$$\eta_s = \frac{\text{Mass of Sulphur in the Form of SO}_2 \text{ Produced by the Flare}}{\text{Mass of Sulphur in the Form of Sulphur Based Fuel Exiting the Flare}} \quad (\text{Eq. 3.2})$$

This parameter quantifies the ability of a flare to completely oxidize sulphur-based fuels and is also determined using mass conservation equations. The value of η and η_s will not necessarily be the same for flares that have blended streams of hydrocarbon and sulphur-based fuels. Only hydrocarbon fuels are considered in this report.

3.2 METHODOLOGY FOR MEASURING EFFICIENCY

The methodology for measuring the efficiency of a flare using the closed-loop wind tunnel has been described in detail previously [17]. In principle, the procedure is straightforward in that the closed-loop wind tunnel acts as a reaction vessel in which a flare is burned and the product gases are collected, contained, and analyzed. In practice, there are several complexities that must be carefully considered to ensure the accuracy of the methodology.

Theoretically, one could simply burn a flare for a fixed period of time at a specified flow rate and measure the change in concentration of CO₂ in the tunnel between the start and end of this time. Knowing the volume of the tunnel and the composition of the flare gas, one could then calculate the efficiency. This approach introduces several uncertainties and other problems in maintaining the integrity of a mass balance that significantly reduce its expected accuracy. The uncertainties include accurately measuring the gas flow rate, absolute concentrations of CO₂ in the tunnel, and volume of the tunnel. The mass balance problems include properly accounting for tunnel leakage (exfiltration and infiltration), ignition transients, temperature changes during experiments, and reburning of combustion products that are recirculating in the tunnel. Instead, the approach employed here was to use an online, real-time gas analysis of the accumulation rates of the major carbon species in the tunnel to calculate the efficiency. Using the accumulation rates of species at early times in the experiment provides a technique to overcome the potential uncertainties and problems mentioned above.

Equation 3.3 is an expression of the conservation of mass for the accumulation of carbon dioxide (CO₂) in the wind tunnel. Unfortunately, there are 9 unknowns, including Q_{in} , Q_{out} , $Q_{CO_2,emit}$, $Q_{combust}$, and V , all of which are difficult to measure.

$$\underbrace{V \frac{d}{dt}(\rho_{CO_2} Y_{CO_2})}_{\text{Accumulation of CO}_2 \text{ in tunnel}} = \underbrace{\rho_{CO_2, \infty} Y_{CO_2, \infty} Q_{in}}_{\text{Transport into tunnel due to infiltration}} - \underbrace{\rho_{CO_2} Y_{CO_2} Q_{out}}_{\text{Transport out of tunnel due to leakage}} + \underbrace{\rho_{CO_2} Q_{CO_2, emit}}_{\text{CO}_2 \text{ produced and emitted by flare}} + \underbrace{\rho_{CO_2} Q_{CO_2, inert}}_{\text{Flow into tunnel as part of flare gas}} + \underbrace{\eta \rho_{HC} Y_{HC} Q_{combust}}_{\text{Addition of CO}_2 \text{ due to reburning of products}}$$

where Y_{CO_2} = concentration of CO_2 in the tunnel (Eq. 3.3)

$Y_{CO_2,\infty}$ = concentration of CO_2 in the ambient air

ρ_{CO_2} = density of CO_2 in the tunnel

$\rho_{CO_2,\infty}$ = density of CO_2 in ambient air

Q_{in} = volume flow rate of ambient air leaking into the tunnel

Q_{out} = volume flow rate of air leaking out of the tunnel

$Q_{CO_2,emit}$ = volume flow rate of CO_2 emitted by the flare

$Q_{CO_2,inert}$ = volume flow rate of CO_2 into tunnel as part of flare gas

ρ_{HC} = density of hydrocarbons in the tunnel

Y_{HC} = concentration of hydrocarbons in the tunnel

$Q_{combust}$ = volume flow rate of tunnel air consumed by the flare

V = internal volume of the windtunnel

η = carbon conversion efficiency of the flare

The volume flow rates of gases infiltrating and exfiltrating the tunnel are not independent quantities and are related by Equation 3.4, which has been written with the assumption that the flare gases exist only in the vapour phase (i.e., no liquid fuels). The methodology for measuring efficiencies of flares that contain liquid fuel droplets is discussed separately in Section 7.1.4.

$$\underbrace{Q_{out}}_{\text{Exfiltration}} = \left(\underbrace{Q_{in}}_{\text{Infiltration}} + \underbrace{\gamma Q_{fuel}}_{\substack{\text{Fuel in and molar imbalance} \\ \text{between reactants} \\ \text{and products}}} + \underbrace{Q_{inert}}_{\substack{\text{Inert gas} \\ \text{flow in fuel}}} \right) \frac{T}{\underbrace{T_{\infty}}_{\substack{\text{Heating of} \\ \text{wind tunnel} \\ \text{gases}}}} \quad (\text{Eq. 3.4})$$

where γ = ratio of moles of combustion products to moles of reactants

T = mean temperature of gases in the windtunnel

T_{∞} = temperature of ambient air

Q_{inert} = volume flow rate of inert gases entering with the flare gases

Q_{in} = volume flow rate of ambient air leaking into the tunnel

Q_{out} = volume flow rate of air leaking out of the tunnel

Q_{fuel} = volume flow rate of fuel in the flare gases

Combining Equations 3.3 and 3.4, and using the ideal gas law results in Equation 3.5, which is still an expression of the mass conservation of carbon dioxide, but still has four variables that are not easily measured: V , Q_{in} , $Q_{CO_2,emit}$, and $Q_{combust}$.

$$V \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) = \frac{Y_{CO_2,\infty} Q_{in}}{T_{\infty}} - \frac{Y_{CO_2}}{T_{\infty}} (Q_{in} + \gamma Q_{fuel} + Q_{inert}) + \frac{Q_{CO_2,emit}}{T} + \frac{\eta Y_{HC} Q_{combust}}{T} \quad (\text{Eq. 3.5})$$

Equation 3.5 is an ordinary differential equation that is valid at all times during an experiment. At different times during an experiment, some of the terms in this equation are dominant and will allow other terms to be neglected. For example, if an experiment were allowed to run in the wind tunnel for a very long time, the mass of carbon dioxide would rise to a constant value as the rate of leakage from the tunnel increased to match the rate of supply from the flare. Equation 3.5 would still be valid under these conditions, and the first term (the differential accumulation term) would drop to zero and eliminate the need for knowing the volume of the tunnel.

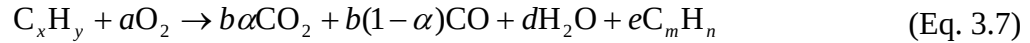
Alternatively, near the start of an experiment, several other simplifications are apparent. Shortly after the flame is ignited ($t = t_o$), conditions in the tunnel will exist such that $T \rightarrow T_{\infty}$, $Y_{CO_2} \rightarrow Y_{CO_2,\infty}$ and since Y_{HC} is negligibly small, the last term (addition of CO_2 due to reburning) is also negligible. Thus for $t \rightarrow t_o$, Equation 3.5 is reworked to form Equation 3.6, which is a valid statement of the conservation of mass of carbon dioxide in the wind tunnel at early times.

$$T_{\infty} V \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \bigg|_{t \rightarrow t_o} = -Y_{CO_2,\infty} (\gamma Q_{fuel} + Q_{inert}) + Q_{CO_2,emit} + Q_{CO_2,inert} \quad (\text{Eq. 3.6})$$

In principle, everything in Equation 3.6 is either known or measurable except the amount of carbon dioxide emitted by the flare, $Q_{CO_2,emit}$. Thus, it would be possible to use this expression to determine the mass flow rate of CO_2 emitted by the flare and use Equation 3.1 to calculate the efficiency. Unfortunately, there are problems associated with

accurately measuring the effective internal volume of a complex structure like a wind tunnel. Instead, it is possible to monitor the concentration of a few species in the tunnel and solve a system of equations to eliminate the need to know the internal volume of the wind tunnel.

Following the same procedure described above, similar mass conservation equations can be written for the accumulation of carbon monoxide (CO) and unburned hydrocarbons (HC) in the tunnel. In the case of flares that produce little or no soot, the overall combustion equation for a general hydrocarbon fuel (C_xH_y) can be written as shown in Equation 3.7.



where C_xH_y = general hydrocarbon fuel

a, b, d, e = unknown stoichiometric coefficients

α = molar fraction between fully oxidized carbon (CO_2) and partial oxidized carbon (CO)

C_mH_n = general hydrocarbon in the products of combustion

After algebraic manipulation, the coefficients in Equation 3.7 can be solved in terms of the variables in the three forms of Equation 3.6 (i.e. one mass conservation equation each for CO_2 , CO, and HC) and results in Equations 3.8-3.10.

$$\left. \frac{VT_\infty}{Q_{flare}} \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \right|_{t \rightarrow t_0} = -Y_{CO_2, \infty} (\gamma Y_{C_xH_y} + Y_{inert}) + \eta x Y_{C_xH_y} + Y_{CO_2, flare} \quad (\text{Eq. 3.8})$$

$$\left. \frac{VT_\infty}{Q_{flare}} \frac{d}{dt} \left(\frac{Y_{CO}}{T} \right) \right|_{t \rightarrow t_0} = -Y_{CO, \infty} (\gamma Y_{C_xH_y} + Y_{inert}) + \frac{(1-\alpha)}{\alpha} \eta x Y_{C_xH_y} \quad (\text{Eq. 3.9})$$

$$\left. \frac{VT_\infty}{Q_{flare}} \frac{d}{dt} \left(\frac{Y_{HC}}{T} \right) \right|_{t \rightarrow t_0} = -Y_{HC, \infty} (\gamma Y_{C_xH_y} + Y_{inert}) + x \left(1 - \frac{\eta}{\alpha} \right) Y_{C_xH_y} \quad (\text{Eq. 3.10})$$

where $Y_{C_xH_y}$ = mole fraction of hydrocarbon compounds in the flare gas

$Y_{CO_2, flare}$ = mole fraction of carbon dioxide in the flare gas

Y_{inert} = mole fraction of inert compounds in the flare gas

Q_{flare} = volume flow rate of flare gases

Inspection of these three equations reveals there are only three unknowns: η , V , and α , as all the remaining terms can all be measured experimentally. By taking ratios of these equations, the tunnel volume (V) can be eliminated from the two remaining but independent equations. Unfortunately, η and α remain coupled in these equations and it is not possible to write an explicit expression for combustion efficiency, but it can be solved for by iterative techniques. Further simplifications of Equations 3.8-3.10 are possible which provide a more physically-based expression for calculating efficiency. Specifically, by considering actual data from wind tunnel experiments, the terms involving ambient concentrations of CO_2 , CO and HC may be neglected because $Y_{\text{CO}_2,\infty} \sim 0.000350$, $Y_{\text{CO},\infty} \sim 0.000002$ and $Y_{\text{HC},\infty} \sim 0.000003$

Figure 3.1 shows the time traces of the measured concentration of CO_2 , CO , and HC as they accumulate in the closed-loop wind tunnel during a typical experiment. Initially the species exist at their ambient background concentrations before the flare is ignited. Following a brief mixing transient, the concentrations of all three species rise in a steady, linear fashion. The linearity of this rise is a validation for the assumption that mass fluxes other than those produced by the flare are small (i.e. the reburning term in Equation 3.5 is negligible). It is worth noting the magnitude of the species being measured in the tunnel during this typical experiment. The measured CO and HC concentrations at the end of the test are of the order of tens of ppm and were the reason to neglect reburning. The CO_2 concentration has risen to approximately 0.1 %, while the measured O_2 concentration dropped from 20.66 % to 20.51 %.

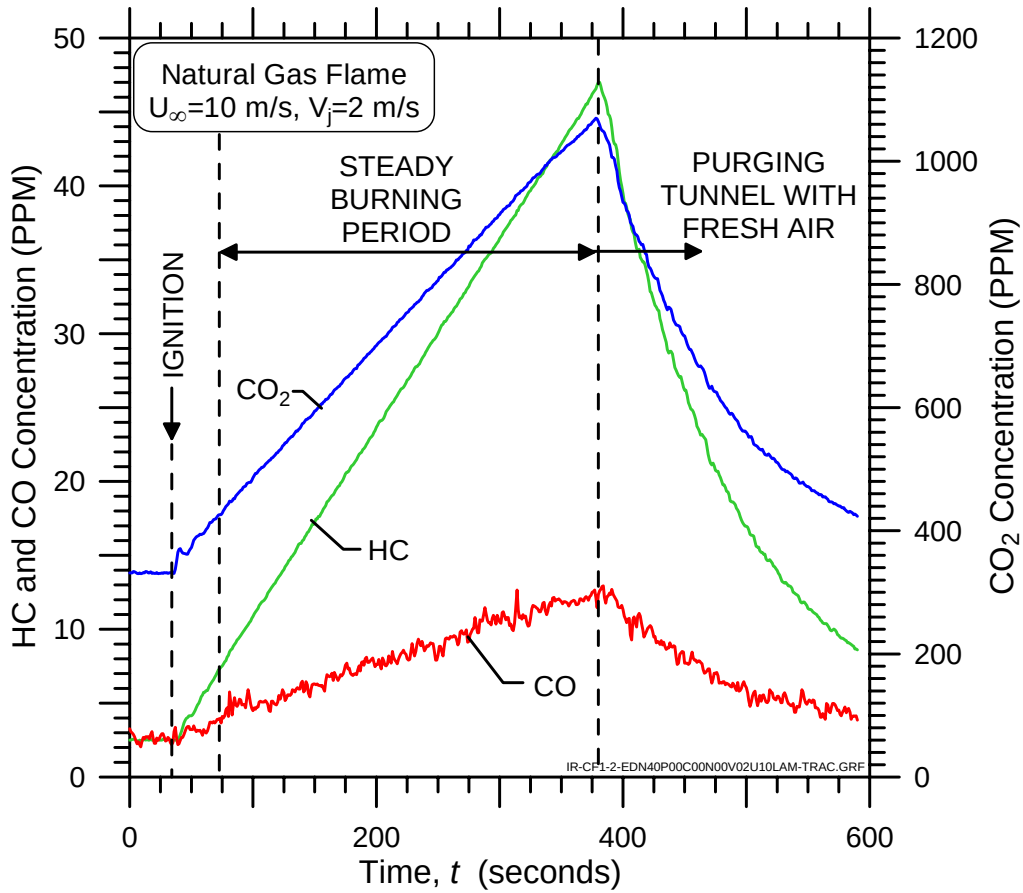


Figure 3.1: Time traces of concentrations of major carbon containing species during a typical experiment in the closed-loop wind tunnel

Data in Figure 3.1 can be processed further and presented into a form that is more useful in terms of Equations 3.8-3.10. Figure 3.2 shows the same data as Figure 3.1 but now the measured concentrations are divided by the measured absolute temperature of the wind tunnel, which has risen approximately 3 K during the experiment. Data from the steady burning period in Figure 3.2 can be fitted with a least squares regression line and the slopes of the curves are a direct measure of the differential terms in Equations 3.8-3.10. For example, the term $\frac{d}{dt} \left(y_{CO_2} / T \right)_{t \rightarrow t_0}$ in Equation 3.8 is simply the slope of the CO_2/T line in Figure 3.2.

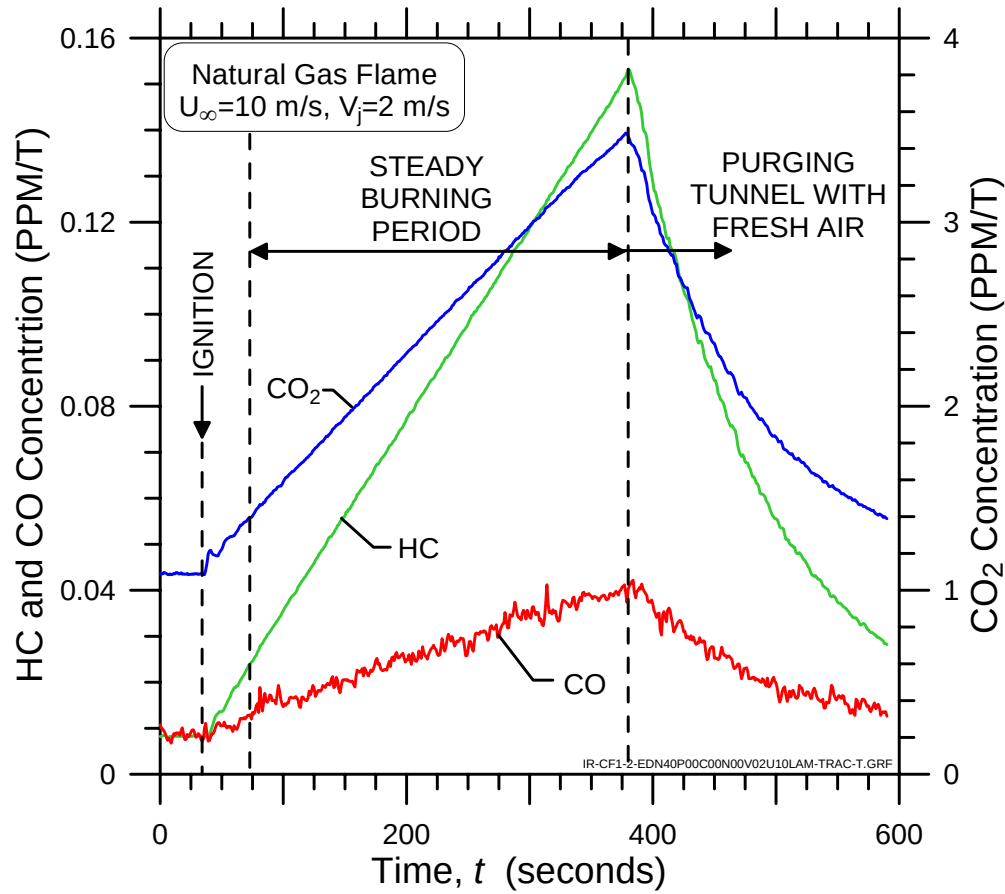


Figure 3.2: Ratio of concentrations of major carbon containing species divided by temperature during a typical experiment

Revisiting equations 3.8-3.10 with this typical experimental data allows the magnitude of each term to be assessed and it can be shown that the influence background concentrations of CO_2 , CO , and HC can be neglected without affecting the accuracy of the calculation [17]. With this additional simplification, the efficiency, η , can be solved explicitly from Equations 3.8-3.10 as shown in Equation 3.11.

$$\eta = \frac{\frac{B}{A+C} - \frac{Y_{CO_2, flare}}{xY_{C_xH_y}}}{1 + \frac{B}{A+C}} \quad \text{where} \quad \begin{aligned} A &= \frac{d}{dt} \left(\frac{Y_{HC}}{T} \right) \Big|_{t \rightarrow t_o} \\ B &= \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \Big|_{t \rightarrow t_o} \\ C &= \frac{d}{dt} \left(\frac{Y_{CO}}{T} \right) \Big|_{t \rightarrow t_o} \end{aligned} \quad (\text{Eq. 3.11})$$

This final version of the efficiency equation is much more intuitive than the previous equations, and closer inspection reveals that the efficiency essentially reduces to the relative slopes of the CO₂, CO, and HC curves as measured in the wind tunnel. For example, if there is no CO₂ in the flare stream (i.e., $Y_{CO_2, flare} = 0$) then

$$\eta = \frac{B}{A+B+C} \quad (\text{Eq. 3.12})$$

Lastly, this approach of estimating the combustion efficiency of a flare of a given set of conditions takes between 10 to 12 minutes to complete, which includes 5 to 7 minutes of burning time with the remainder being for setting the conditions and purging the tunnel for the next test.

3.2.1 Estimates of Uncertainty in Efficiency Measurements

Detailed sensitivity and uncertainty analyses of the closed-loop wind tunnel methodology for measuring efficiencies of flares have been published previously [17] and will only be briefly reviewed here. The essential point of this technique is that the slopes of the concentration traces of CO₂, CO, and HC are the important factors in the efficiency calculations. These slopes can be determined much more precisely than single-magnitude concentration readings which are more prone to signal drift and noise. The fact that these three slopes are then written in the form of a ratio in the final efficiency equation, further minimizes the influence of the errors of individual measurements in the uncertainty of the measured efficiency. For a flare burning pure methane with a measured efficiency of 97.18%, the calculated uncertainty is +/- 0.6% absolute (19 times

out of 20). For the same flare under different wind conditions and with a measured efficiency of 91.79%, the calculated uncertainty is $\pm 0.15\%$ absolute (19 times out of 20).

While these statistical uncertainties are small, it is important to note that they only reflect the uncertainties of the terms present in Equation 3.11. Assumptions used in the development of this methodology must be tested by other means. Proof of the well-mixed nature of the gases in the tunnel, important for the successful implementation of the methodology, has been described in Section 2.1.5.3. The negligible influence of background concentrations of HC, CO, and CO₂ has been proven by a detailed sensitivity analysis [17].

Probably the most important consideration in developing this closed-loop wind tunnel methodology for measuring the efficiency of natural gas and propane flares was the assumption that the mass of soot was negligible in terms of the other products of incomplete combustion. The basis for this assumption was drawn from the combustion literature. Data from the EPA work on efficiencies of propane-fuelled flares have shown that less than 0.5 % of the mass of fuel ends up as soot [9]. More recent research has shown these amounts to be even lower under the influence of cross-flowing air [18]. A sensitivity analysis of the efficiency calculation shows that at these amounts of soot the influence on the efficiency calculation is negligible. In the case of natural gas fuelled flares, soot has even less of an influence since it is well documented that natural gas flames have a much lower propensity to produce soot than propane flames [19]. Furthermore, in cases where the amount of soot becomes significant (e.g. with the addition of liquid fuel droplets to the flare stream), a separate methodology is used as described in Section 7.1.4.

Finally, during the course of this research, a second independent methodology for measuring the efficiency of flares in the wind tunnel was also developed and used [20]. This “fuel reference methodology” was also found to be a robust and accurate technique for measuring the efficiency of flares. Although the methodology developed in the

previous section was ultimately found to be slightly faster and more reliable, the two approaches were initially used simultaneously as an additional verification of the accuracy and repeatability of the efficiency measurements.

Before presenting the results of efficiency tests it is useful to provide some general observations on the flares being tested. The first of these observations relate to the visual aspects of the flame and its structure as seen through long and short exposure photographs. These images show the flames that can exist in a crosswind, and act as a reference to connect flame shape to the combustion efficiency results. The other important observation is based on an analysis of the major hydrocarbons that accumulate in the tunnel during typical efficiency tests. The composition of these hydrocarbons provides insight into the mechanism that causes the reduced combustion efficiencies at higher wind speeds. The mechanism for wind-driven inefficiencies is then pursued by spatially mapping the hydrocarbon emissions ejected from flares using single-point measurements, as well as using sheet-laser imaging to observe the instantaneous structure of hydrocarbon emissions. Once the mechanism for creating wind-driven inefficiencies is established, the efficiency is quantified over a wide range of operating conditions.

3.3 VISUALIZATION OF THE FLARE

Figure 3.3 shows a series of short and long exposure photographs of what are, in general, highly luminous propane flames in a crosswind. Comparable images of natural gas flames are shown in Figure 3.4. While the long exposure photographs show the overall position and size of the flame, the short exposure images provide an interesting insight into the various fluid mechanic structures in the flow as the shear layer vortices are made visible by the flame. For the images presented here, the jet exit velocity of the fuel, V_j , was held constant at 2 m/s and the crosswind speed, U_∞ , was varied from 1 to 27 m/s. Thus, for a given fuel type, this fixes the mass flow rate of fuel. Also, noted on each of the images is the combustion efficiency (discussed in detail later) and for most of the flames only a small fraction of the fuel is not consumed.

In describing the appearance of flames in a crosswind, it is convenient to define the momentum flux ratio, R , as shown in Equation 3.13.

$$R = \frac{\rho_j V_j^2}{\rho_\infty U_\infty^2} \quad (\text{Eq. 3.13})$$

where R = momentum flux ratio between the jet of flare gases and the crosswind

V_j = mean exit velocity of flare gases

U_∞ = mean wind speed

ρ_j = density of the fuel jet

ρ_∞ = density of the crossflowing air

Initially, the effect of the crosswind is to increase the overall length of the flame. However, after reaching a peak length (at $R = 0.15$ to $R = 0.084$), the flame begins to shorten with further increases in wind speed. This maximum flame length corresponds to the appearance of detached pockets of combustion, which are apparent in the short exposure photographs. By contrast, as illustrated in the photographs, the width of the flame decreases monotonically with increased wind speed. Ultimately, at very high wind speeds, the main tail of the flame is extinguished and only a combustive recirculating vortex on the downstream side of the flare stack remains of the original flame.

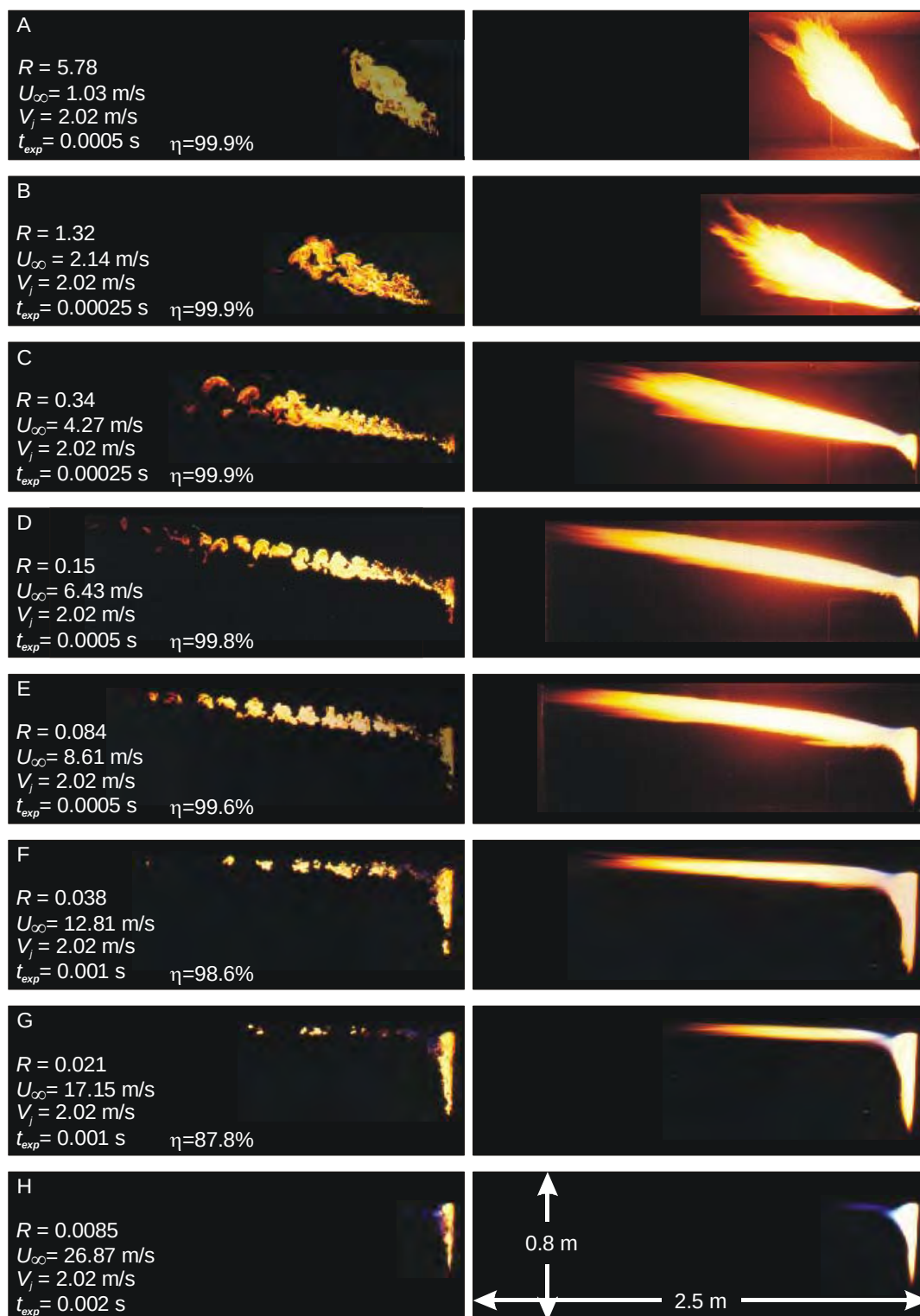


Figure 3.3: Long and short exposure colour images of a propane flame in a crosswind

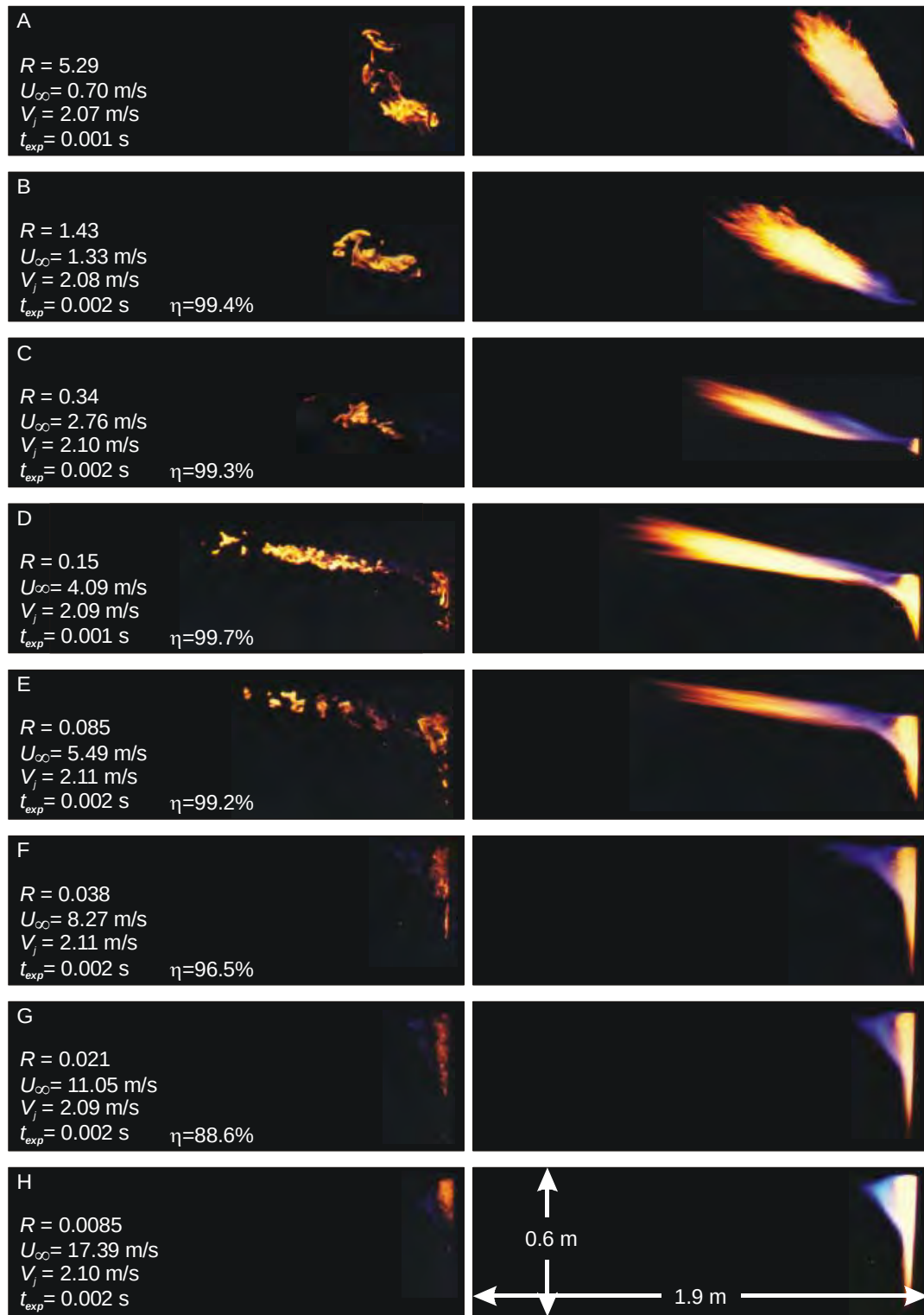


Figure 3.4: Long and short exposure colour images of a natural gas flame in a crosswind

At the higher momentum flux ratios shown in Figure 3.3 (e.g., $R = 5.78$), the propane flame exists above the stack and is highly radiative. As the crosswind velocity is increased and R is reduced to 1.32 the onset of "downwash" occurs as a portion of the combusting gases verge on being drawn into the low-pressure region on the downwind side of the stack. While not readily apparent in the photographs, at this and lower momentum flux ratios a non-reacting mixing layer appears on the upper surface of the flame near the flare stack as shown schematically in Figure 3.5. As the fuel exits from the flare stack, it must first be mixed with air before combustion can occur. When the crosswind speed is increased, this process becomes more apparent as the upper layer of the flame separates from the flare stack and the non-reacting mixing layer forms. Although it might be expected that this region would be a source for fuel to be stripped away and inefficiencies to occur, experiments discussed later in this chapter will show that this is not the case [21].

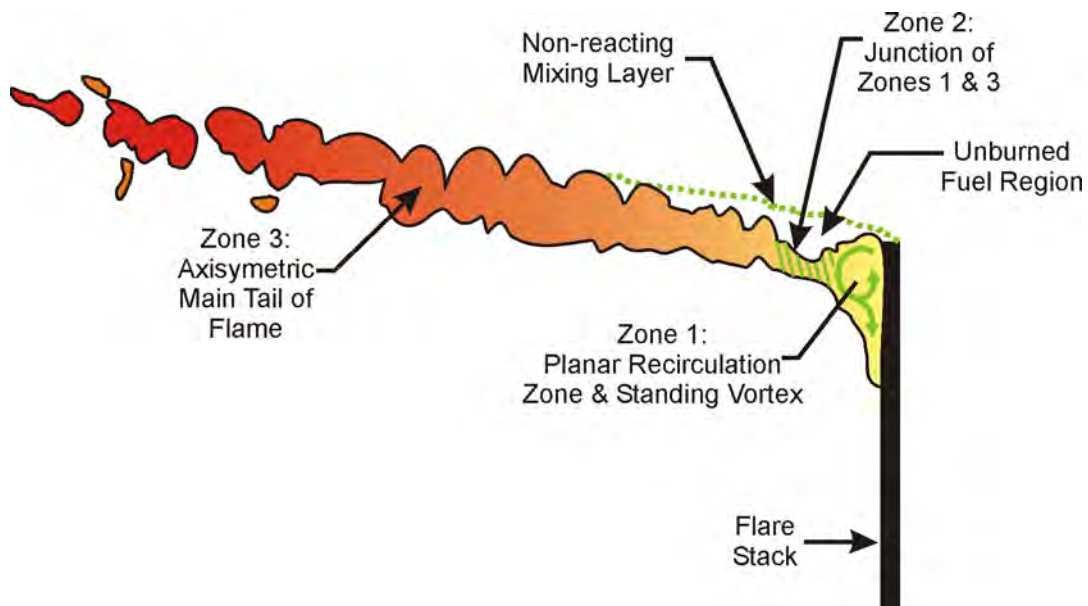


Figure 3.5: Schematic of a wake-stabilized flame showing three-zone structure

As the wind speed is increased further and R is further reduced, a three-zone flame structure becomes apparent which was first described by Gollahalli and Najundappa [22]. As sketched in Figure 3.5, a planar stationary vortex attached to the burner tube defines the first zone; the long axisymmetric tail of the flame forms the third zone; and the

junction that connects these two main parts of the flame defines the second zone. While the recirculating vortex may not be clearly defined in photographs, it is easily apparent to the naked eye when the flame is in motion. This recirculation zone grows down the tube as R is reduced, and may extend 30 diameters or more down the leeward side of the flare stack. This recirculating vortex is critical to the stabilization of the flame and acts as a continual ignition source for the main tail of the flame (Zone 3). Flames operating under this condition are referred to as “wake-stabilized flames”.

The natural gas flames shown in Figure 3.4 were taken at the same approximate values of R and the same fuel jet exit velocity as the propane flames of Figure 3.3. In general, these natural gas flames are much less luminous and shorter in length since less oxygen needs to be entrained into the flame to burn equal volumes of fuel when compared to propane flames. This difference in flame length is more pronounced than the photographs might suggest and the change of scale of the images should be noted. Despite the differences in flame color and length, the flow structures of the natural gas flames are essentially the same as the propane flames. Although the shapes and positions of the flames for the two fuel types are qualitatively related to the momentum ratio, R , as suggested by [23-25], important changes in structure do not coincide at fixed values of R . For example, the maximum flame length of both the propane flames and the natural gas flames occurs in the vicinity of $R=0.15$, but the extinction of the tail region of the flame (zone 3) occurs at a much higher momentum ratio ($R=0.021$) for the natural gas flames than for the propane flames ($R=0.0085$). It seems apparent that R alone is not sufficient to account for the visual differences between the propane and natural gas flames.

The flare stack used in these images was 24.7 mm in outside diameter, which is about four times the diameter used in previous studies [26, 27]. In general, the average shape and structure of the flames at these two scales are quite comparable. The fact that these similarities exist over a factor-of-four change in diameter is encouraging for the feasibility of modeling simple flares over a wide range of scales. The external cold-flow Reynolds number (Re) for this 24.7 mm diameter flare ranges from 1570 to 25,120 as the crosswind is increased from 1 m/s to 16 m/s, which corresponds to the laminar regime of

boundary layer separations. The next expected transition of the external flow regime will not occur until Re reaches $\sim 5 \times 10^5$ at which point the stack boundary layer becomes turbulent. As an example, this transition to turbulence occurs at 16 m/s when the stack diameter is 470 mm and, hence, puts many industrial flares in the same external flow regime as the laboratory flares being tested here.

3.4 PRINCIPAL MECHANISM OF INEFFICIENCIES

In this section, the main source of flaring inefficiencies will be explored. Data will be presented to show that most of the wind-driven flare inefficiencies are a result of a fuel-stripping mechanism [28]. As described in Equation 3.11, combustion inefficiencies arise due to the emission of either CO or hydrocarbons. Upon reviewing the raw experimental results, e.g., Figure 3.1, it becomes apparent that the inefficiency associated with flares is set primarily by the amount of hydrocarbons emitted and not the amount of CO emitted. In fact, the rate at which CO accumulated in the wind tunnel was only weakly dependent on the operating condition of the flare. In contrast, the hydrocarbon accumulation rates varied considerably with operating conditions and were strongly connected to wind speed. With this information in mind, this section aims at quantifying the composition and the location of hydrocarbon emissions from flares. This research led to the proposition of a fuel-stripping mechanism as the principal source of flaring inefficiencies.

3.4.1 Analysis of Emitted Hydrocarbons

Gas chromatographic analyses, such as the one shown in Figure 3.6, of the unburned hydrocarbons collected in the wind tunnel following a flaring test show that these post-reaction gases have a very similar volume fraction distribution as the hydrocarbon fuel stream (i.e., hydrocarbon emissions from natural gas flares are primarily methane while emissions from propane flares are primarily propane). These results suggest that inefficiencies of flares are mainly due to a portion of the fuel being stripped from the flame or passing through the flame without any significant chemical reaction occurring.

This experimental evidence does not support the notion that hydrocarbon emissions are a result of partial or incomplete combustion.

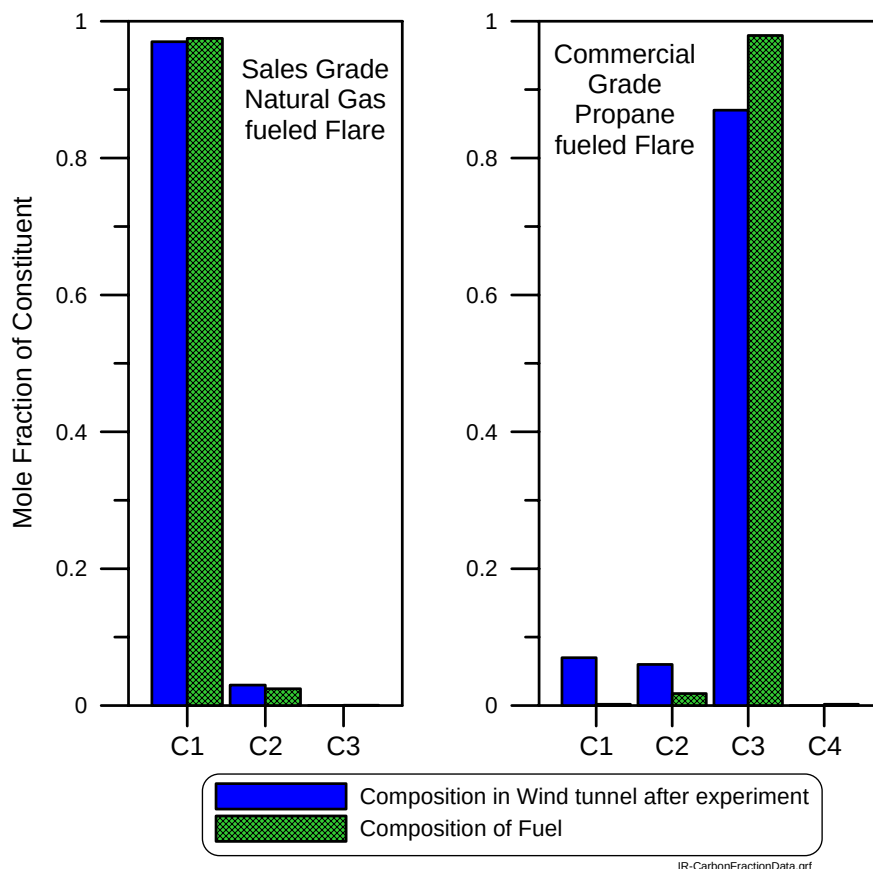


Figure 3.6: Comparison of the composition of hydrocarbons in the flare stream to those in the wind tunnel gases after burning either a propane or a natural gas flare

3.4.2 Fuel-Stripping Mechanism

In Section 3.4.1 it was established that the hydrocarbons being released are, in fact, unburned fuel as opposed to some product of partial or incomplete combustion. While this is useful information, it does not reveal the fluid dynamic mechanism responsible for this phenomenon. Figure 3.7 shows the various hypotheses that were considered as pathways for the ejection of fuel from the flare stream exiting the stack to the ambient surroundings. The theory is that fuel must somehow find an exit path from a control volume, which surrounds the flare stack and the flame, to the ambient surroundings. Each of these pathways was tested experimentally using the methods described below.

At the beginning of this investigation, it seemed most probable that fuel leakage would occur out the top of the non-reacting mixing layer and disperse upwardly. In another scenario, some of the fuel originating from this same mixing layer would be ejected by the counter-rotating vortices, developed by the bent-over jet, either laterally or even beneath the flame. Alternately, all the fuel may not be captured within the flame pockets and would simply get carried downstream and out into the ambient environment at the region where the flame tip is located. These are but three of the several possibilities considered as mechanisms for emitting fuel gases without their participation in combustion. It was also unclear whether the fuel was emitted in a steady stream or a result of a highly transient flow structure (e.g., the shedding of a vortex). Each of these pathways was tested experimentally, using methods that will be described below, to determine the validity of one or more of these hypothesized mechanisms.

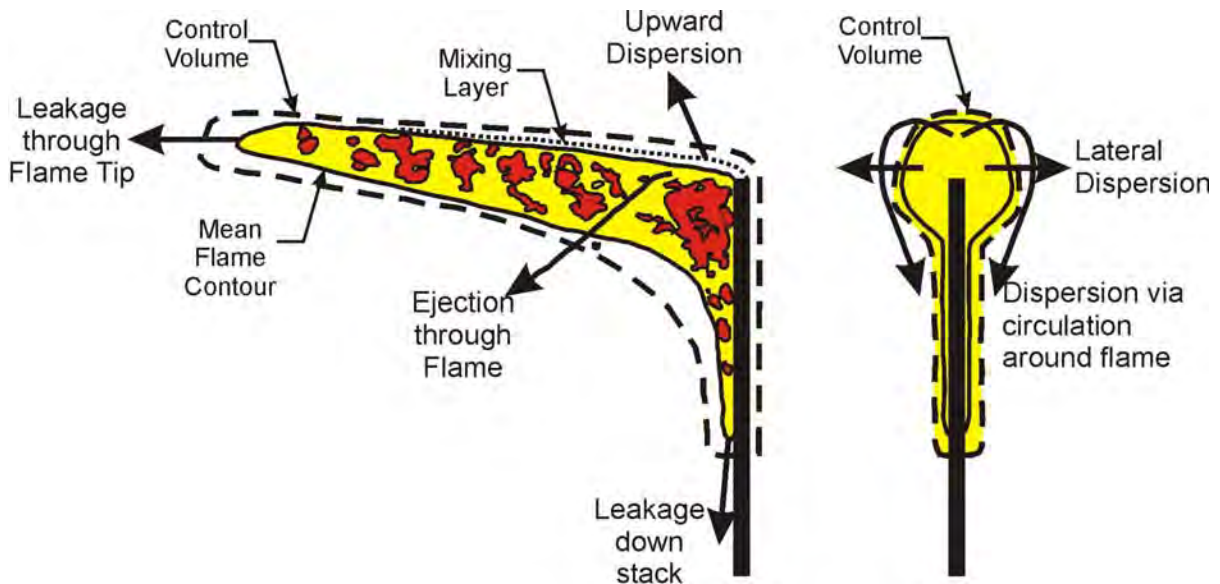


Figure 3.7: Potential pathways of fuel leakage shown in both a side and stream-wise perspective

3.4.3 Fast Flame Ionization Mapping

3.4.3.1 Experimental Approach

In order to detect highly transient and local bursts of unburned fuel being emitted from the flame, an experimental method was developed to provide a reliable means of locating hydrocarbon “leaks” from the flare. This methodology was based on a technique using single-point sampling with a fast flame ionization detector (FFID). FFID technology was well-suited to this application because of the fast response times to changing concentrations of hydrocarbons. This technique and the corresponding results have been previously reported in detail [28].

3.4.3.2 Experimental Setup and Methodology

Like all flame ionization techniques, the FFID uses a hydrogen flame to burn any hydrocarbons being sampled by an aspirating probe. When sampled hydrocarbons burn in the combustion chamber within the FFID module, they produce ions in proportion to the concentration of hydrocarbons. These ions can be detected and converted to a readable voltage signal that is calibrated to a known hydrocarbon concentration. The differences between FFID and standard flame ionization detectors (FID) are the placement of the combustion chamber relative to the sample probe and the aspiration rate. For the FFID, the combustion chamber is located very close to probe tip and the flow rates are near sonic in velocity so that the system has faster response times. The FFID used in this work is a Cambustion Model HFR 400 and is capable of response of times in the order of 1 millisecond to a resolution of 4.1 ppm.

As shown in Figure 3.8, the FFID and probe were mounted on the computer controlled two-dimensional traversing system (see Section 2.1.1.1 and Figure 4.1). This arrangement allowed the tip of the probe to be placed at various locations in the flow in order to analyze the gases at specific points of interest around the flame. After a time-series of data was taken at one point and stored using a data acquisition system, the probe was moved, with the traverse, to the next point of interest. This configuration allowed for

the mapping of the entire area of interest about the flame (i.e., the surface of the control volume). This technique was essential in order to explore all the possible pathways of hydrocarbon ejection and, consequently, sources of inefficiency as shown in Figure 3.7.

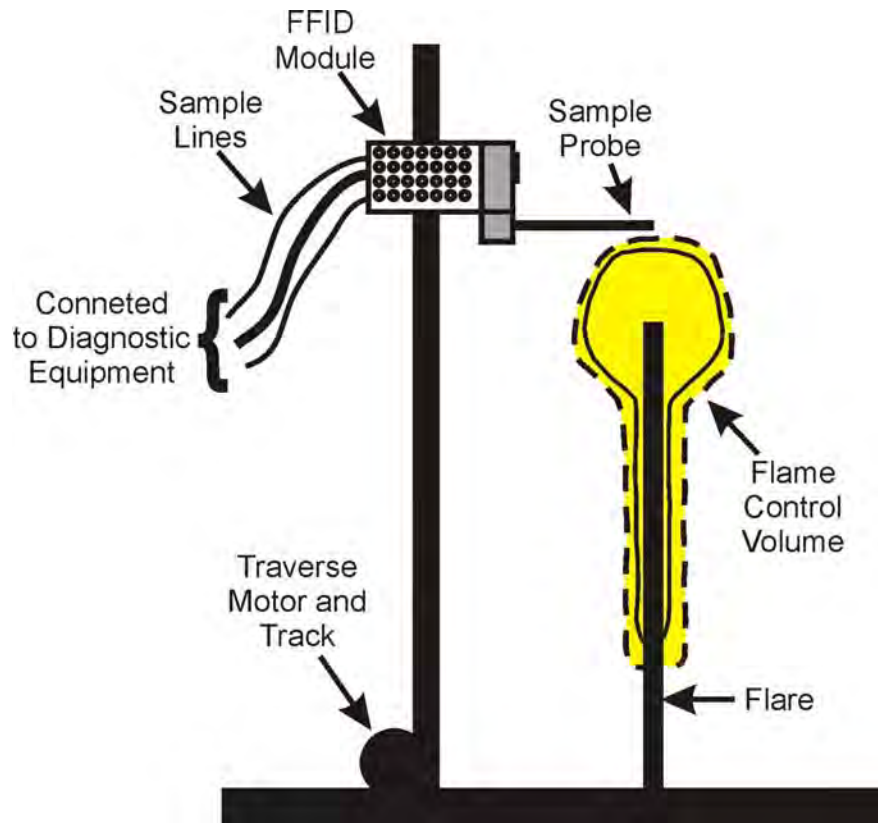


Figure 3.8: FFID Setup for Mapping Hydrocarbon Emissions from a Flare

In these experiments jet diffusion flames of natural gas were burned in the closed-loop wind tunnel. Reactant gases flowed from a vertical flare stack (24.7 mm O.D. / 22.1 mm I.D.) that protruded 70 cm into the test section of the wind tunnel. The exit velocity of the fuel gas, V_j , was fixed at 1 m/s and the crosswind velocity, U_∞ , was varied to a maximum of 8 m/s. The data reported here is for the case of the wind speed fixed at 8 m/s, which equates to a momentum flux ratio of 0.01. At this low momentum flux ratio, the flame is wake-stabilized. Figure 3.9 is a schematic of the outline of this flame as seen by a long exposure photograph. Also shown in Figure 3.9 are the FFID measurement locations in the flow that are downstream of the central plane of the flare stack. Measurements were also taken outside of this central plane in order to include

lateral locations within the mean flame image. In this way all of the hydrocarbon-ejection pathways were tested.

The signal from the FFID recorded at each of these measurement points was sampled at 3600 Hz. To avoid aliasing effects, the signal was sent through a low-pass Butterworth analog filter with a cut-off frequency of 1000 Hz. At each measurement location, a series of 131072 data points were collected over a 36.4-second period. Data processing was conducted in several steps. In order to account for any slight increases in background hydrocarbon concentrations during this period, the data was fitted with a least-squares best fit line that was then subtracted from the data. Figure 3.10 shows a typical time trace of the hydrocarbon signal from a measurement location beneath the flame. In order to isolate the peaks of the hydrocarbon concentration in the raw signal, a concentration threshold was applied to the time-series data. The choice of this threshold was determined systematically by first calculating the probability of finding data above an arbitrary threshold for all possible choices of the threshold. The resulting probability function of finding data above a threshold versus the chosen threshold had a characteristic “knee-shaped” curve. The point of maximum curvature on this curve was used to choose the particular threshold to use. This process was repeated for each of the measured time-series, i.e., each FFID measurement point, of the hydrocarbon concentration. With a chosen threshold, the probability density function of the time spacing between concentration peaks was determined by locating up-crossings of the threshold within the instantaneous signal. Probability density functions of peak width were determined in a similar manner.

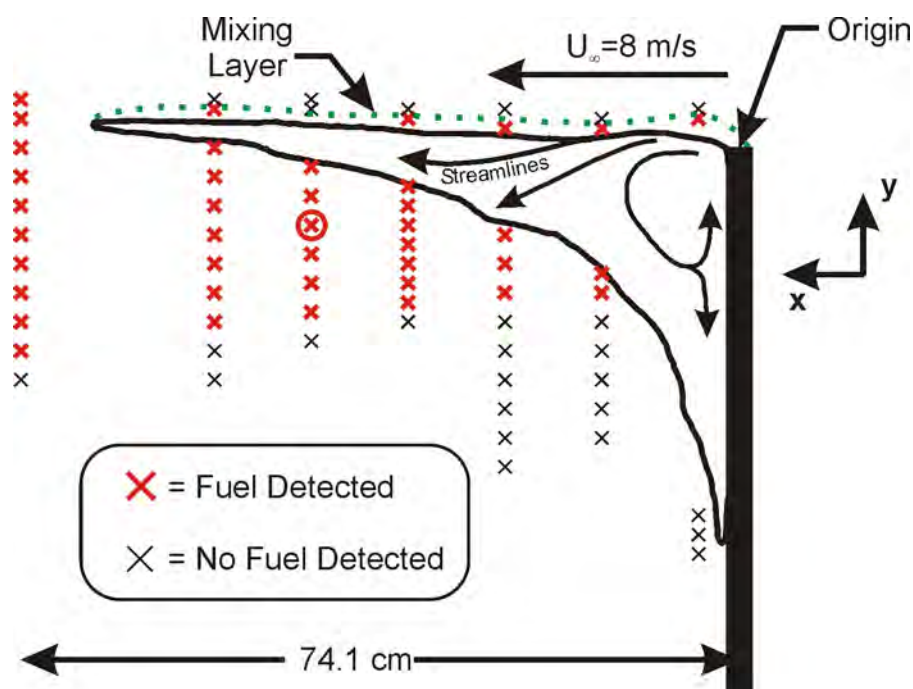


Figure 3.9: Schematic of the Flame in Cross-flow showing locations of FFID measurement points. Light cross-hairs show points with no hydrocarbon peaks.

3.4.3.3 Results and Discussion

In other published works [28] the results of these FFID experiments are analyzed in detail. In this previously published literature, the emphasis was the mean concentrations of the hydrocarbons at each measurement location in order to determine the relative flux of hydrocarbons and the time interval between bursts to consider any periodicity in the ejection process. In this report, the focus is on the occurrence of hydrocarbons at any particular location in order to track the hydrocarbons back to the source and, consequently, to define the mechanism of hydrocarbon ejection.

Figure 3.10 shows the hydrocarbon concentration signal taken at the location demarcated by the circled crosshair in Figure 3.9. The presence of sharp peaks in the data indicates that hydrocarbons are ejected from the flame in a highly intermittent process. By observing the distribution of darker crosshairs (points with measurable hydrocarbon peaks) and lighter crosshairs (points with no measurable peaks of hydrocarbon concentration) in Figure 3.9, it is apparent that unburned hydrocarbons exist over a much wider area beneath the flame than above the flame. As well, the region of measurable

hydrocarbons extends further downward as the flow moves downstream of the burner tube. Above the flame, sharp changes in the FFID signal were apparent over distances as small as one centimetre. These results were indicative of the mixing layer of unburned fuel that exists on the upper surface of the flame indicated by the dashed line in Figure 3.9. Measurement points inside this layer showed bursts of hydrocarbon concentration as high as 17% (170,000 ppm), whereas points just 1 or 2 cm above showed no measurable peaks in concentration. Although it might be expected that unburned fuel could be stripped from the mixing layer by shear-layer-type vortices, this does not seem to be happening as indicated by the sparse number of crosshairs above the flame shown in Figure 3.9.

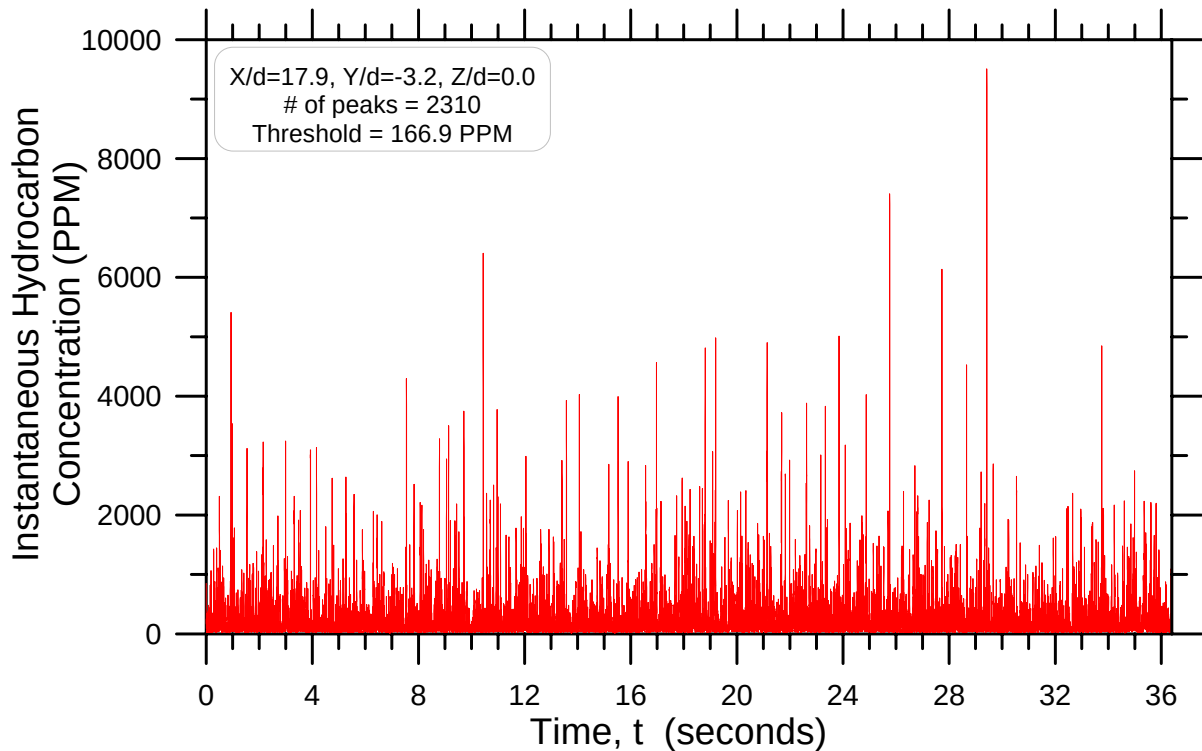


Figure 3.10: Typical instantaneous hydrocarbon concentration signal below the flame corresponding to the circled crosshair in Figure 3.9.

For measurement locations beneath the flame, apparent gradients in hydrocarbon concentration were much less severe. The magnitude of the peaks was greatest for points directly below the flame and decreased slowly as the probe was moved downward. The

largest peaks of hydrocarbon were found in the locus of points 34.1 cm downstream of the burner tube (i.e., the fourth x-axis measurement position in the positive x-direction) and the magnitudes of these peaks decreased slightly as the probe was moved farther downstream from the flare along the x-axis. For measurement locations beyond the flame tip, the magnitudes of the hydrocarbon peaks are characteristic of points beneath the flame and do not appear to be associated with fuel leakage from the upper mixing layer.

FFID measurements taken off the central axis of the flow also had few peaks and the concentrations of the peaks were also diminished. In fact, sampling at lateral locations outward from the mean flame location showed no hydrocarbons. This observation is important because it eliminates any mechanism of fuel transport in which fuel originates from the upper non-reacting mixing layer and migrates to a location under the flame where it exists in its highest concentrations.

The area of highest hydrocarbon concentrations beneath the flame corresponds to the middle of three zones in the flame as shown in Figure 3.5. This region, zone 2, is characterized as the junction between the recirculating vortex adjacent to the flare stack (zone 1) and the long tail of the flame (zone 3) as described previously by [22]. Flow in zone 2 is highly strained and is marked by local extinctions of the flame [28]. In this context, it is proposed that the region of highest concentration of hydrocarbons beneath the flame is consistent with the intermittent ejection of fuel through zone 2. Streamlines sketched in Figure 3.9 show the strongly divergent mean flow in zone 2 and to help illustrate this process. Although this may be a reasonable explanation for the existence of unburned fuel beneath the flame, the dispersion of that fuel over a relatively large area suggests there may be other important and unseen features in the flow field.

In an attempt to understand better this phenomenon of fuel being stripped from the flame, it is helpful to examine other scientific literature pertaining to non-reacting jets in cross-flow. Studies of non-combusting jets in cross-flow [29-31] have revealed the presence of tornado-like wake-vortices that are shed from the jet and the stack. These coherent

structures are aligned vertically, parallel to the stack, and extend up into the jet. It is expected that these same structures would exist in the present flow field and it is further speculated that the reduced pressure within these vortices could be at least partially responsible for drawing the unburned hydrocarbons down beneath the flame. This vortex shedding would then result in the intermittent ejection of hydrocarbons from the flame and into the ambient environment.

FFID measurements of the hydrocarbon concentration above and below a low-momentum flux ratio diffusion flame in a crosswind have shown that hydrocarbons are ejected from the flame in a highly intermittent and spatially variable process that is most apparent on the underside of the flame. This observation is evidence for the existence of a fuel-stripping mechanism that is responsible for measured carbon conversion inefficiencies in flames of this type. It is proposed that the standing vortex next to the burner tube draws unburned fuel from near the exit of the stack to the underside of the flame. Once the unburned fuel is under the flame, it is drawn into the ambient environment by the wake vortices, which are shed from the burner tube where the wake vortices shed from the burner tube draw this unburned fuel away from the flame as shown in Figure 3.11. In this diagram, the sequence of events is labeled 1 through 3: in frame 1, the fuel packet leaves the flare stack and enters the combustion zone; in frame 2, the fuel packet does NOT interact with the flame and, instead, moves through the mean flame region unchanged; and finally, in frame 3, the fuel packet is ejected from the flame chemically unchanged and is emitted into the ambient environment as pollution.

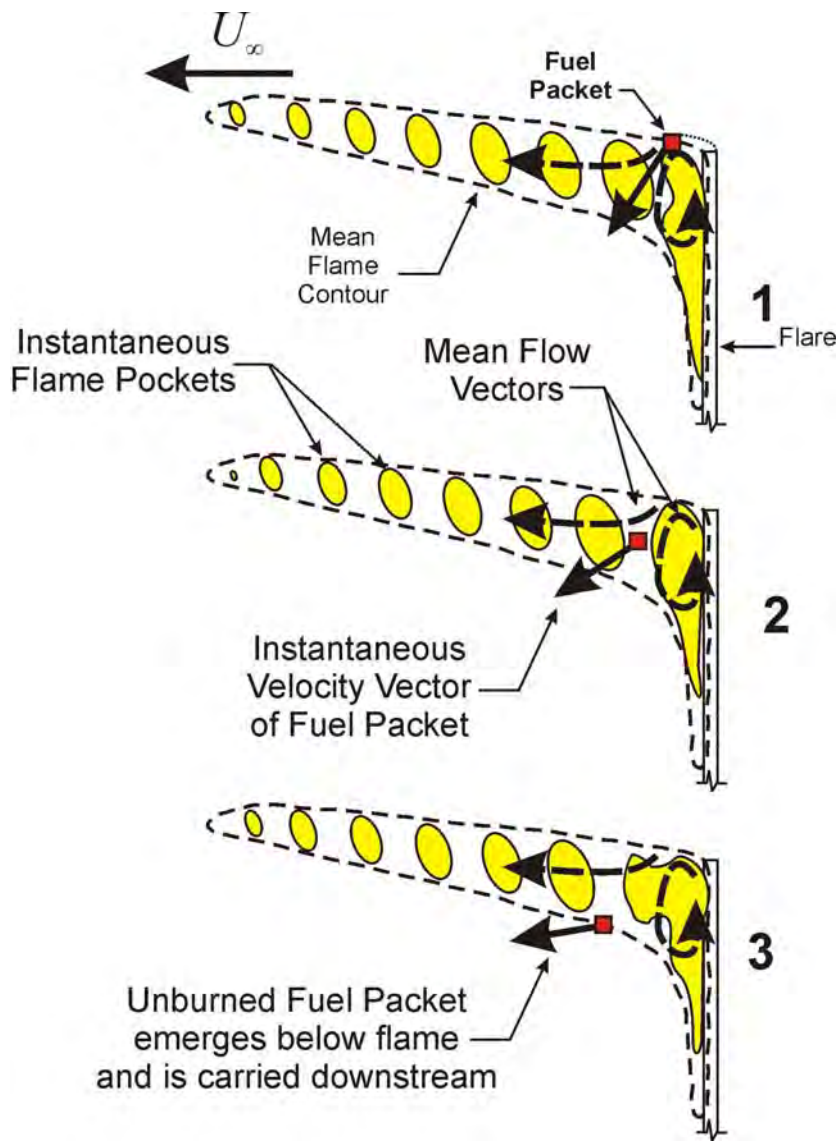


Figure 3.11: Sequential Schematic of Fuel-Stripping Mechanism

3.4.4 Sheet Laser Imaging

3.4.4.1 Experimental Approach

In an effort to confirm visually the FFID mapping described above, an experimental method was developed for taking high-speed pictures of the bursts of hydrocarbon that were ejected from the flame. Although fuel-stripping model is strongly supported by the above FFID method, this hypothesis is based on a series of highly time-resolved, single-

point measurements that cannot show what is happening at neighboring points. Flow visualization techniques provide a comprehensive two-dimensional map of the instantaneous location of the unburned fuel packets that could further support the proposed model for fuel stripping.

3.4.4.2 Experimental Setup and Methodology

Flow visualization typically involves a number of common elements: identifying an area of interest within a moving fluid; finding an acceptable method of marking or “seeding” the fluid flow; illuminating the fluid-seed mixture in the region of interest; and imaging the ensuing flow patterns. In terms of understanding the mechanism of wind-driven inefficiency, the area of interest within the gas flow encompassed the region of the sudden bursts of hydrocarbons located through the use of the FFID. From the previous single-point FFID tests, it was determined that the ejection of raw fuel into the surroundings occurred on or near the slice of flow downstream of the central axis of the flare stack. Hence, the goal of this visualization work was to capture two-dimensional images of the instantaneous fuel and flame locations in the plane directly behind the flare stack, i.e., the leeward side.

While seemingly trivial, the choice of seed particles is critical to the accuracy of any flow visualization technique. If the seed particles are too big, the particles will not accurately follow the flow streamlines of the fluid because of differences in mass density and momentum. These differences can result in the particles not being able to respond accurately to changes in fluid velocity or direction. In addition, these particles can experience unacceptable levels of gravitational settling. In this case, another complicating feature for the choice seed particles is the desire to mark only fuel in the flow. Therefore, the particles must disappear (or change dramatically) as they pass through the flame where the hydrocarbon fuel molecules are being consumed. These seeding challenges were met by adding small droplets of silicone oil to the fuel stream. The droplets of silicone oil were created using a blast atomizer placed at the base of the flare stack. A portion of the fuel stream was passed through the atomizer and this droplet

laden flow was then re-introduced to the main flare stream. The mass-mean diameter of these oil droplets was approximated to be 5 micrometers [32]. Droplets of this size and mass density can easily follow the flow, but the real advantage of using silicone is that it evaporates at approximately 200°C. Given the size and boiling point of the silicone, these particles will disappear within a millimeter of the flame [32]. Therefore, this approach to seeding allowed the fuel to be marked right up to the flame surface where they would be destroyed if the gas surrounding them burn, but if combustion did not occur (i.e., fuel stripping occurs) then that portion of the flow would remain marked.

The flow visualization of the marked, i.e., droplet-laden, fluid was achieved by illuminating the flow with a powerful light source. Once the fluid was illuminated, light scattering (Lorenz-Mie scattering) occurred off the seed particles. The interpretation of the illuminated flow was the following: regions that scatter light would be associated with fuel; and dark regions would be associated with ambient air (i.e., unseeded fluid) or combustion products (i.e., once-seeded fluid wherein the seed evaporated). In order to illuminate an area of interest, a light sheet was created using a 400 mJ/pulse Nd-Yag laser. This laser beam was passed through two sets of cylindrical optics to expand the beam (originally 0.9 cm in diameter) in two directions. The light was subsequently reflected off a large mirror (200 mm diameter) into the wind tunnel through a glass window in the tunnel floor as shown in Figure 3.12. The primary expansion of the sheet was in the streamwise (x) direction but the sheet was also expanded slowly in the cross-stream (z) direction so that the sheet was approximately 7 cm wide through the region of interest. This wide sheet permitted the visualization of the full width of the fuel stream downstream of the flare.

In order to characterize the bursts of ejected unburned fuel, it was necessary to capture “instantaneous” and “simultaneous” images of both the fuel stream and the luminous flame. Such images allowed for a better understanding of the possible pathways of fuel. One possible pathway would result in the combustion of fuel, while another pathway would result in the ejection of fuel. Using this flow visualization technique, it was possible to distinguish between these two critical pathways of fuel in order to define

visually the phenomenon of fuel stripping. Simple observation of the fuel with the flame did not distinguish between fuel that would be burned (because it was surrounded by a flame) and the fuel that would be dispersed into the air (because it was not or ever will be near any flame). The flow was illuminated by a pulse of 532 nm wavelength light (green) and the natural luminosity of the flame was either blue or yellow. Given these contrasting colours, it was decided to use color imaging to distinguish between the various components of the flow. In addition, color imaging using color slide film provided high spatial resolution over the considerable flow area (up to approximately 1.4 m x 0.7 m). Even though the photographic medium was chosen, two challenges were still present. Firstly, the need of instantaneous images required short exposure times in order to reduce the blurring of images. This meant that a shutter speed of 1/500s should be used. Secondly, the emitted light levels of the flame necessitated the use of the most light sensitive film available. After some experimentation, the second challenge was overcome by using Kodak Ektachrome 1600 film which was subsequently pushed two additional stops during processing to reach an effective A.S.A rating of 6400. The first challenge will be discussed below in detail.

The basic photographic process was accomplished using a Nikon F1 camera and an f1.4 aperture, 55 mm lens that was mounted perpendicularly to the laser sheet. In order to obtain clear, instantaneous images of the flames, a more advanced photographic setup was required. As with most commercial cameras, the minimum fully-open shutter time was limited to 1/125 s. This was a significant constraint since the shutter must be fully open during the 7-nanosecond laser pulse. Hence, a compromise had to be reached between light sensitivity and speed. On the one hand, if a “slow” shutter speed were used, i.e., 1/125 s, to allow for sufficient light to expose simultaneously the entire film frame, then a complete but blurred image would result. On the other hand, if a “fast” standard shutter speed were used to allow for a crisp image of the flame, then only a portion of the image would be exposed during the laser firing due to the mechanics of the camera shutter.

In order to overcome the above problems a novel photographic technique was developed. This technique employed an external mechanical shutter system and a spinning disc. The spinning disc (30 cm in diameter and rotating at 3000 rpm) had an elliptical hole aligned to the camera lens in order to create the required (1/500 s) fully-open exposure time, as shown in Figure 3.12. Accurately synchronizing the firing of the laser, the opening of the camera shutter, and the occurrence of the hole in the spinning disc over the lens was non-trivial. Since the high-power laser could not be easily pulsed on demand, timing was synchronized to the laser Q-switch signal, which was fixed at 10 Hz. An optical slot switch with a Schmidt trigger was mounted on the spinning disc and manually synchronized with the Q-switch signal of the laser using an oscilloscope such that the mechanical shutter was open for 1/500 s while the laser was firing. When the pulse of the laser and the opening of the disc shutter were synchronized, a signal generator and delay circuit were used to open the camera shutter and record a photograph. Thus, although the camera shutter was fully open for the standard time interval of 1/125 s, light from the flame only passed through the disc shutter for 1/500 s resulting in 1/500 s flame exposures synchronized with the Mie scattering associated with the 7 ns laser pulse .

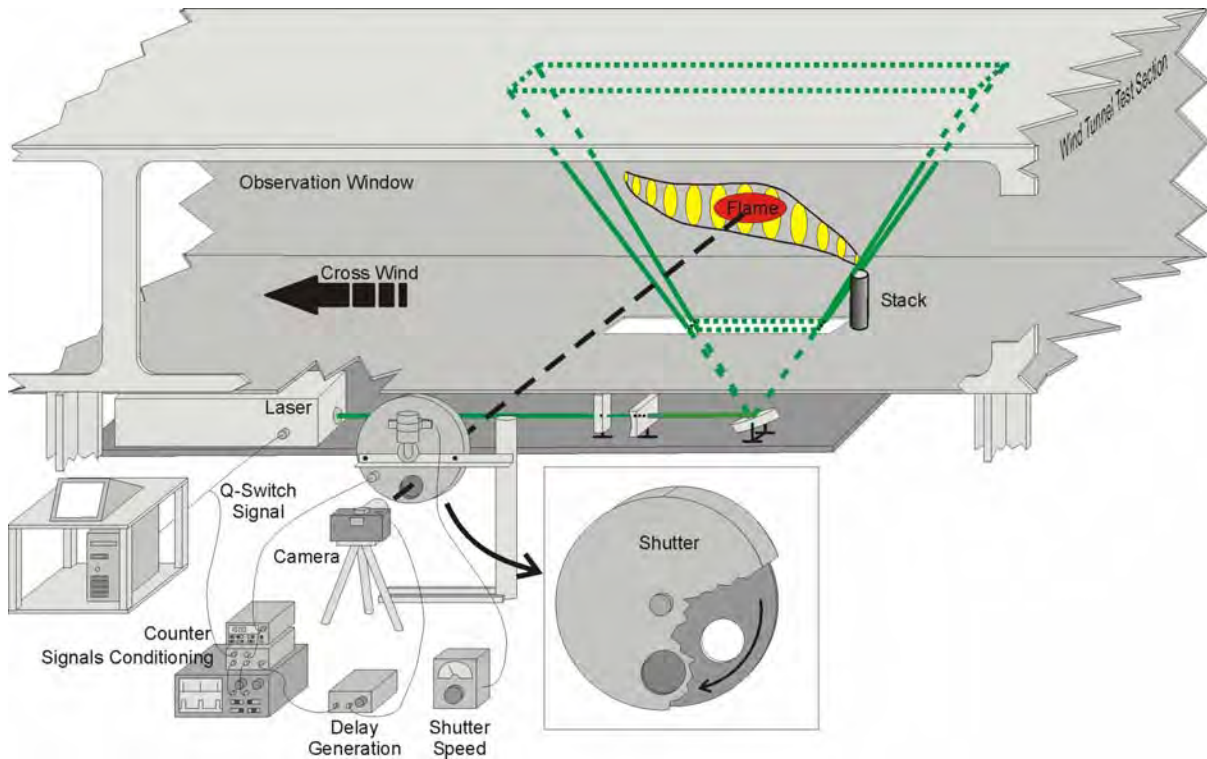


Figure 3.12: Schematic of the setup used for flame visualization

3.4.4.3 Discussion and Results

Figures 3.13 and 3.14 show photographic images of natural gas flares with exit velocities of 1 m/s, but with various crosswind speeds. Unburned fuel in the images appears as green as the fine silicone oil droplets scatter the 532 nm light from the laser sheet. Close inspection of images 3.13b through 3.13e illustrates that the silicone oil is an excellent tracer for the fuel as dots of green fuel can be seen surrounded by the deep blue haze of the diffusion flame that is consuming them. At very low crosswind speeds ($U_\infty \sim 1$ m/s), the flame may be either rim stabilized or wake-stabilized as shown in images 3.13a and 3.13b. At higher crosswind speeds, the upwind side of the flame separates from the burner rim and the flame is stabilized in the wake of the burner tube. As the wind speed is further increased, the recirculating vortex on the leeward side of the burner tube grows stronger and the flame remains stabilized.

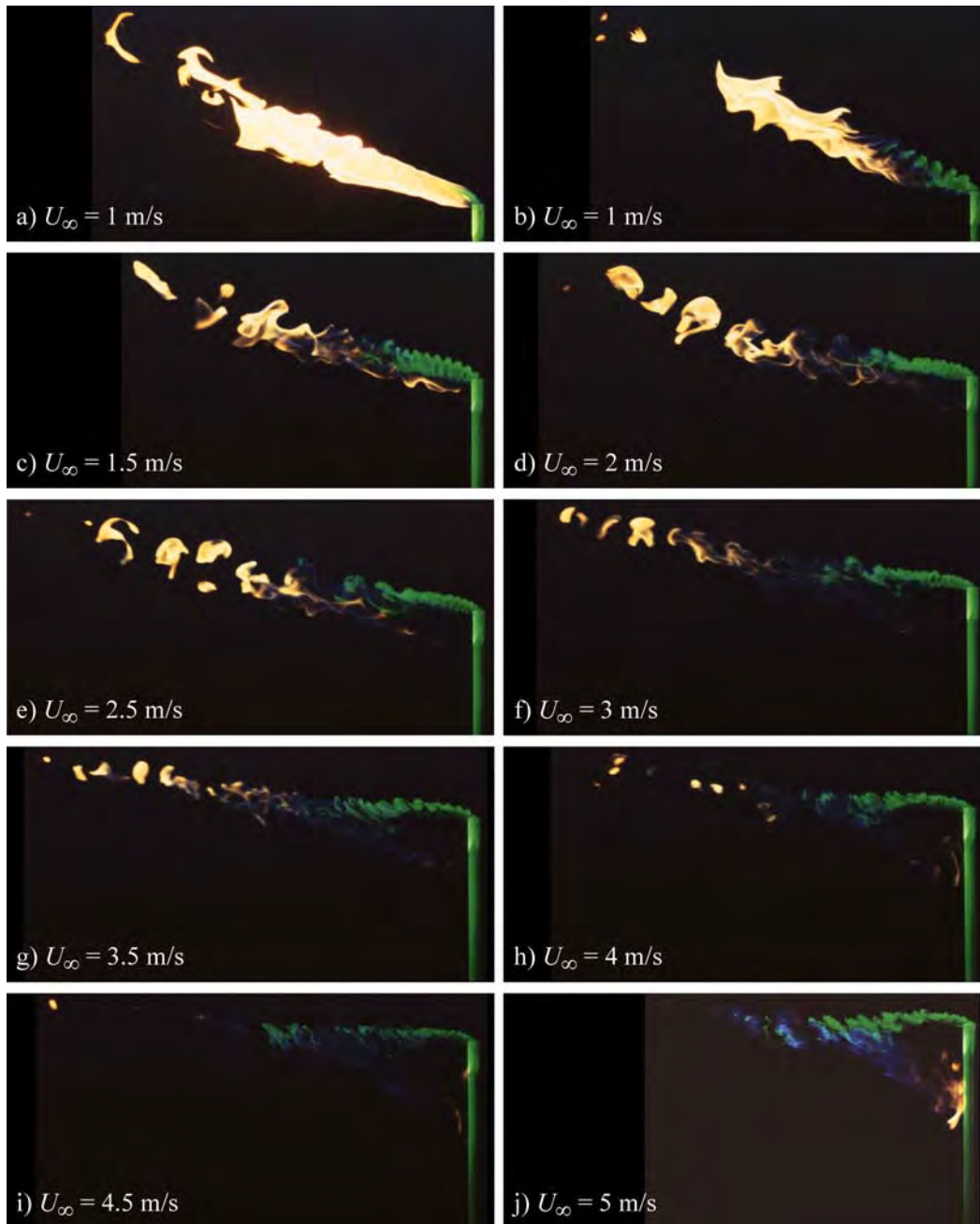


Figure 3.13: Colour images showing unburned fuel regions in wake-stabilized flames at various levels of crosswind speed. Green in images is Mie scattering of 532 nm laser light by fine silicone oil droplets seeded into the fuel stream.

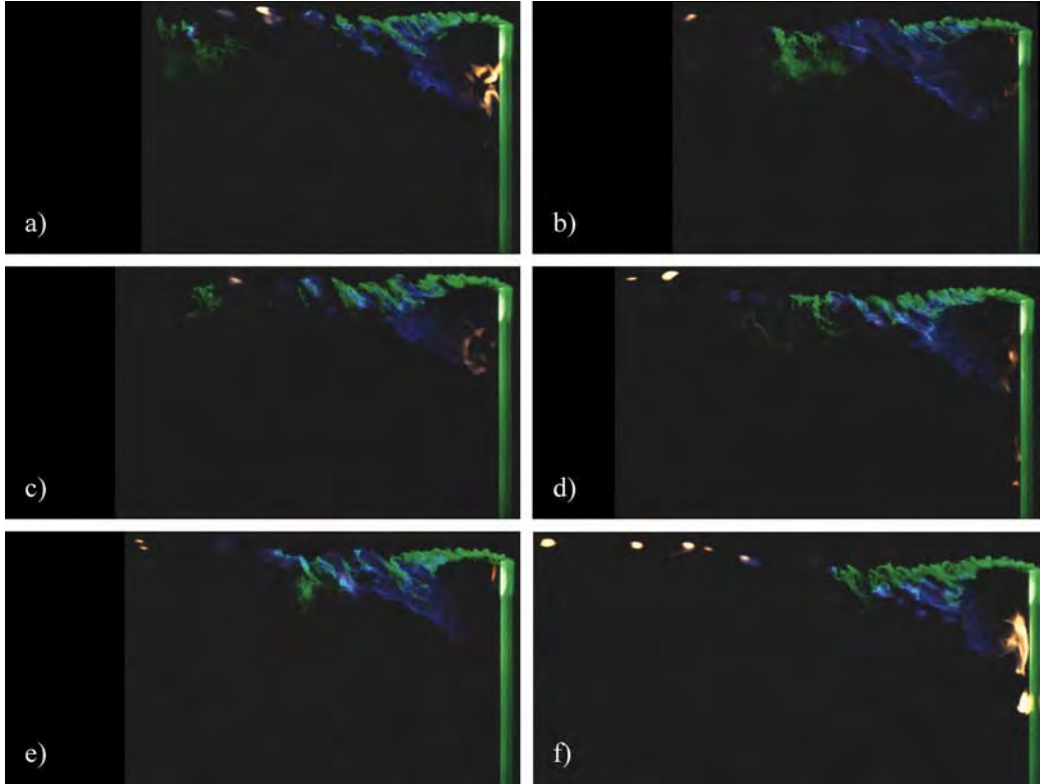


Figure 3.14: Multiple realizations of the wake-stabilized flame at $U_{\infty} = 5.5\text{m/s}$. Unburned fuel is apparent beneath the flame on a path to escape combustion. Images also show discrete pockets of combustion interspersed with coherent bits of unburned fuel.

In image 3.13c, vortex rings in the fuel the jet are readily apparent. These rings are created from the vorticity in the boundary layer on the inside of the stack and have been seen by several researchers studying cold jets in crossflow [e.g. 30, 31]. As the crosswind speed is increased further, these rings begin to interact and distort. Close inspection of image 3.13g reveals evidence of vortex pairing and roll up in the upper mixing region. As the three-zone structure of the flame becomes more clear, the images show that unburned fuel begins to penetrate into Zone 2 (refer to Figure 3.5) of the flame. Perhaps the most interesting observation is that at higher wind speeds, unburned fuel can be found to exist between the discrete pockets of combustion as shown in image 3.13j.

Figure 3.14 shows multiple realizations of the flame at a crosswind speed of 5.5 m/s where the overall inefficiency of the flame is approximately 3 % and illustrates the

stochastic nature of the flow. Images 3.14a, b, c, d, and e clearly show coherent bits of unburned fuel beneath the flame, which are on a path to escape combustion. These results substantiate the FFID results described above, which showed that the majority of the unburned fuel was being ejected on the underside of the flame. These images also confirm the observation that fuel is not stripped away from the non-reacting mixing layer on the upper surface of the flame.

Almost all of the images show discrete pockets of flame interspersed with coherent bits of unburned fuel. It appears that these coherent bits are periodically ejected through Zone 2 of the flame where they escape combustion. This phenomenon leads to the chromatographic results shown in Figure 3.6 in which post-reaction wind tunnel hydrocarbon concentrations mirrored those of the fuel used.

Consideration of all of the images in Figures 3.13 and 3.14 would suggest that the structural nature of the ejected bursts of unburned fuel is directly attributable to the vortex rings in the upper shear layer, which were clearly apparent at lower wind speeds. Although these coherent bits are grossly distorted as they interact and stretch and are forced through Zone 2 of the flame, they are able to maintain some coherence and avoid being consumed via combustion. It is believed that this is the fuel-stripping mechanism that leads to the measured inefficiencies in wake-stabilized jet diffusion flames in crossflow.

3.4.5 Conclusions Regarding Mechanisms of Inefficiencies

In the first stage of this research unburned fuel was traced back to its source, the underside of the flame. This investigation was accomplished using FFID techniques which allowed short bursts of hydrocarbons to be recorded. Once recorded, a map could then be made of the spatial variation of these bursts. These experiments confirmed the existence of these hydrocarbon leaks but did not produce a comprehensive picture of the trajectory of these fuel packets. In order to map the pathways of fuel being ejected from the flame, flow visualization techniques were employed. Flow visualization produced successive images clearly showing the trajectory of the fuel packets in relation to the bulk

flame structure. Photographic images show that, as the crosswind speed is increased, the flame breaks into discrete pockets of combustion interspersed with coherent bits of unburned fuel. At higher wind speeds these bits of fuel are ejected through the underside of the flame as a result of the mean flow induced by the standing vortex on the leeward side of the burner tube. These images help clarify the fuel-stripping mechanism and suggest that the mean flow induced by this standing vortex transports and stretches ring vortices of fuel from the upper shear layer and to the underside of the flame. These coherent bursts of fuel are ejected from the flame without burning and ultimately cause the measured inefficiencies.

3.5 MEASURING AND MODELING OF COMBUSTION EFFICIENCY

In this section, the experimentally-measured efficiencies of pipe flares exposed to cross winds are presented. The main parameters observed to affect the measured efficiency were flare stream composition, wind speed, flare gas exit velocity, and stack diameter. With regards to flare stream composition, it was important to consider different fuels (e.g., methane –, ethane –, or propane – based flare streams) and the impact of adding inert compounds (e.g., nitrogen or carbon dioxide) to the fuels. The following sections will contain a presentation of this material in a step-wise manner in order to isolate the relative effects of changing each of these parameters while the others remained fixed. The results of the efficiency experiments with natural gas and propane flares are presented first in terms of the changing wind speed, then in terms of changing flare gas exit velocity, and finally with respect to changing stack diameter. Once those results are presented, a simple model based on the relative magnitude of buoyancy and momentum is developed to collapse the efficiency data together for each of the gas compositions. The final experimental data of this section is presented to show the profound effect of the addition of inert compounds on flare efficiency. This data is then used to create a more generalized expression to predict the efficiency of either natural gas or propane flares as a function wind speed, gas exit velocity, stack diameter, and energy density of the flare stream.

3.5.1 Inefficiency as a Function of Wind Speed

The remaining sections of this chapter discuss the results of measured conversion efficiencies of flares burning gaseous fuels and the development of a semi-empirical model to correlate the data. The results are reported in terms of percentage inefficient, which is simply $(1-\eta)*100\%$, in order to focus on the fuel mass not burned. Experiments were performed following the methodology described in Section 3.2.

Figure 3.15 shows the measured inefficiencies ($1-\eta$) of a 24.7 mm diameter flare burning propane in the presence of a crosswind. These results demonstrate that the crosswind has a strong effect on the combustion efficiency with a dependency that is approximately exponential. At relatively low wind speeds the inefficiencies are quite low ($< 0.25\%$), but as the crosswind is increased the inefficiency rises dramatically. For the data in Figure 3.15, there is an apparent breakpoint in the curve in the vicinity of 2% inefficiency, after which the combustion efficiency degrades extremely rapidly with further increases in the wind speed. However, at low to moderate wind speeds the conversion efficiency is quite high. In order to present a reference point for the wind speed, it should be noted that the mean wind speed for Alberta is approximately 2.2-5.3 m/s [33]. Deviations in wind speed from these means can be considerable, but over 95% of wind speeds recorded in Alberta are below 10 m/s.

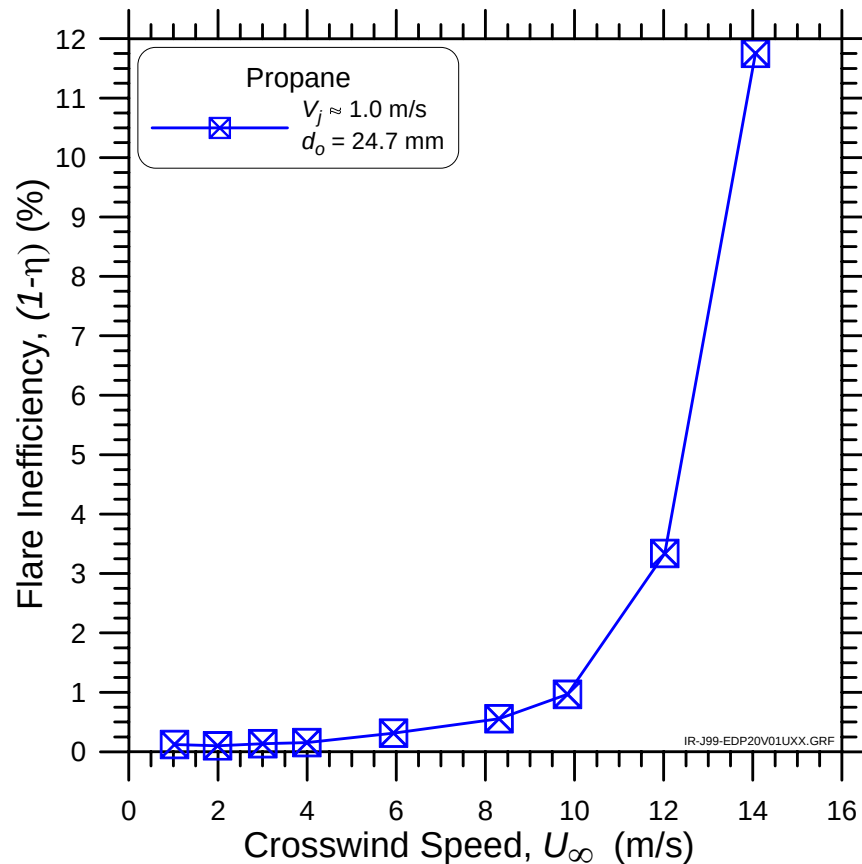


Figure 3.15: Effects of crosswind on the inefficiency of a 24.7 mm propane flare

Similar results for the same flare burning natural gas are shown in Figure 3.16. Again, the inefficiencies are very low at low wind speeds but rise dramatically as the crosswind is increased. The natural gas flames are, however, more susceptible to the effects of the crosswind and it takes lower wind speeds to induce comparable levels of inefficiency to those found in propane flares. Also, the dramatic rise in the inefficiency at high crosswind speeds is less severe. For example, at a crosswind speed of 8 m/s, with a 1 m/s exit velocity, a 24.7 mm diameter flare burning propane has an inefficiency of 0.5%, but under the same conditions with natural gas the inefficiency is 4.5 %.

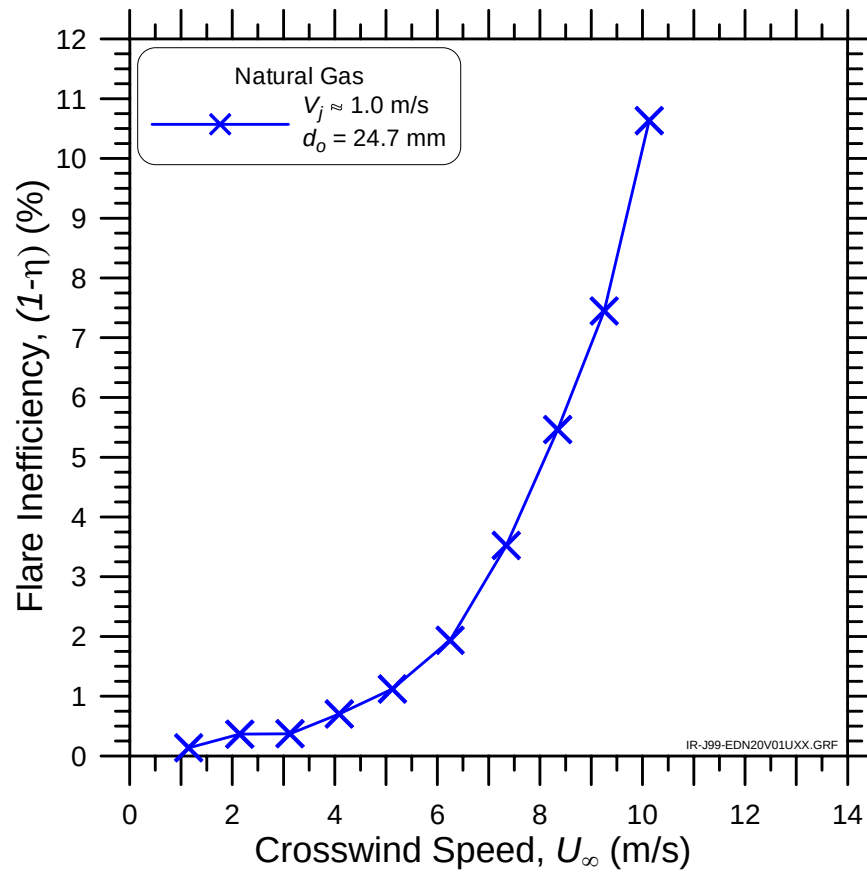


Figure 3.16: Effects of crosswind on the inefficiency of a 24.7 mm natural gas flare

These results are important for two reasons. First, the data at low wind speeds agrees with earlier research conducted by the Energy and Environment Research Corporation that was funded by the EPA [7-9]. As explained in Section 1.2, this earlier work tested flares under restricted wind conditions and found that efficiencies were almost uniformly above 98 %. Both the natural gas and propane data from the current work suggests efficiencies above 99 % at wind speeds below 2 m/s. Second, the current results have identified the trend for a strong rise in inefficiency at high wind speeds, which had not been demonstrated previously.

3.5.2 Effects of Varying Gas Exit Velocity

Although the data presented in the previous section have shown that the crosswind speed is extremely important in determining the efficiency of a flare, it is but one of many

important parameters. Figure 3.17 shows a family of inefficiency curves for the 24.7 mm propane flare burning at three different fuel jet exit velocities, V_j . The data demonstrate that the efficiency of the combustion also depends on the mean fuel jet exit velocity, V_j . Higher velocity fuel jets are less sensitive to the effects of crosswind. For example, at $U_\infty = 12$ m/s, the 1 m/s propane jet has an inefficiency of 3.5 % whereas for the 2 m/s propane jet, the inefficiency is only 1 %.

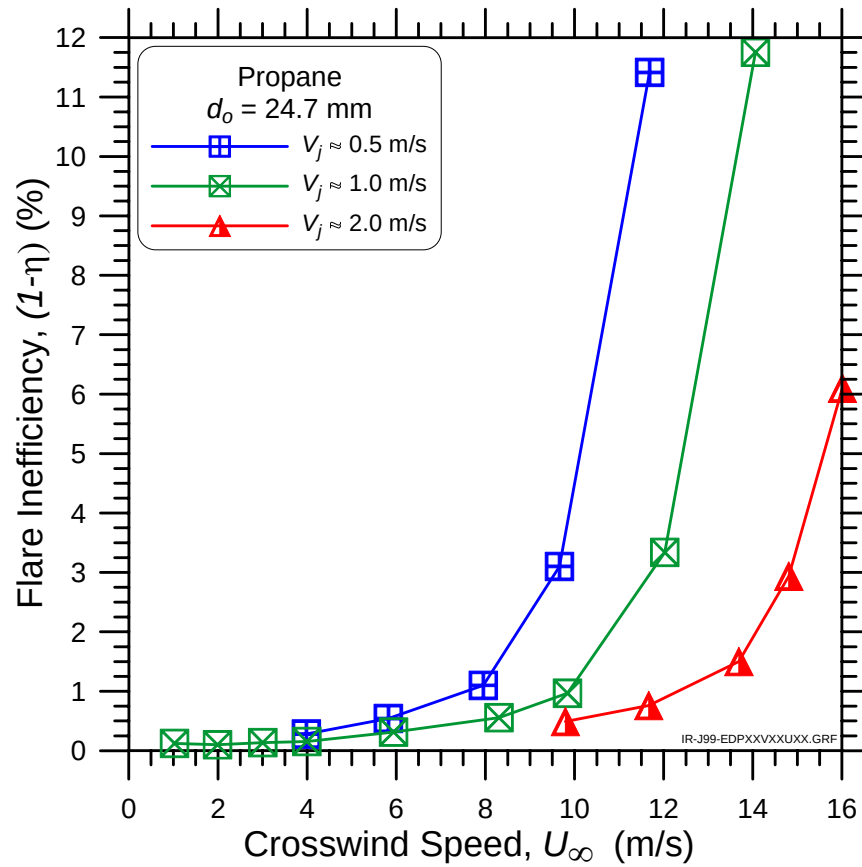


Figure 3.17: Effects of varied flare gas exit velocity on the inefficiency of a 24.7 mm propane flare

Data for a comparable natural gas flare at a variety of exit velocities are shown in Figure 3.18. The influence of fuel jet exit velocity on efficiency is again apparent, and for both the natural gas and the propane data the effect is non-linear. For example, for the natural gas flare, the difference between curves for $V_j = 0.5$ and 1 m/s (a difference of 0.5 m/s) is more apparent than the difference between the curves for $V_j = 2$ and 4 m/s (a difference of 2 m/s). Thus, although higher exit velocity flares would appear to be more efficient in

terms of their resilience to the effects of crosswind, this effect diminishes as the exit velocities are increased.

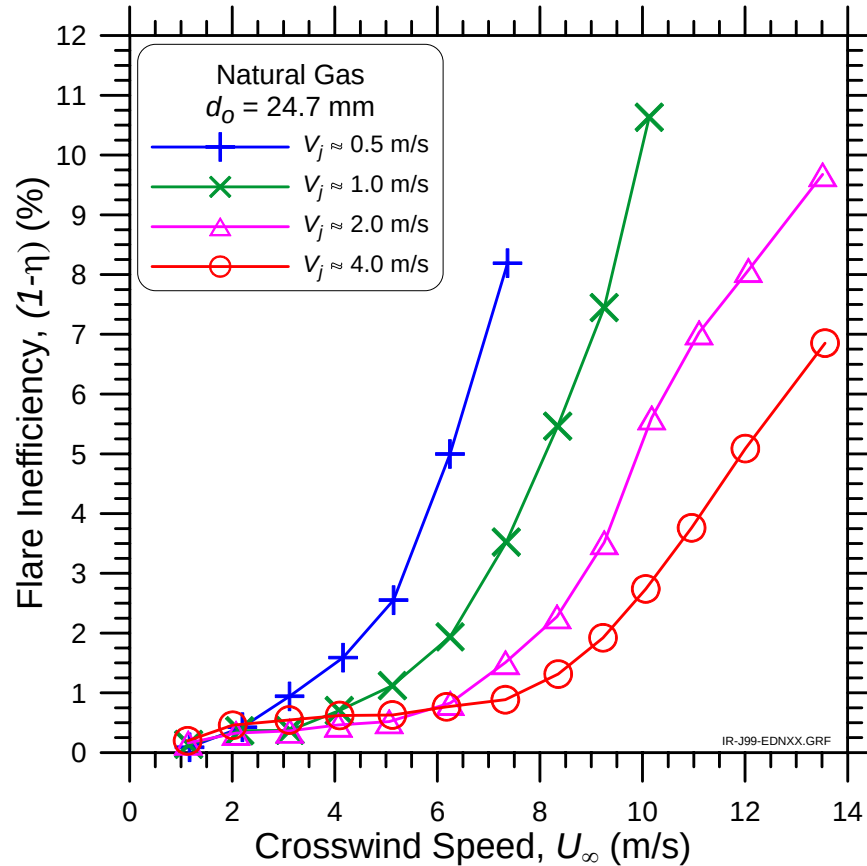


Figure 3.18: Effects of varied flare gas exit velocity on the inefficiency of a 24.7 mm natural gas flare

These conclusions regarding the effects of increasing flare gas exit velocity need to remain bounded within the context of the exit velocities tested and the prevailing flow regimes (i.e., low values of R). Extrapolation of these results to high-velocity jets would be unwise without further evidence. In a practical sense, these conclusions apply to situations like solution gas or acid gas flares, but not to emergency or well-test flares. Some results will be presented in Chapter 8 regarding higher exit velocity jets.

3.5.3 Effects of Varying Stack Diameter

The effects of changing the diameter of the flare stack have also been investigated and are of primary importance to the application of this work. Figure 3.19 shows a family of

inefficiency curves for four flares of different outside diameters, d_o , burning propane at a fixed exit velocity of 1 m/s. The same characteristic curve shapes are apparent for each of the different flare diameters with larger-diameter flare stacks being slightly more resistant to the effects of increased crosswind speed. For example, at a wind speed of 11 m/s, the 18.6 mm diameter propane flare operates at an inefficiency of 9 % whereas the inefficiency of the 37.2 mm diameter flare is only 1%.

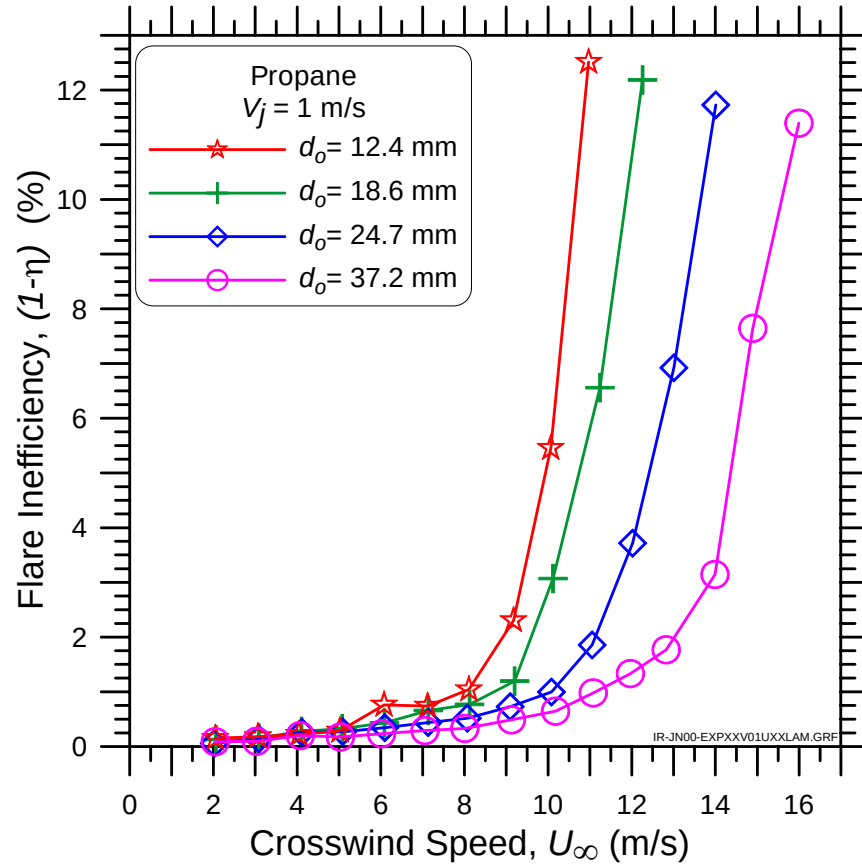


Figure 3.19: Effects of flare stack diameter on the inefficiency of a 1 m/s exit velocity propane flare

Figure 3.20 shows a similar set of inefficiency curves for a series of different diameter flares burning natural gas. For both the propane and the natural gas data sets, the effect of increasing the flare diameter on the efficiency of the flares is again non-linear. However, at this point, the most important observation is that the trends of inefficiency as a function of wind speed are the same for all diameters – low inefficiency at low wind speeds and increased inefficiency with increased wind speed. This similarity suggests

that the results are scalable over a range of diameters. This hypothesis is investigated further in chapter 8.

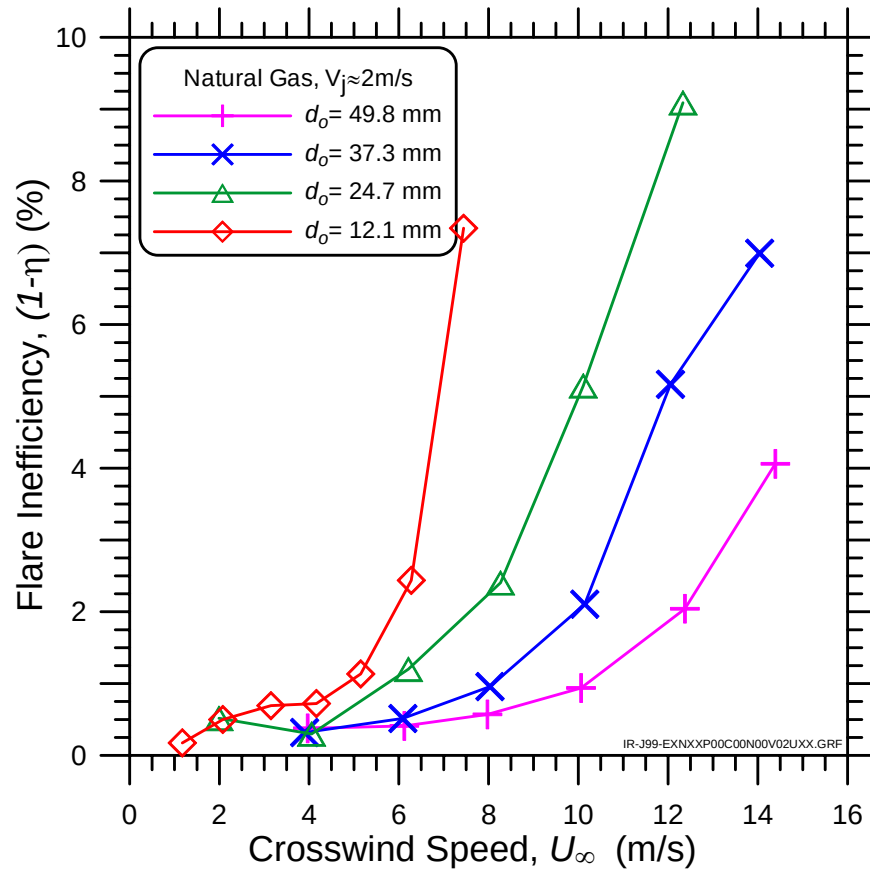


Figure 3.20: Effects of flare stack diameter on the efficiency of a 1 m/s exit velocity natural gas flare

3.5.4 A Model for Flare Streams of Fixed Composition

The data presented in the previous three sections highlight the complexity of gas flaring. Basic input parameters such as wind speed, fuel exit velocity, fuel composition, and flare diameter all have varying effects on the efficiency of a flare. The fact that these parameters all vary in the field underscores the need for a broad understanding of the behavior of solution gas flares as opposed to individual and consequently unusable data points.

Initial attempts to model the combustion efficiencies of these flares involved trying to connect geometric similarities in the mean flame shape to the measured inefficiencies. The photographic images presented in Section 3.3 and in other works [22-27, 34] suggest

that the momentum flux ratio (R) is important in determining the flame shape. Unfortunately, the inefficiency data do not collapse with respect to R since the magnitude of inefficiency shows a significantly greater dependency on U_∞ than V_j , whereas the parameter R weights these velocities equally.

Figure 3.21 shows correlated data for the 24.7 mm flare burning either natural gas or propane at a variety of exit velocities. The parameter $U_\infty / V_j^{1/3}$ successfully predicts the effect of varied flare gas exit velocity on flare efficiency. This parameter originates from the ratio of the buoyancy flux, the density difference of the fuel jet and the ambient air, to the momentum flux of the crosswind. This ratio of fluxes is known as the Richardson number and after some algebraic manipulation the relationship $U_\infty / V_j^{1/3}$ can be derived [35]. This same theory also suggests that $d_o^{1/3}$ should be the relevant scaling parameter for the effect of flare diameter on efficiency. Figure 3.22 shows the data for different diameter propane flares of Figure 3.21 but now collapsed onto a single curve using the non-dimensional parameter $U_\infty / (g V_j d_o)^{1/3}$, where g is the gravitational constant.

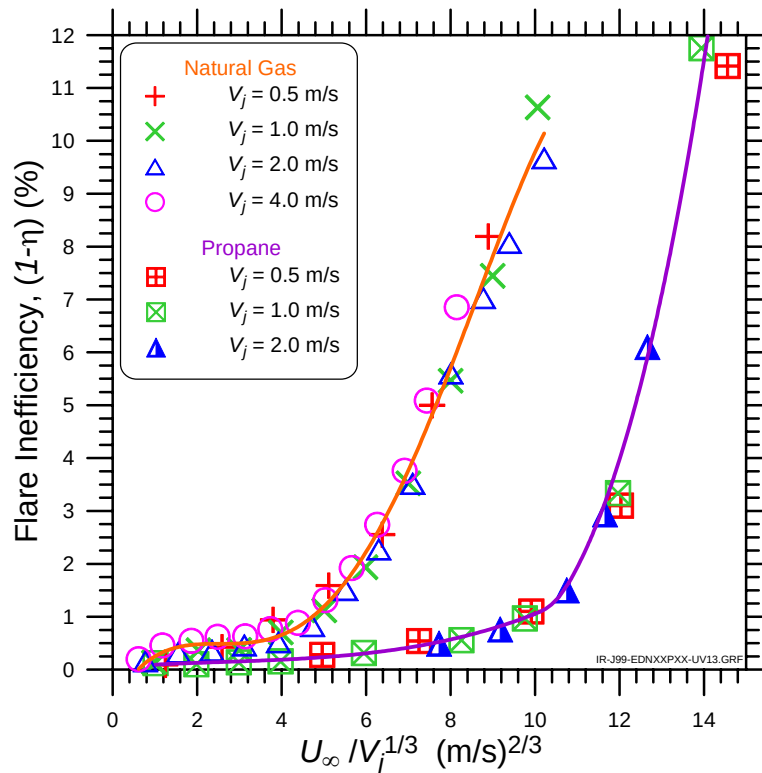


Figure 3.21: Exit velocity correlation for Natural Gas and Propane flares

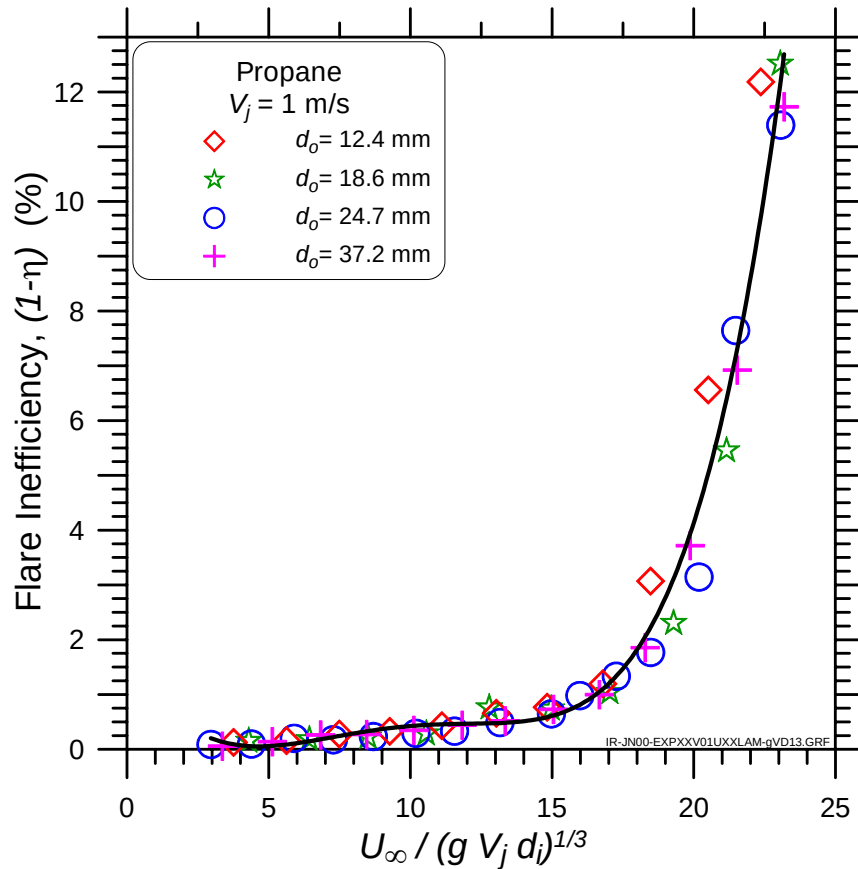


Figure 3.22: Correlated effects of changing flare stack diameter on the inefficiency of a flare burning propane

Although the collapsing of the data by this Richardson number based model is encouraging and lends some credibility to the importance of buoyancy and momentum in these flows, important aspects of the data are not described by this approach. The main issue being that it is difficult to account for variations in fuel composition.

3.5.5 The Efficiency of Flares with Fixed Fuel Composition but Added Diluents

To explore the effects of fuel composition, efficiency experiments were systematically conducted with propane- and natural gas-based flare streams. For each of these fuel types, the flare stream was diluted with nitrogen and carbon dioxide (0 to 80% by volume) while keeping d_o and V_j fixed. These experiments were conducted to identify the relative importance of density, momentum flux, and relevant thermal-physical properties of the fuel stream.

3.5.5.1 Propane Based Flare Streams

Figure 3.23 shows inefficiency curves for several mixtures of commercial-grade propane diluted with N_2 and CO_2 . Since propane and CO_2 have the same molecular mass, working with mixtures of these gases allowed the mass density and momentum flux of the flare stream to be held constant while other parameters including the energy density (MJ/m^3) were varied. The data show that increasing CO_2 in the fuel had a strong, non-linear impact on the inefficiency of the flare. Energy density is reported as both the higher heating value (HHV) and the lower heating value (LHV) on the graphs (i.e. HHV/LHV). As the fuel energy density is reduced, the flame becomes more susceptible to the crosswind, and the rapid rise in inefficiency begins at much lower wind speeds. For the minimum energy density mixture that was tested ($18.7\text{-}MJ/m^3$ HHV), the flare falls to below 80% efficient before the wind speed reaches 5 m/s. If the energy density is reduced further the flames destabilize, separate from the stack, and extinguish.

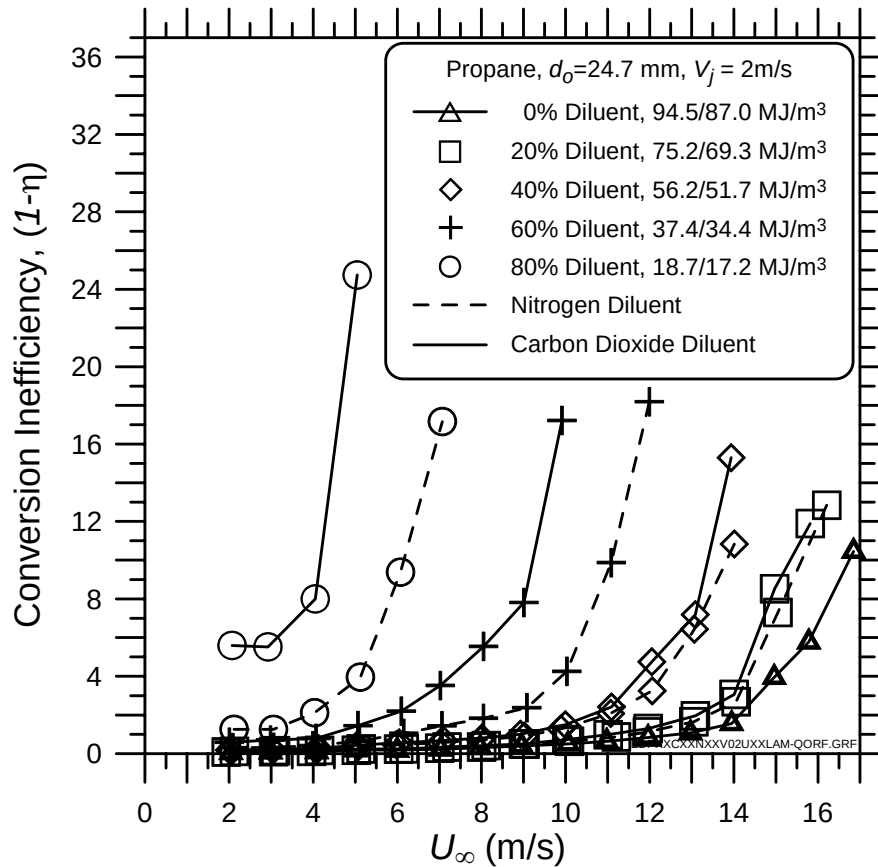


Figure 3.23: Inefficiency of Propane / N_2 and Propane / CO_2 flares at $V_j=2\text{-m/s}$ and $d_o= 24.7\text{-mm}$. Reduced energy density has a significant, adverse effect on inefficiency. Effect of increased N_2 is strong, but less than that of added CO_2 .

Figure 3.23 also shows results for propane/N₂ fuel mixtures at the same energy densities as the propane/CO₂ mixtures. As the energy density is reduced, however, the mass density and momentum flux decrease. Despite these complicating features, the data show distinct similarities — as the amount of diluent was increased, the efficiency of the flame was adversely affected. Comparison of data for the two diluents reveals that adding CO₂ had a slightly greater effect than adding N₂ in equal volumes. This difference in efficiency between the two gases increased with the amount of dilution. Since the energy density is unaffected by choice of diluent, this implies the importance of mass density and/or potentially some other thermal-physical properties (e.g. heat capacity or thermal conductivity etc.). These parameters have been considered and will be discussed below.

3.5.5.2 Natural Gas Based Flare Streams

Figure 3.24 shows the measured inefficiencies of various natural gas/CO₂ and natural gas/N₂ blends as functions of the crosswind velocity. The same trends evident in the propane blend data are again apparent, although the natural gas based flares are far more susceptible to the crosswind.

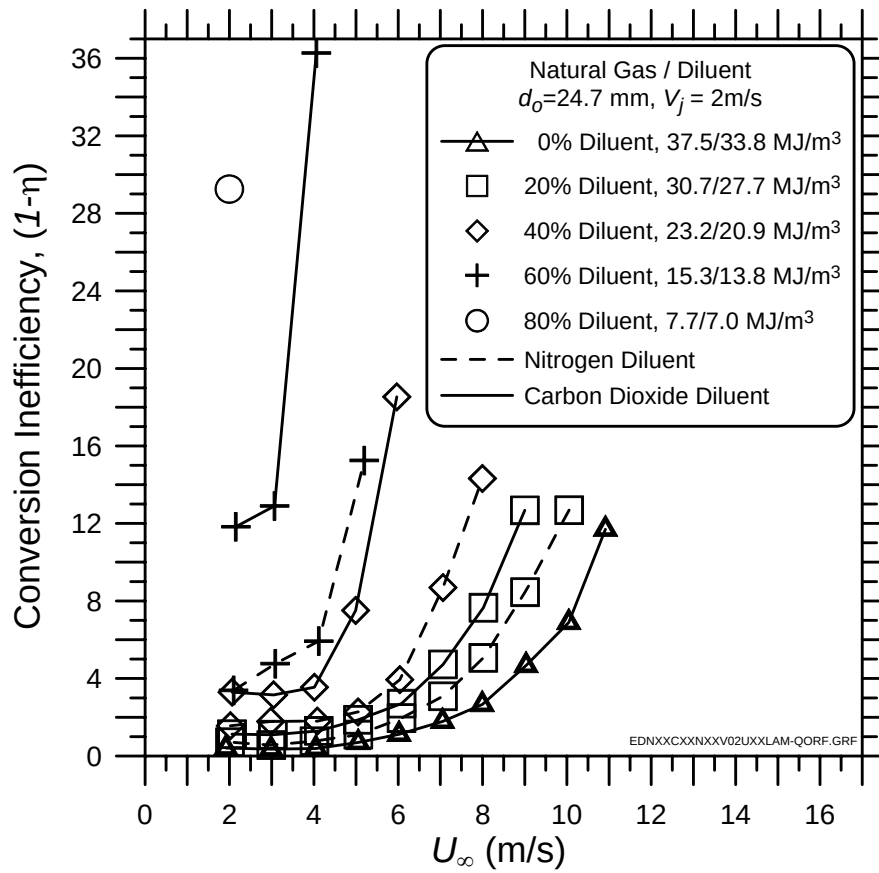


Figure 3.24: Inefficiency of Natural Gas / N₂ and Natural Gas / CO₂ flares at V_j=2-m/s and d_o = 24.7-mm. Curves are displaced vertically as well as to the left with increased diluent fraction.

The families of inefficiency curves of the natural gas blends exhibit a second trend that is more noticeable than in the propane based data. At high diluent levels, the inefficiency curves of natural gas based blends shift upward as well as to the left. Although, this is apparent in the propane/CO₂ data of Figure 3.23, it is more significant in Figure 3.24. At lower wind velocities, extrapolation of the natural gas/CO₂ and natural gas/N₂ curves show that some differences in inefficiency would remain at a crosswind velocity of 0 m/s. This secondary trend presents an added difficulty in modeling the data and suggests that energy density, in some form, will be needed in addition to the partial Richardson number expression used previously.

3.5.5.3 Modeling the Effects of Diluents in the Fuel

With the possible exception of the vertically displaced natural gas inefficiency curves noted above, all of the inefficiency curves in Figures 3.23 and 3.24 seem sufficiently alike that they should be governed by the same physical processes. Unfortunately, the mechanism driving the inefficiencies is complex and a general model to describe all of the data in these figures has yet to be developed.

Some qualitative understanding of the relative importance of the various fluid properties can be made by comparing results from natural gas and propane flares as the levels of dilution increase. As a common diluent is added to each fuel, the thermal-physical properties of the two mixtures converge. For example, the single data point for 80% N₂ in natural gas has a mass density only 17% less than its propane/N₂ counterpart, even though the mass density of natural gas is 62% less than propane. There is a similar convergence concerning the jet momentum flux and the fluid properties such as thermal conductivity and thermal diffusivity. Conversely, the ratio of energy densities between the fuel streams remains constant (~2.5) with increased dilution (or reduced energy density). Reviewing Figures 3.23 and 3.24 shows that the inefficiency curves for the two fuel types with the same diluent continue to diverge with increased dilution. Thus, although the fluid mechanics in the flares converge with increased dilution, the efficiency diverges suggesting that the energy density is a primary variable in determining flare efficiency.

Figure 3.25 shows inefficiency curves of four different fuel blends with similar energy densities and identical stack diameters and exit velocities (i.e., keeping the identified principle variables constant). At this point, results from ethane/N₂ fueled flares are introduced to have a broader range of data for discussion. Although these curves show the same general trend, they are not coincident and demonstrate that energy density alone does not determine inefficiency. Table 3.1 provides a list of potential parameters that could affect the combustion efficiency. The maximum and minimum dilutions with air are included as an alternate characterization of the onset of flame extinction (as opposed to energy density). Thermal diffusivity is included as a surrogate for the kinematic

property of laminar flame speed [36], which has been used in jet diffusion stabilization studies [37] but could not be reliably calculated here for all these mixtures.

Comparison of these curves and the parameters in Table 3.1 suggest that no simple monotonic dependency can explain the differences in the inefficiency data. For example, the mass density of the flare stream (raised to some power and made non-dimensional by a ratio with the density of air) could be introduced to bring the ethane and propane data together, but the natural gas data would remain separate. Similar attempts using any of the other parameters in Table 3.1 fail in similar ways. From these results, it is apparent that until a more complete understanding of the inefficiency mechanism is available, separate models will be needed for natural gas based flares and either propane or ethane based flares.

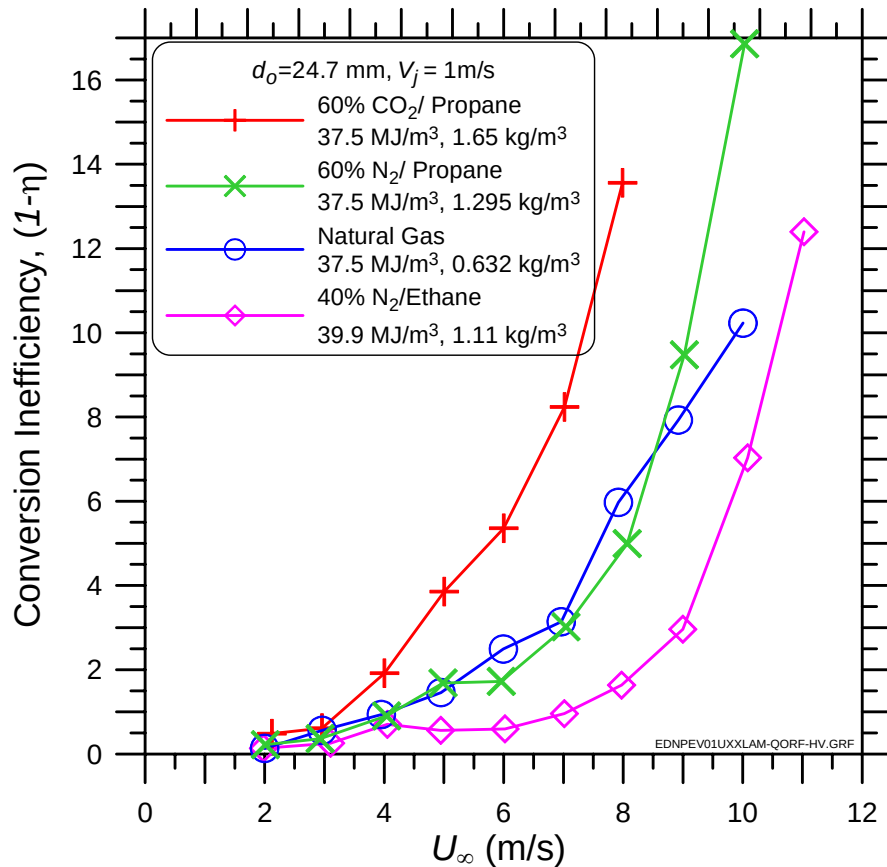


Figure 3.25: Comparison of inefficiency curves of four different fuel blends with similar energy densities. Using the parameters listed in Table 3.1, there is no simple monotonic trend that can be used to correlate data from all four curves.

Table 3.1: Properties of different fuel blends shown in Figure 3.25

Property (Evaluated at 298 K and 1 atm unless otherwise stated)	40% Propane / 60% CO ₂	40% Propane / 60% N ₂	Natural Gas	60% Ethane / 40% N ₂
Energy Density (MJ/m ³) @15 C	37.5	37.5	37.5	39.9
Mass Density (kg/m ³)	1.65	1.30	0.63	1.11
Heat Capacity (J/mol-K)	51.7	46.7	35.7	43.3
Maximum Dilution ^a	17.7	18.8	19.6	20.0
Minimum Dilution ^a	5.3	5.5	6.6	5.8
Thermal Conductivity (W/mK)	0.0171	0.0224	0.0352	0.0231
Thermal Diffusivity (m ² /s)	0.803E-5	1.16E-5	2.42E-5	1.30E-5

a – Ratio of volume of air to volume of fuel mixture

Figure 3.26 shows an empirical correlation incorporating all of the data shown in Figures 3.23 -3.25 and additional data for ethane/N₂ blends ranging from 0 to 80% N₂, with the dimensionless parameter $U_{\infty}/(gV_j d_o)^{1/3}$ on the horizontal axis. The vertical axis is the inefficiency scaled by the cube of the mass-based lower heating value (LHV_{mass}). The use of the mass-based heating value implies the importance of specific heat release to support combustion and incorporates the mass density into the problem as suggested by Figure 3.25. The choice of its exponent is justifiable only because it correlates the data. Attempts to incorporate the heating value into the term on the horizontal axis instead of the vertical axis were less successful, showing that the connection between inefficiency and $U_{\infty}/(gV_j d_o)^{1/3}$ is not a simple power-law relationship.

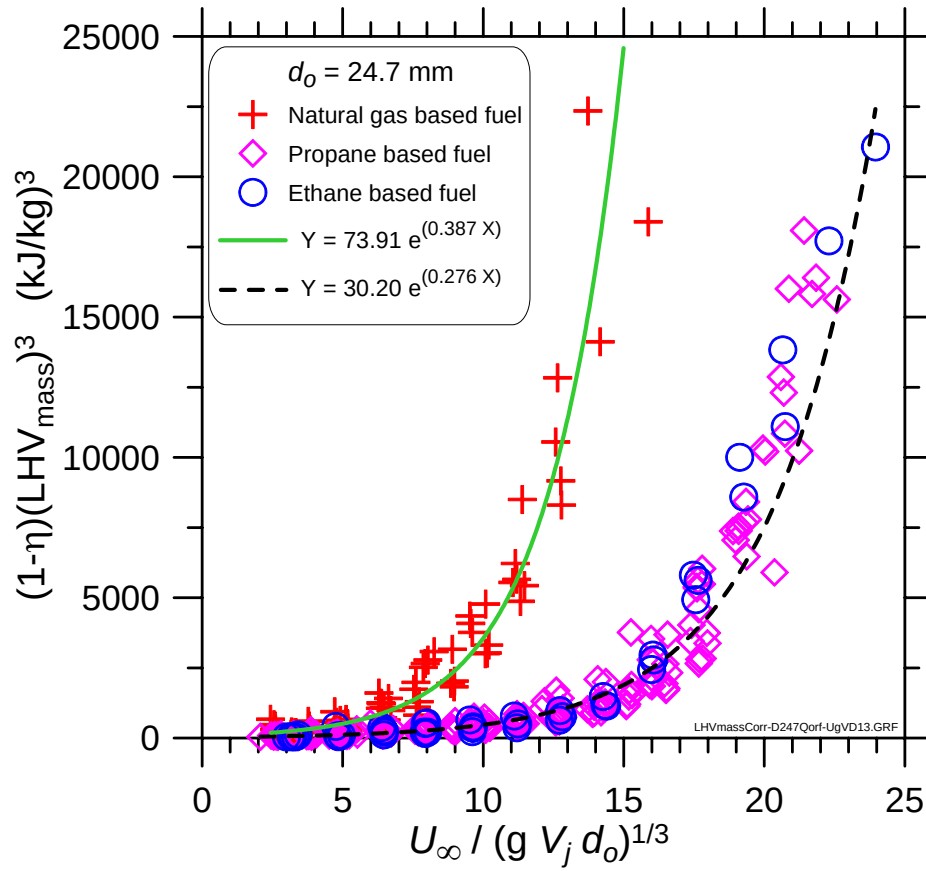


Figure 3.26: Empirical correlation for various fuel blends (hydrocarbon base plus either CO₂ or N₂) using mass-based lower heating value. Note that d_o is constant for all data. Propane and ethane based data follow the same trend where as natural gas based data are displaced.

Figure 3.26 includes fuel streams based on natural gas, ethane, and propane with CO₂ or N₂ as diluents although it must be noted that the burner tube diameter, d_o , is constant at 24.7 mm for all data. While this plot has significant practical utility, it is most interesting that the propane- and ethane-based data follow the same trend, which is separate from that of the natural gas-based data. This may be an indication that the inefficiency mechanism(s) of natural gas are somewhat different than those of ethane and propane.

3.5.6 A Parametric Correlation for Combustion Inefficiency

Based on the above data, a parametric correlation was developed. This data will be revisited in Chapter 8 in order to test its validity to larger-scale flares. The physical parameters that influence combustion efficiencies, shown in the above work to be

important, are: fuel type, wind speed (U_∞), exit velocity (V_j), stack outside diameter (d_o), and the specific energy content of the fuel mixture (expressed here as the lower heating value, LHV_{mass}). The above experiments revealed that increasing the amount of diluent in the fuel has a profound effect on inefficiency ($1-\eta$) in that reduced energy density flames become much more susceptible to the effects of the crosswind resulting in lower combustion efficiencies. A model was developed to correlate experimental data spanning $2 \leq U_\infty \leq 17$ m/s, $0.5 \leq V_j \leq 4$ m/s, $12.2 \leq d_o \leq 49.8$ mm with fuel dilutions using CO_2 or N_2 of up to 80% (by volume). This model is

$$(1-\eta) \cdot (\text{LHV}_{\text{mass}})^3 = A \cdot \exp\left(B \frac{U_\infty}{(gV_j d_o)^{1/3}}\right) \quad (\text{Eq. 3.14})$$

where A and B are coefficients and $U_\infty/(gV_j d_o)^{1/3}$ is a dimensionless parameter based on the partial Richardson number. The inclusion of LHV_{mass} to the third power emphasizes the importance of the specific energy density of the fuel stream in affecting the combustion efficiency. Separate coefficients were needed to describe natural gas and propane or ethane based flare streams. For natural gas based flare streams the data used to estimate the coefficient comes from those presented in this chapter and Chapter 8, which includes flares up to $d_o \leq 114.3$ mm, and resulted in $A = 133.3 (\text{MJ/kg})^3$ and $B = 0.317$. (These coefficients are consistent with those presented in Chapter 8 which arises from the non-dimensional form of Equation 3.14 that resulted from normalizing the lower heating value of the flare stream with the lower heating value of methane.) For propane and ethane $A = 32.06 (\text{MJ/kg})^3$ and $B = 0.272$.

3.6 CONCLUDING REMARKS

This chapter had three main objectives. The first objective was to identify the principal mechanisms that create inefficiencies in flares exposed to cross winds. The second objective was to identify the important parameters that affect the inefficiency of flares. Integral to this second objective was the quantification of these effects through controlled experiments. As part of meeting these first two objectives, experimental methodologies

had to be developed. The third objective was to develop a simple, phenomenological model based on, and validated with respect to, the collected data that could be used to estimate or predict the efficiency of flares as a function of wind speed, flare gas exit velocity, stack diameter, and flare stream composition.

The gas chromatograph analyses of the emissions from flares operating in the wind tunnel at the U of A showed that the dominate cause of inefficiency was a fuel-stripping mechanism. This phenomenon resulted in raw fuel being stripped from the flare stream and dispersed in the atmosphere without being involved in combustion. In order to verify these results, single-point hydrocarbon measurements were also taken in and around the flame to trace the origins of the stripped fuel. The bulk of the stripped fuel was being emitted in intermittent bursts from the underside of the flame in the wake of the flare stack. A two-dimensional flow visualization technique was developed and used to characterize the fuel-stripping mechanism. The goal of this new technique was to photograph the ejection of raw fuel from the flame. Ultimately, this technique showed of how a packet of raw fuel, which leaves the flare stack, can be transported through a physical region where the flame exists and be emitted in bursts of unburned fuel. The principal feature of this mechanism for inefficiencies due to fuel stripping is the standing vortex that exists on the leeward side of the flare stack. The interaction between this vortex and the ring vortices that emerge from the stack results in the fragmentation of the flame into discrete pockets as captured in the high-speed photographs. Within this fragmentation process not all of the fuel packets interact with the flame and, as such, are transported by the standing vortex, unchanged, to a location beneath the flame. This ejected raw fuel remains physically separated from the flame so it does not ignite and is dispersed into the ambient air resulting in combustion inefficiencies.

The implication of this fuel-stripping mechanism for the field operation of flares is that hydrocarbon emissions will be characterized according to the gas type of the flare stream, i.e., primarily methane flares will have emissions dominated by methane. The emission of methane into the atmosphere has a greater greenhouse gas effect than the emission of carbon dioxide resulting from the complete combustion. This mechanism for reducing

the combustion efficiency has more serious local implications for flares that contain H_2S . Applied to sour gas flares, this mechanism would result in increased inefficiencies such that the emissions of interest would shift from SO_2 to H_2S .

The overall combustion efficiency of pipe flares in a crosswind was measured over a range of operating conditions. This combustion efficiency is defined by the effectiveness of the flare to oxidize carbon, contained within the hydrocarbon fuel of the flare stream, to carbon dioxide. The fuels used in these experiments were either undiluted sales-grade natural gas, undiluted commercial-grade propane or these same fuels diluted with carbon dioxide or nitrogen. The flares tested included stacks with outside diameters ranging from 12.1 to 49.8 mm and flare gas exit velocities ranging from 0.5 to 4 m/s. The wind speed was varied from 1 to 16 m/s.

A methodology to calculate the overall efficiency of flares burning in a closed-loop wind tunnel was developed and derived from the mass-based conversion of the major carbon containing species in the emitted gases. The principle behind this methodology was to track the rate of the accumulation of the major carbon containing species in the wind tunnel to determine the relative amount of carbon in the fuel being fully oxidized to carbon dioxide. Implicit to this experimental method was the assumption that the gas-phase carbon dioxide, carbon monoxide and hydrocarbons dominate the carbon mass in the combustion products. This assumption limited the testing of flare streams to those flares with a low propensity to emit soot. An uncertainty analysis of this method concluded that errors in the measured efficiency were approximately $\pm 0.6\%$ absolute.

One of the most important conclusions of the above research was that the wind had a strong impact on the combustion efficiency of these flares. At calm and low wind speeds, the efficiencies of natural gas and propane flares were very high ($> 99.5\%$). With increased wind speed, the efficiency fell slowly and then, at high wind speeds, there was a dramatic decline in the efficiency caused by the stripping of fuel. The critical wind speed at which the efficiency rapidly dropped depended on the exit velocity of the flare stream, the size of flare stack, and the composition of the flare gas. In all cases, the

dependency of efficiency on wind speed was approximately exponential. The observed dependency of the overall efficiency on changes in exit velocity and stack diameter was less dramatic than the dependency on wind speed. Flares with higher exit velocities and larger stack diameters were less susceptible to effects of wind.

By considering the ratio of the buoyancy flux of the gases to the momentum flux of the wind as the important parameters defining the flow, a simple model was proposed to connect the effects of wind speed (U_∞), exit velocity (V_j), and outside stack diameter (d_o). This suggested model resulted in the parameter $U_\infty / (V_j d_o)^{1/3}$. The use of this parameter was successful in collapsing the data for the individual flare gas stream compositions but it did not bring the data together from different fuels. The effectiveness of the parameter $U_\infty / (V_j d_o)^{1/3}$ was exceptionally effective for describing data from propane-fueled flares. However, data from natural gas flares showed a slightly increased dependency on flare stack diameter compared to $U_\infty / (V_j d_o)^{1/3}$. The main conclusion of this research is that flare efficiency correlates well with the ratio of the buoyancy flux of the gases to the momentum flux of the wind, and not with the ratio of the flare jet momentum flux to the momentum flux of the wind.

The effects of flare stream composition were explored by diluting the fuel (either methane in the natural gas flares or propane) in the flare stream with either carbon dioxide or nitrogen. The efficiency of the flare was shown to be highly sensitive to the volumetric dilution of the fuel in the flare stream by these inert compounds. It was further discovered that the effect on efficiency was dependent on the composition of the inert compounds added. On a volumetric basis, the addition of nitrogen was found to result in larger inefficiencies than similar conditions using carbon dioxide. Once the energy density was reduced below 20 MJ/m^3 , the efficiency no longer approached 100 % in calm winds. Below an energy density of 15 MJ/m^3 (HHV), the flame became unstable and there were significant conversion inefficiencies at wind speeds as low as 1 m/s. Based on these results, a semi-empirical relationship was developed that can be used to predict the carbon conversion efficiency of either natural gas or propane flares as a function of the wind speed, exit velocity, stack outer diameter, and the specific lower

heating value of the flare stream that accounts for the dilution of the fuels with inert compounds.

4 SCALING THE PLUMES OF FLARES IN A CROSSWIND

In the previous chapter, the focus of the research was to characterize and understand the overall combustion efficiency of a flare with respect to wind speed, flare gas exit velocity, stack diameter, and flare gas composition. In this and the following chapter, the focus shifts toward examining the plume of combustion products that is emitted by the flare. Chapter 5 presents information on the local composition (local efficiencies) of the plume of combustion products emitted by the flare as determined by point sampling from within the plume. The value of this technique is the flexibility to use it in an open wind tunnel environment where the products of combustion do not accumulate over time. This technique will again be used in Chapter 8 which explores the efficiencies associated with larger scale flares tested at the NRC facility. However, before discussing those results it is necessary to have an understanding of the size and shape of the plume and how the plume evolves as it is created. In addition, by studying the overall structure of these plumes, relationships can be established to help demonstrate the scalability of these flows.

The wind tunnel used in these experiments is part of the University of Alberta Flare Research Facility and was described in detail in Chapter 2. The experiments were conducted in a low turbulence crosswind to preserve, as much as possible, the coherent structures of the plumes. These structural features of the plume provide important information regarding the fluid mechanics in the near field of the flame, as well as capture the large-scale influences of the stack on the flow. Furthermore, by relating the features seen in the plumes of flares to those in non-reacting buoyant plumes, a framework for scaling the size of these plumes was developed with respect to wind speed, exit velocity, and stack diameter. Understanding these features of the flow were important in interpreting compositional measurements taken within the near plume of a flare and helps also in understanding the origins of the inefficiencies (Chapters 3 and 5).

4.1 EXPERIMENTAL SET-UP AND METHODOLOGY

Since the products of combustion near a flare are hot with respect to the ambient crosswind, the method used here for tracking the mean plume was to measure the mean temperature of the flow-field downstream of the flare. The temperature-sensing elements used for these measurements were unshielded type-T thermocouples with a junction size of approximately 0.5 mm in diameter. Thermocouple junctions of this size are too large to be used to track sharp fluctuations in gas temperature as the products of combustion mix with the cool ambient air, but can provide a good measure of mean temperature.

To measure the mean temperature, the thermocouple voltage was sampled 500 times a second over a 10-second period. These 5000 sampled voltages were converted to temperature, which were then averaged to calculate the mean temperature at the measurement point. Longer sampling times were tested but the 10 second average was shown to provide a representative mean temperature in this steady flow situation.

In order to visualize the thermal plume structures, two-dimensional cross-stream mappings were constructed by taking many mean temperature measurements within a chosen y-z plane downstream of the flare. The co-ordinate system used in these experiments was shown in Figure 2.3 where the +z direction creates a right-hand system and the origin is located at the top and center of the flare stack. These two-dimensional mappings were collected at various downstream locations and allowed the evolution of the plume to be followed in the stream-wise direction.

In order to collect the amount of data needed to create these mappings in a timely manner, a rake of 27 thermocouples spaced 2 cm apart was mounted along a 60 cm long holder. The rake of thermocouples was oriented horizontally and the computer-controlled traverse was used to position it in the flow. For these experiments, the rake was moved in 2 cm vertical steps across the full height of the plume, which resulted in up to 910 mean temperature measurements being recorded at each downstream location. The total time to collect a single temperature mapping was of the order of five minutes. The wind tunnel was then purged of the accumulated combustion products in preparation for taking the next set of measurements

at the next set of test conditions. A schematic of the experimental set-up is shown in Figure 4.1

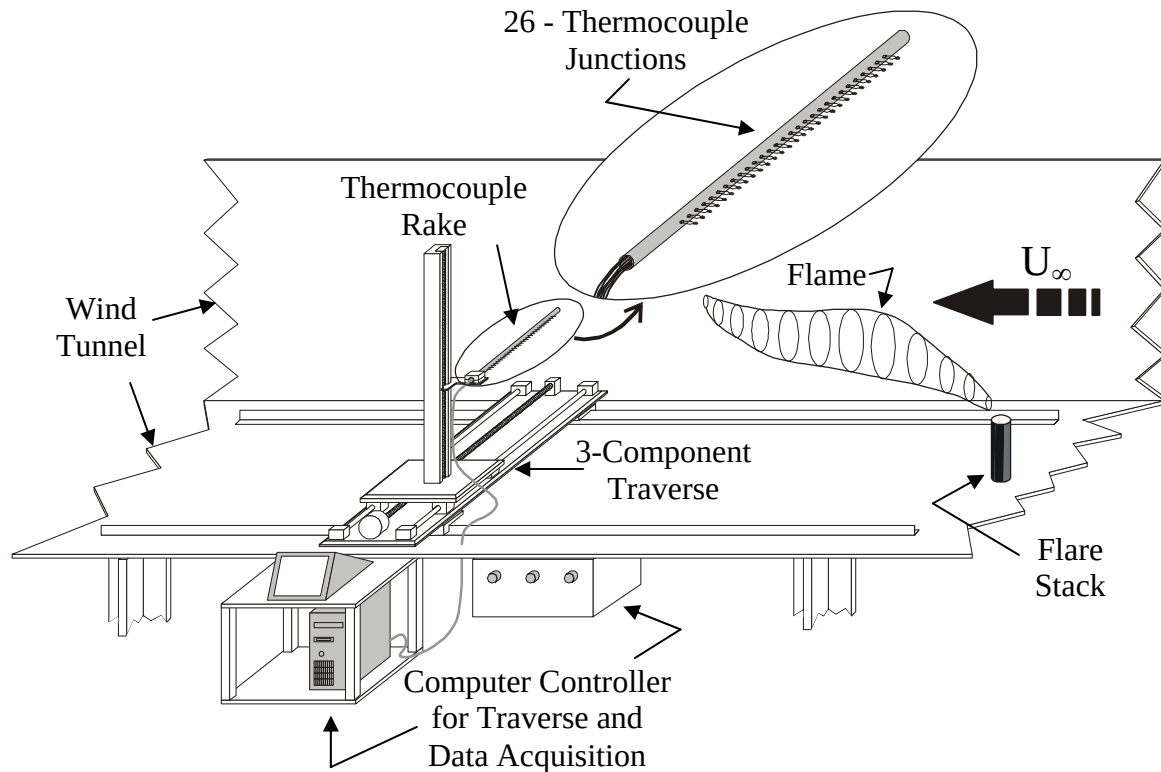


Figure 4.1: Schematic of experimental set-up measuring the mean temperature of the plume downstream of the flare

Using unshielded thermocouples near a flame raised the potential problem of thermal radiation from the flame to the thermocouple that could create large differences between the gas temperature and the thermocouple temperature. To test if this effect was important in this particular flow situation, the mean temperature of a thermocouple placed near the flame was compared to a reference thermocouple placed well upstream of the flare. The thermocouple near the flame was placed approximately 20 cm to the side of the flame where it was exposed to radiation from the full flame length, but was well outside the flow of combustion products. The reference thermocouple was placed approximately five meters upstream of the flare where flame radiation was negligible. On the one hand, when the fuel being flared was natural gas, there was only a one Celsius degree difference between the mean temperatures recorded by the two thermocouples. On the other hand, when propane

was flared, the two thermocouples had a mean temperature difference of over 50 Celsius degree. Consequently, the results presented in this chapter are for natural gas flares only since the radiative component of the heat transfer is much less than that of propane flares.

Figure 4.2 shows a typical mean temperature mapping of the plume of a natural gas flare 2.1 m downstream of a 22.1 mm diameter (d_i) flare stack. The flow conditions that produced this plume were an exit velocity of 1 m/s and a crosswind speed of 3 m/s. The mean temperature field is represented on the lower plane of Figure 4.2 as a three dimensional surface where height is a measure of the temperature. On the upper plane, the same information is presented as a contour plot where the lines are selected isotherms. The various shades of blue on both planes provide a quantitative indication of the mean temperature by referencing the shading to the temperature scale shown as part of the figure. The isotherms and shading will be used to convey a qualitative sense of shape and structure within the plume. Also, shown as part of Figure 4.2 is the projection of the flare stack onto the measurement plane to give a visual reference of the position of the plume relative to the origins of the flare stream.

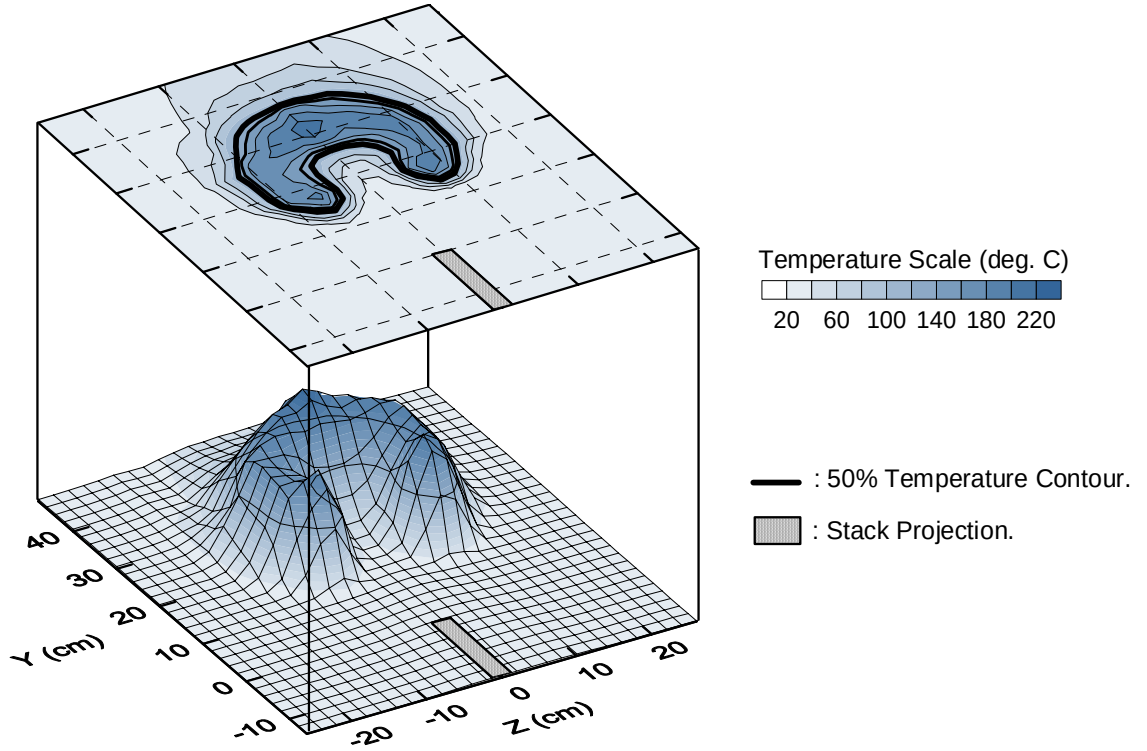


Figure 4.2: Typical mean temperature map of the plume of a natural gas flare. Test conditions: $x = 2.1$ m, $d_i = 22.1$ mm, $U_\infty = 3$ m/s and $V_j = 1$ m/s.

In order to consider the quantitative scaling of the cross-stream size of these plumes, it was necessary to define a characteristic dimension for the plume structure. In the case of plumes whose shape changes dramatically over the range of tests conditions, the characteristic dimension of the plume (d_p^*) cannot be as simple as either the width or height of the plume. The d_p^* used here is defined as the square root of the cross-sectional area contained within the temperature contour defined by the half-mean temperature rise relative to the ambient temperature, which is given by

$$\frac{T - T_\infty}{T_{\max} - T_\infty} = 0.5 \quad (\text{Eq. 4.1})$$

where T = mean temperature contour of interest
 T_{∞} = ambient tunnel air temperature
 $T_{\max}$ = maximum mean temperature in the measurement plane

The bold line in Figure 4.2 shows this 50% temperature contour. The choice of bounding the plume by the half-mean temperature rise is arbitrary but consistent with the notion of a half-width of a jet and is a conveniently conserved scalar for tracking the plume.

4.2 PLUME SIZE AND SHAPE

As mentioned earlier, the mean size and shape of a plume downstream of a flare can provide insight into the dominant flow structures that participated in the combustion of the flare gases and the subsequent dispersion of the products of combustion. The interactions between the flare gases, flame, combustion products, and flow around the flare stack are complex. By independently varying the wind speed (U_{∞}), jet exit velocity (V_j), and flare stack diameter (d_i), these interactions can be observed.

Deducing the dominant flow structures and their interactions with the flame from just the plume shapes is only possible because of a large body of scientific literature on a closely related flow. This related flow is the less complicated case of a non-reacting, buoyant jet issuing from a cylindrical tube into a transverse cross-flowing stream. The plumes created by these non-reacting jets in cross-flow are well documented [c.f., 39-42] and show a striking similarity to the plumes formed by the flares considered here. Given these similarities, the inference is made that the same types of flow structures (e.g., counter-rotating vortices, wake vortices, etc.) exist in both the reacting and non-reacting flows. Other researchers have previously reported plume shapes from propane flares in a crosswind [23-25] in order to discuss the flow structures. Their results show qualitative agreement with the results presented here and lead them to similar conclusions regarding the important flow structures that exist in flares in a crosswind.

4.2.1 Effects of Changing Wind Speed

One of the main variables that affect the shape of a plume (assuming jet exit velocities typical of solution gas flares) is the wind speed. Figure 4.3 shows a series of mean temperature contour plots when $d_i = 22.1$ mm and $V_j = 0.5$ m/s at four different wind speeds $U_\infty = 2, 4, 6,$ and 8 m/s. All of these temperature maps were collected 110 cm downstream of the flare stack and the individual plots have been scaled and aligned so that the size and location of the plumes can be compared directly with each other.

The plume shown in Figure 4.3a ($U_\infty = 2$ m/s) has a very distinctive kidney shape which is located well above the tip of the flare stack. The dominant flow structure that creates this shape of plume is a pair of counter-rotating vortices that are associated with the bending of the jet of flare gases in the direction of the crosswind and the buoyancy of the combustion products. The flame that created this plume was itself bent over by the wind and located almost entirely above the top of the stack. Since the flame and combustion products were both well above the stack, they were not significantly affected by any of the wake flow structures created by the stack.

As U_∞ is increased, the trajectory of the flame is made more horizontal and the products of combustion are moved into a region where they are increasingly influenced by the flow structures created by the stack. In Figure 4.3b ($U_\infty = 4$ m/s) the core of the mean thermal

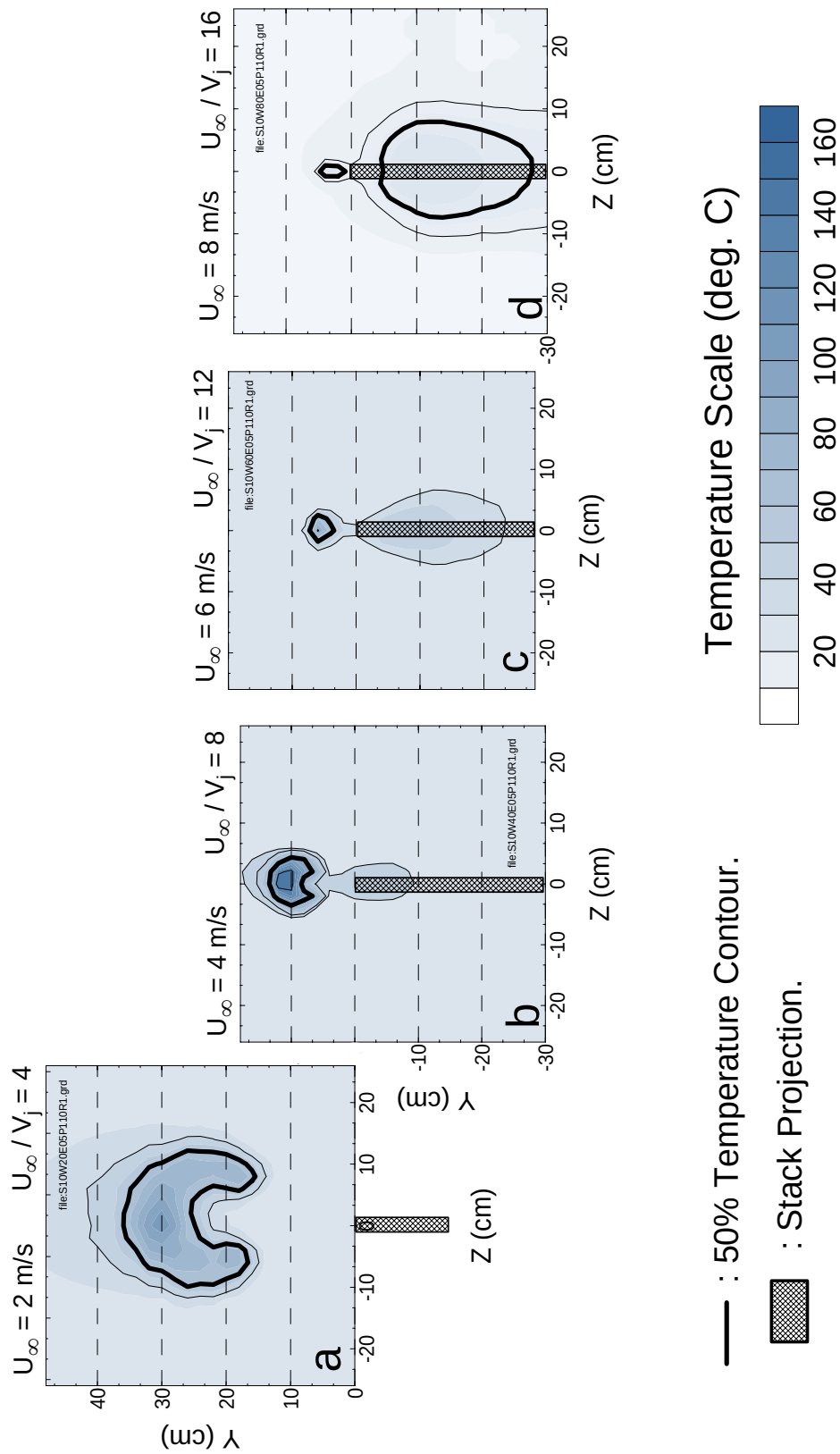


Figure 4.3: Temperature maps of flare plumes in crosswind showing the effects of changing wind speed.
 Test conditions: $x = 1.1 \text{ m}$, $d_i = 22.1 \text{ mm}$, $V_j = 0.5 \text{ m/s}$, and $U_\infty = 2, 4, 6$, and 8 m/s

plume is still kidney shaped, but the lower edge of the plume is starting to distort. In the mean thermal plume, there appears to be a small finger of combustion products that has been drawn downward and away from the main plume. Time signals from isolated experiments with fine junction thermocouples show that the hot combustion products appear in these locations for short, intermittent bursts. The flow structures that create this effect are wake vortices that are shed periodically from the stack [21, 42].

As the crosswind was increased further, the amount of gases drawn into the wake flow of the stack becomes more pronounced. Figure 4.3c ($U_{\infty} = 6$ m/s) shows the development of a second peak in the mean temperature field that is located below the height of the stack tip. The relative magnitude of this second peak grows with increasing crosswind speed. The appearance of hot fluid in the wake of the stack is no longer as intermittent. A portion of the flare gases is now being consumed by part of the flame that is trapped within a standing eddy attached to the leeward side of the flare stack. This recirculating flow is able to draw jet fluid continually into this region. The importance of this recirculation zone in terms of bringing flare gases into the wake region is documented in [26, 27]. It is also important to note that under these conditions a significant portion of the products of combustion are located well below the tip of the visible flame, which is approximately at the stack height. The implications of having combustion products spatially distributed well below the visible flame raises a concern about the appropriateness of making point measurements in the near plume of a flare. This point is discussed further in Chapter 5 when the composition of the plume is presented.

Figure 4.3d shows the relatively extreme situation in which $U_{\infty} = 8$ m/s. Under these conditions the whole flame is trapped in the recirculation zone behind the stack and the entire plume is now affected by the wake flow. The maximum temperatures of the upper and lower temperature peaks seen in Figure 4.3d are essentially the same, but in terms of the mass flux of combustion products, the lower peak was dominant.

The transformation from kidney shaped plumes (Figure 4.3a) to plumes formed by wake trapped flames (Figure 4.3d) occurs in a progressive and continuous manner as U_{∞} is

increased. There do not appear to be any sharp transitions or sudden changes in flow patterns, so it is difficult to provide a well-defined demarcation between the different plume shapes.

4.2.2 Effects of Changing Flare Gas Exit Velocity

Figure 4.4 shows the mean temperature maps of a $d_i = 22.1$ mm flare exposed to a crosswind of $U_\infty = 6$ m/s at three different jet exit velocities $V_j = 0.5, 1.0,$ and 2.0 m/s. All of these temperature maps were collected 140 cm downstream of the flare stack.

For $V_j = 0.5$ m/s (Figure 4.4a), the 50% temperature contour is essentially circular and a significant part of the plume was being drawn into the wake flow of the stack. When the exit velocity was doubled (Figure 4.4b) or quadrupled (Figure 4.4c), the height of the plume above the flare stack was increased only slightly because of the increased jet momentum. Similarly, the shape of the plume only showed the smallest indications of becoming more kidney-shaped with these increases in jet velocity. Hence, the change in plume shape over a factor-of-four increase in V_j does not appear as dramatic as that observed by an equal change in wind speed (Figure 4.3).

Since U_∞ has a much stronger influence on the behavior of the plume than V_j , it is apparent that neither the velocity ratio nor the momentum flux ratio properly characterizes the flow field of this regime of flares in a crosswind. This result was somewhat expected given that the overall efficiency results shown in Chapter 3, also related to the flow field, did not correlate with either of these parameters. The other force that plays an important role in characterizing these flows is the buoyancy of the products of combustion. In Section 4.2, the scaling of the plume size is considered by a ratio of jet buoyancy flux to crosswind momentum flux, which proves to be a more successful approach to correlating the data.

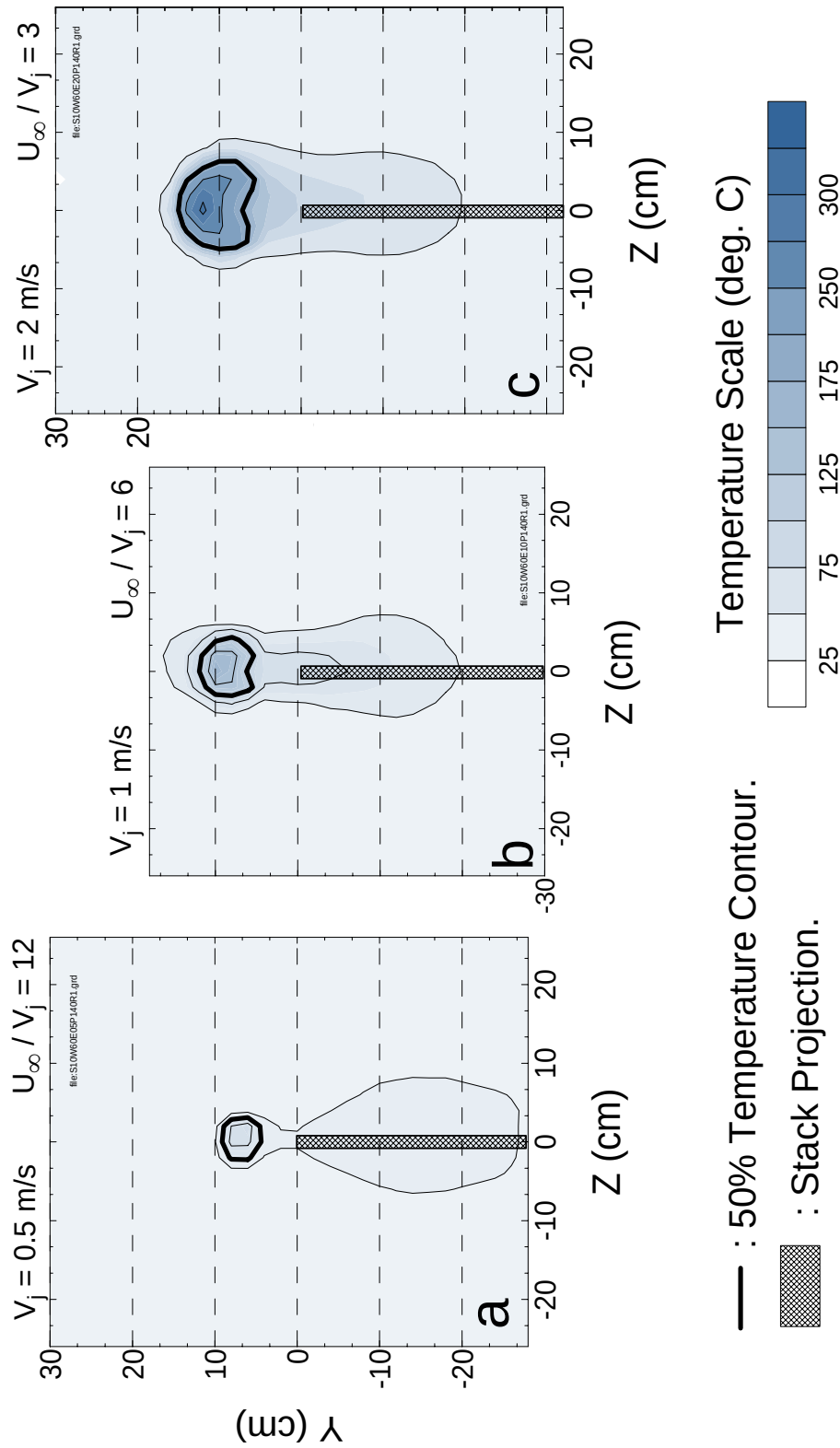


Figure 4.4: Temperature maps of flare plumes in crosswind showing the effects of changing exit velocity.
 Test conditions: $x = 1.4 \text{ m}$, $U_\infty = 6 \text{ m/s}$ $d_i = 22.1 \text{ mm}$, and $V_j = 0.5, 1.0$ and 2.0 m/s ,

4.2.3 Effects of Downstream Location

Figure 4.5 shows mean temperature maps of a $d_i = 22.1$ mm flare with a $V_j = 1.0$ m/s in a $U_\infty = 3$ m/s crosswind at three different downstream locations ($x = 1.4, 1.7$, and 2.0 m). A comparison of these three contour plots shows that the plume at the measurement plane closest to the flare ($x = 1.4$ m) is the smallest and has the highest mean temperatures (approximately 220°C). As the gases are advected downstream they mix with and entrain cool ambient air. Consequently, the cross-section of the plume increases in size but has a lower mean temperature as the enthalpy of combustion is disbursed into a greater amount of air. As the combustion products are advected downstream, they continue to rise relative to the flare stack primarily due to their buoyancy.

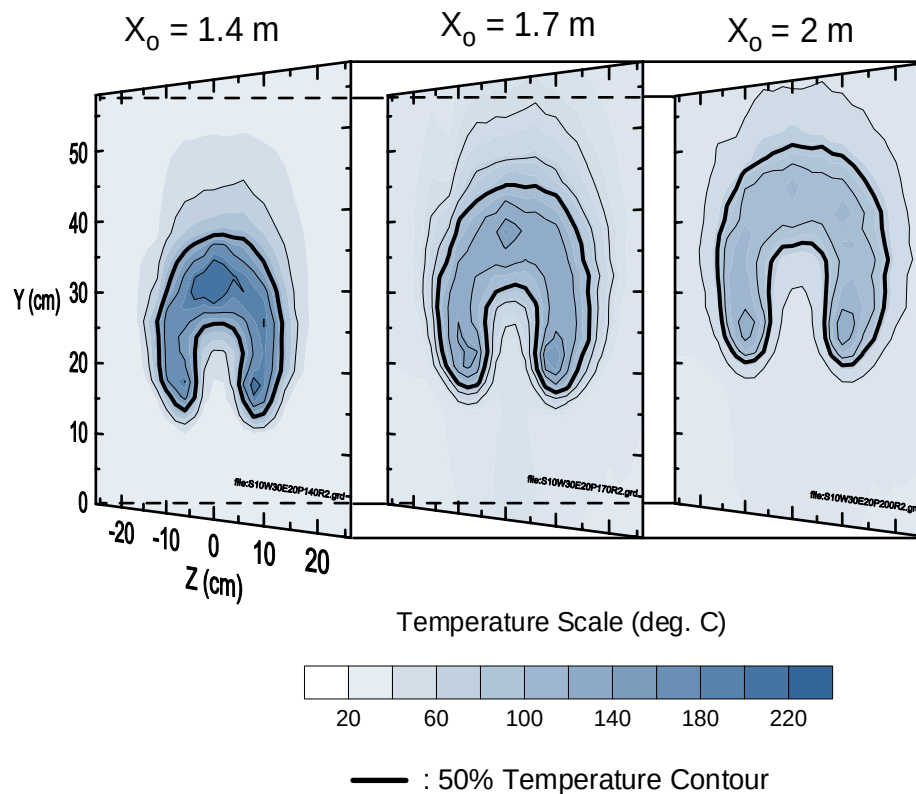


Figure 4.5: Temperature Maps of Flare Plumes in Crosswind Showing the Effects of Collecting Data at Various Downstream Locations.

Test Conditions: $d_i = 22.1$ mm, $V_j = 1.0$ m/s, $U_\infty = 3$ m/s and $x = 1.4, 1.7, 2.0$ m

These contour plots also show that the overall shape of the plume is similar as one goes downstream. However, the plume is still growing and evolving as it advects downstream as evidenced by the elongation of the kidney shape as shown in Figure 4.5. This evolution of shape is also seen in the following section on the effects of changing stack diameter.

4.2.4 Effects of Changing Stack Diameter

Figure 4.6 shows the mean temperature maps for three different stack diameters, $d_i = 16.7$, 22.1 and 33.3 mm, with a common exit velocity of $V_j = 2.0$ m/s and a crosswind speed of $U_\infty = 3$ m/s. All of these temperature maps were collected 170 cm downstream of the flare. This same methodology was used at the NRC wind tunnel in Ottawa to evaluate larger flares with an inner diameter of 102.3 mm. The results concerning these larger flares will be presented in Chapter 8 and integrated with the results presented here.

The three plumes shown in Figure 4.6 are kidney shaped but appear to be at a different stages in their evolution. Unlike non-reacting, buoyant plumes where the full buoyancy of the jet gases exists at the exit of the stack, the flame continues to create buoyant gases along its length. Having the source of buoyant gases spread out over different distances, based on flame length, changes the time that the buoyant forces have to affect the plume trajectory by a given downstream location (x). For example, the measurement plane of the largest diameter stack in Figure 4.6 is located just off the end of the flame tip and the plume has not had the time to fully form its kidney shape. Having this spatially distributed buoyant source is one of the complicating features of scaling and predicting the shapes of the plumes of flares.

4.3 SCALING THE PLUMES OF FLARES

For now, the scaling of the plumes of flares is considered only in terms of the overall cross-sectional size of the plume as a function of wind speed, flare gas exit velocity, stack diameter and distance downstream of the stack. Quantifying the variations in plume shapes is currently an intractable problem. Results given in the previous section (Section 4.2),

suggested that the dominant forces affecting the plume are not well characterized by the ratio of momentum fluxes but more likely connected to buoyancy and crosswind momentum.

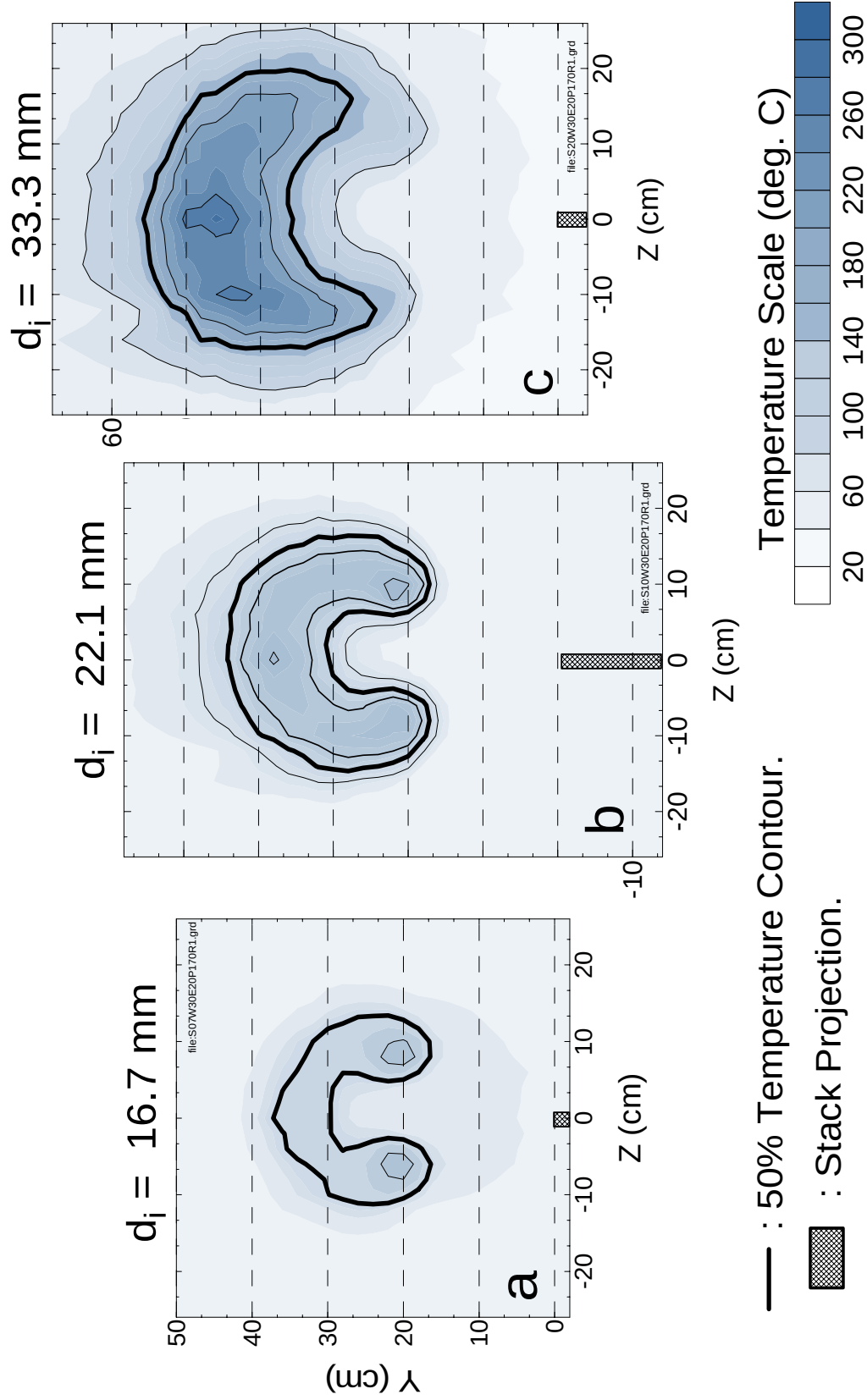


Figure 4.6: Temperature maps of flare plumes in crosswind showing the effects of changing stack diameter.
 Test conditions: $x = 1.7$ m, $U_\infty = 3$ m/s $V_j = 1.0$ m/s, and $d_i = 16.7, 22.1$ and 33.3 mm,

Therefore, the approach taken here for scaling the plume is based strongly on the models developed to predict the size and trajectory of non-reacting plumes, which are based on the combined forces of momentum and buoyancy.

Using the model of Briggs [39, 40] for a non-reacting buoyant jet of fluid being introduced into a cross flowing stream, the characteristic dimension of the plume can be written as

$$d_p^* \propto \left(g \frac{\rho_j - \rho_\infty}{\rho_\infty} \right)^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3} \quad (\text{Eq. 4.3})$$

where d_p^* = Characteristic dimension of the plume
 g = Gravitational constant

The right-hand side of Equation 4.3 is given in Briggs' model as plume rise, and d_p^* is introduced into this expression through Briggs' entrainment assumption, which yields d_p^* proportional to plume rise.

Reacting flows, like flares, involve these same forces, except that the buoyant products would be created along the length of the flame, while in the non-reacting case all the buoyant fluid is introduced at the jet exit. This evolution of buoyant gases along the flame and the fact that different fuels involve different volumes of air to react makes the interpretation of the density term problematic. Therefore, for now, the terms relating to density in Equation 4.3 are removed with some loss of generality, but by considering only natural gas flares it is possible to test the remaining dependencies with respect to plume size. Equation 4.3 is then rewritten as

$$d_p^* \propto g^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3} \quad (\text{Eq. 4.4})$$

In total, 129 mean plumes were mapped for three flare diameters ($d_i = 16.7, 22.1, \text{ and } 33.3 \text{ mm}$) while varying the jet velocity ($V_j = 0.5, 1.0, \text{ and } 2.0 \text{ m/s}$), air velocity ($U_\infty = 1.5, 2, 4, 6, \text{ and } 8 \text{ m/s}$), and downstream location (x). Plumes for the 10.8 mm flares were too small for the spatial resolution of the thermocouple array. Figure 4.7 shows the data from all 129 plumes plotted with respect to the correlation suggested by Equation 4.4 and shows good agreement between the model and experimental data. The average root mean squared (r.m.s.) error between model and experiments shown in Figure 4.7 is 12%. This level of agreement adds significantly to the notion that the dominant forces acting on solution gas flares are the buoyancy flux of the combustion products and the momentum flux of the crosswind. In Chapter 8 this correlation will be expanded further to include flares with an inner diameter up to 102.3 mm. Expanding Figure 4.7 to include these larger flares does not affect the results presented here as excellent agreement remains between the characteristic plume diameter and the ratio of buoyancy to momentum forces for this full range of scales.

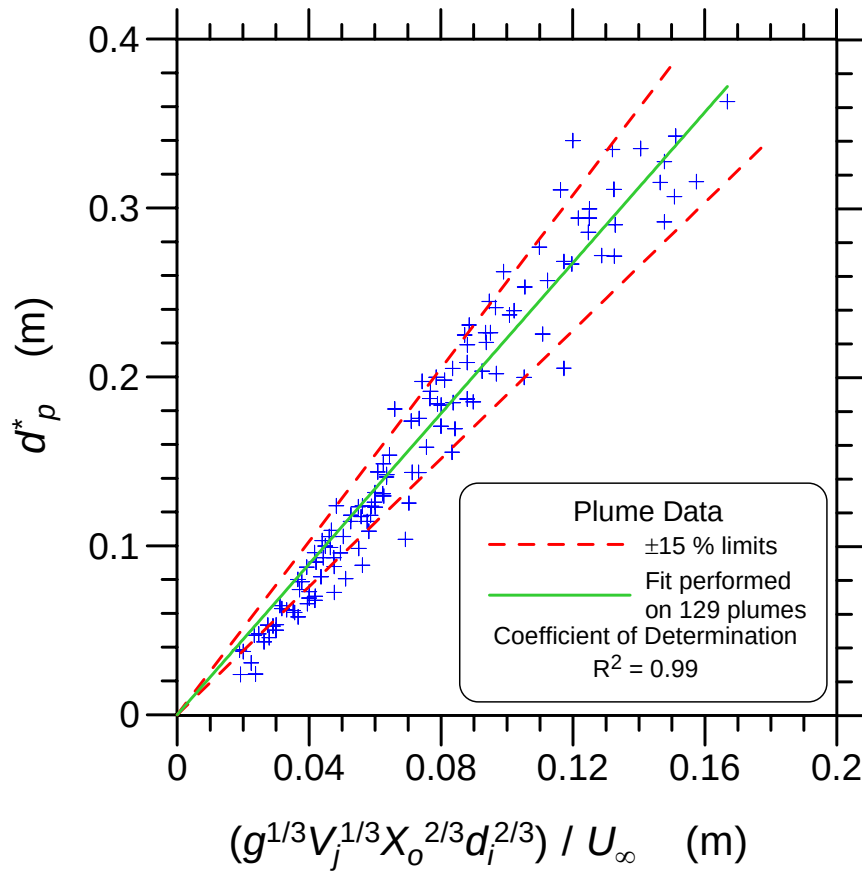


Figure 4.7: Correlation of the Characteristic Plume dimension with the Parameter Suggested by a Ratio of Buoyancy Flux to Momentum Flux

It should be noted that this transverse scaling of the plume with respect to stack size (i.e., $d_p^* \propto d_s^{2/3}$) is different from the linear scale seen for flame length [43] and the scaling of combustion efficiency discussion in Chapter 3.

4.4 CONCLUDING REMARKS

A linear array of thermocouples was used to construct 2-dimensional mean temperature contour maps of the plumes of flares in a crosswind. These maps provide a useful means to visualize the flow patterns and structures that exist downwind of the flare. In total 129 mean plumes were mapped for three flare sizes ($d_i = 16.7, 22.1, \text{ and } 33.3 \text{ mm}$) while varying the jet velocity ($V_j = 0.5, 1.0 \text{ and } 2.0 \text{ m/s}$) and air velocity ($U_\infty = 1.5, 2, 4, 6, \text{ and } 8 \text{ m/s}$) and the downstream location (x) of the measurements.

The observed plume shapes were very similar to those seen in non-reacting buoyant jets issuing into a cross flow. The sizes of the plumes of flares were correlated with a model derived from the ratio of the buoyancy flux to the momentum of the wind. The important conclusion derived from these measurements is that the flows created by flares in a crosswind appear to be scalable, which further adds confidence to the notion that data collected from sub-scale flares tested in a wind tunnel can be used to predict the performance of full-scale flares. It should also be noted that these were the same pair of forces that correlated the overall combustion efficiency data for flares with a common composition as presented in Chapter 3. These experiments and results will be confirmed for larger scale flares in Chapter 8.

5 LOCAL COMBUSTION EFFICIENCY MEASUREMENTS

In Chapter 3, the focus of the research was on measuring and modeling the *overall* combustion efficiency of a flare under a set of well-prescribed conditions in the closed-loop wind tunnel at the U of A. The overall efficiency was estimated by thoroughly mixing the products of combustion with the tunnel air to arrive at an averaged efficiency for the whole flare. In taking that overall perspective, the details of the mechanisms that created the measured inefficiency were lost. Data presented in this chapter helps elucidate the origins of the inefficiencies by considering the spatial variations in the mean composition of the plumes downwind of gaseous flares.

Mean compositional variations across the plume lead naturally to the notion of “local” mean combustion efficiencies, which are representative of the carbon conversion efficiencies of a small region (stream tube) in the flow. These local efficiency measurements are used to create two-dimensional mappings of the mean-combustion efficiency immediately downstream of the flare. Besides providing some insight into the origins of the inefficiency, having the spatial distribution of local combustion efficiencies raises important implications for the use of single-point measurement techniques to estimate the overall efficiency of flares. The technique described in this chapter will be used in Chapter 8 to investigate larger-scale flares.

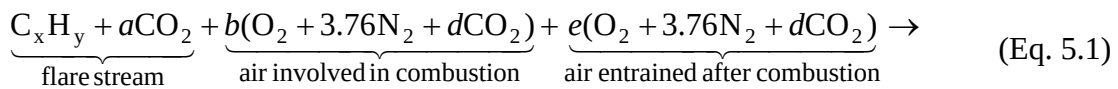
5.1 EXPERIMENTAL METHODOLOGY

Calculating the local combustion efficiency based on the composition of combustion products collected from a small region of the flow downstream of a flare is in principle straightforward. As in Chapter 3, the combustion efficiency is defined by the fraction of carbon mass in the fuel that is converted to CO₂ by combustion. In order to make this idea local to a small region in the plume, this definition needs to be reworked to develop a carbon-mass balance when one only knows the composition of combustion products sampled from that part of the flow. Consequently, the combustion efficiency becomes the ratio of the mass

of carbon in the form of CO₂ produced by the flame to the total carbon mass in all its forms that resulted from the combustion process.

In practice, the application of this definition is made somewhat complex for two main reasons. First, all the major carbon containing species involved in the products of combustion must be measured. This is a non-trivial task particularly if the flame is emitting significant amounts of soot. To overcome this difficulty, the experiments reported here only involve natural gas flares, which do not emit significant amounts of soot [19]. Second, in general, the CO₂ originating from combustion needs to be discriminated from the CO₂ originating from the ambient air that mixes into the products of combustion before a sample is drawn.

To understand more fully the method that was used to estimate the local efficiency, it is helpful to consider the overall stoichiometry as seen by a point downstream of the flare. By the time the flow reaches the sampling point, fuel and air have been involved in combustion and more ambient air has been entrained into the plume. A simplified version of this stoichiometry that is relevant to estimating the carbon-based combustion efficiency is given in Equations 5.1 and 5.2. Equation 5.1 is the reactant side of the stoichiometry, while Equation 5.2 is the product side.



where C_xH_y = general hydrocarbon fuel in flare stream

a = known stoichiometric coefficient for CO₂ in the flare stream

b = unknown stoichiometric coefficient for amount of air involved in combustion

d = known stoichiometric coefficient for CO₂ in the ambient tunnel air

e = unknown stoichiometric coefficient for amount of air entrained into plume

$$\underbrace{f\text{CO}_2 + g\text{H}_2\text{O} + h\text{CO} + i\text{C}_{xx}\text{H}_{yy} + j\text{N}_2}_{\substack{\text{from combustion} \\ \text{from reaction of first two terms in equation 5.1}}} + \underbrace{a\text{CO}_2}_{\text{from fuel}} + \underbrace{bd\text{CO}_2}_{\text{from air}} + \underbrace{e(\text{O}_2 + 3.76\text{N}_2 + d\text{CO}_2)}_{\text{from entrained air}} \quad (\text{Eq. 5.2})$$

where f, g, h, i = unknown stoichiometric coefficients that result from combustion

j = stoichiometric coefficient that balances N_2

$\text{C}_{xx}\text{H}_{yy}$ = general hydrocarbon emission from flare

An important feature of these expressions is that the CO_2 in the plume originates from CO_2 present in the flare stream, combustion air, and entrained air, and from the combustion of the fuel. To calculate the combustion efficiency, the carbon mass in $f\text{CO}_2$ must be compared to that in C_xH_y . Unfortunately, at the sample plane the carbon information about C_xH_y is only available in the form of $f\text{CO}_2$, $h\text{CO}$ and $i\text{C}_{xx}\text{H}_{yy}$.

The first problem to overcome is how to estimate the carbon mass from the generalized hydrocarbon emissions ($i\text{C}_{xx}\text{H}_{yy}$). The composition of the unburned hydrocarbons emitted from a non-sooting gaseous hydrocarbon flare was shown in Chapter 3 to be very similar to the composition of the flare stream. Since the flares considered here were natural gas which is predominantly composed of alkane hydrocarbons, the value of i can be well characterized by an FID (flame ionization detector). If the FID is calibrated with methane (CH_4), the measured concentration is in equivalent methane concentration and allows $\text{C}_{xx}\text{H}_{yy}$ to be written as CH_n (where $n=yy/xx$).

As a result, all the main carbon compounds in the products are measured as C_1 in composition (i.e., CH_n , CO and CO_2) and therefore the local mass based combustion efficiency can simply be expressed in terms of the stoichiometric coefficients in Equation 5.2 as

$$\eta = \frac{f}{f + h + i} \quad (5.3)$$

The values of h and i are readily calculated by concentration measurements from the available CO and HC analyzers that were described in Section 2.1.4.1.

Unfortunately, the value of f is not obtained as directly. All the components in the plume listed in Equation 5.2 are blended together and the concentration of CO_2 measured in the plume is not related solely to f but to the sum of $f + a + bd + ed$. Since a is known from the fuel composition and can be subtracted off, the problem is estimating the value of the bd and ed terms. For natural gas flames the bd terms is always negligible because f is of the order unity, while d is small ($\sim 10^{-4}$) and b never becomes large (< 10). The ed term, which represents the CO_2 originating from the ambient air entrained into the plume without combustion, cannot be neglected. In fact, the products of combustion can be highly diluted by air depending on the sampling location in terms of distance from the flare or proximity to the edge of the plume. To subtract off the CO_2 originating from entrained air, the O_2 concentration in the sample is measured and used in an O_2 balance to provide an estimate for “ e ”. Therefore, in order to measure the local efficiency in the plume of a sales-grade natural gas flare, the concentrations of CO_2 , CO , methane equivalent HC, and O_2 must be measured.

5.2 EXPERIMENTAL SETUP

Figure 5.1 is a schematic of the apparatus and technique used for sampling a small segment of the plume of the flare. The sample probe was a 4.55 mm inside diameter stainless steel tube that was connected to a 25-liter Tedlar bag with 6 mm diameter Teflon tubing. Prior to drawing a sample from the plume, the Tedlar bag was empty. The gases being sampled were aspirated through the probe and into the bag by applying a small negative pressure to the air within the rigid vessel that housed the sample bag. A standard shop vacuum was used to create this negative pressure. For the filling process, solenoid valve S1 was open and valve S2 was closed (see Figure 5.1). To sample the plume iso-kinetically at different wind speeds, the sampling rate could be varied by adjusting the pressure of the air in the rigid vessel. A manual relief valve, which allowed varying amounts of room air to bleed into the vessel, controlled the pressure in the rigid vessel.

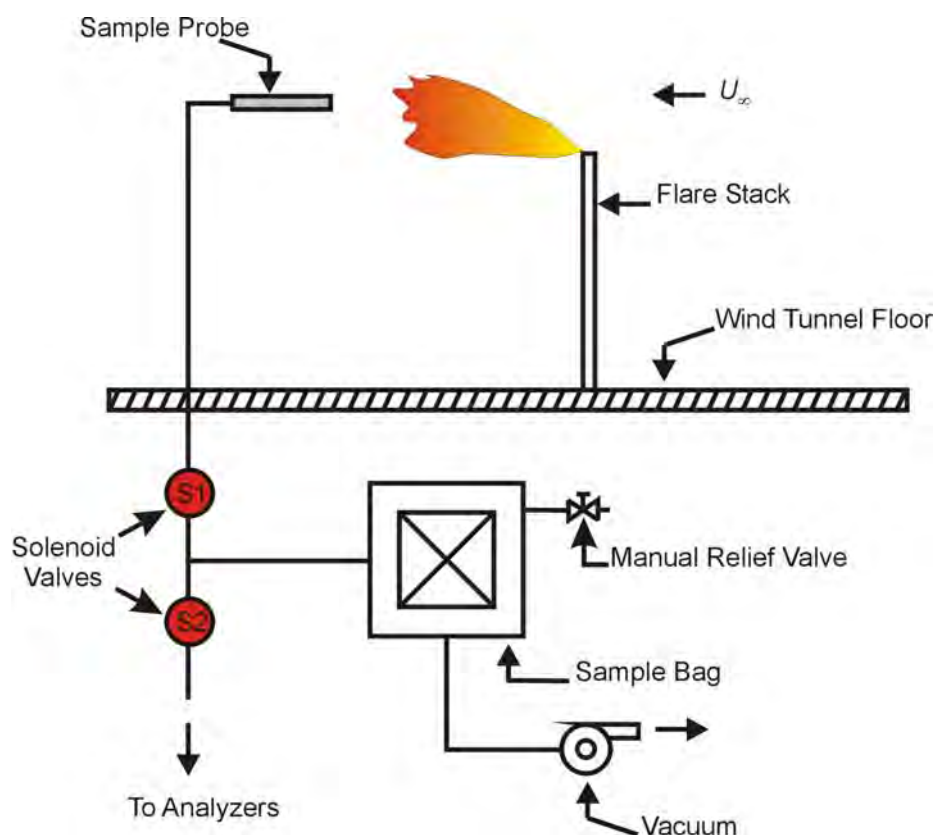


Figure 5.1: Schematic for sampling the plume of combustion products from a flare in a crosswind

The composition of the gases collected within the Tedlar bag, in terms of CO₂, CO, methane equivalent HC, and O₂, was determined by passing the sample through the on-line gas analyzers (Section 2.1.4.1). For this process, the vacuum was shut off to return the rigid vessel to ambient conditions, valve S1 was closed and valve S2 was opened. A diaphragm sample pump was used to extract the gases from the Tedlar bag and transfer them through the gas analyzers. A typical time trace of the measured composition of the gases within the bag is shown in Figure 5.2. Since the concentrations reached steady state values, this technique of sampling and handling the gases resulted in a homogeneous mixture within the bag and did not require any auxiliary mixing. The Tedlar bag was sampled until the bag was completely empty, which took approximately 2 minutes, and thereby prepared the bag for taking the next sample.

To avoid cross-contamination between tests, the bag was first filled with gases from the sample point, then fully exhausted and refilled with gases from the same sample point. The

gases from this second filling were analyzed to determine the local combustion efficiency at the sample location. Further cycles of exhausting and refilling a bag were unnecessary because a stable mixture was observed in the bag after just one cycle.

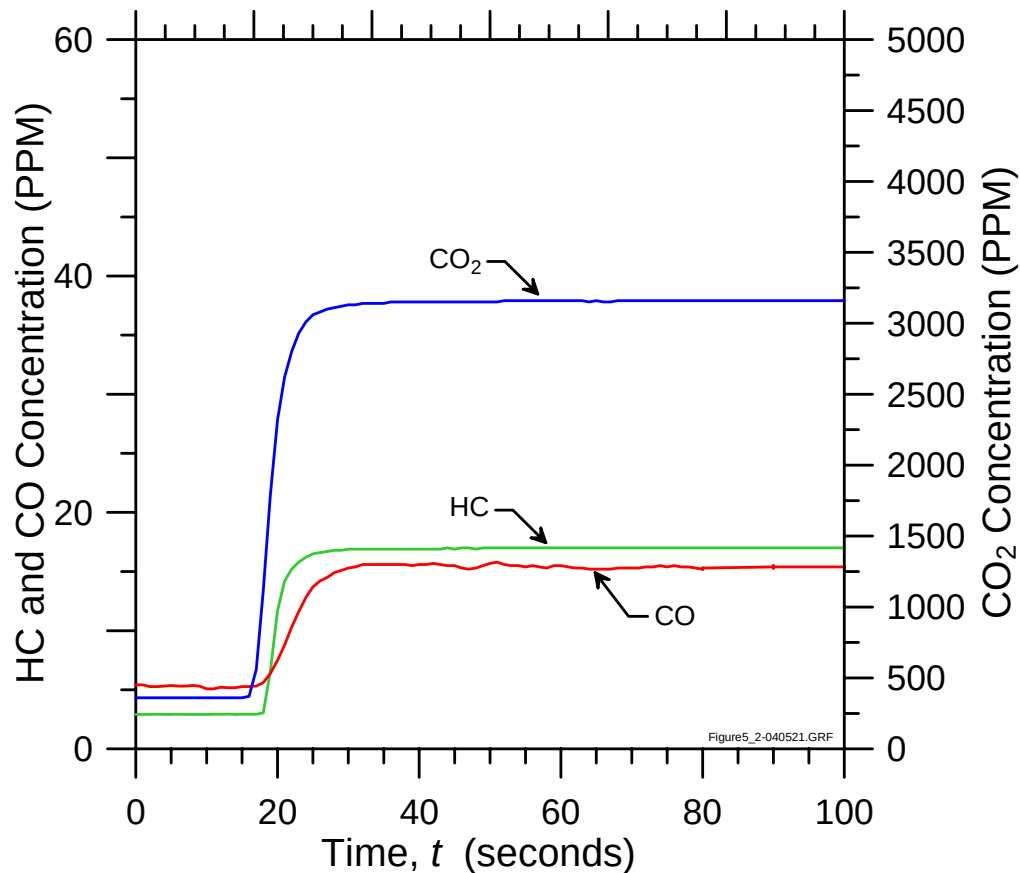


Figure 5.2: Typical time trace of on-line gas analysis from Tedlar bags

Water vapor collected as part of the combustion products can often cause problems by condensing in the sampling system or Tedlar bag once the gases are reduced to room conditions, but this did not occur during any of the tests conducted. The water remained in its vapor phase because sampling occurred far enough downstream in the plume that the products of combustion were substantially diluted with ambient air. In Alberta, ambient air is most often of a low relative humidity and provides the capacity to add the water produced by combustion to the air without reaching saturation at room temperature.

As part of the analysis it is important to consider the effects of working in a closed-loop wind tunnel where the background concentrations of CO₂, CO, and HC are rising, albeit slowly, throughout the sampling process. For this purpose, Equation 5.1 was modified to allow for the presence of CO and HC in the ambient air of a measured concentration. The calculation of efficiency was then performed separately using the ambient concentrations of CO₂, CO, and HC at the start and end of sampling. Since the sampling times were short (2 to 8 minutes), the changes in background concentrations were small and the largest effect observed due to changes in background concentrations was +/-0.1% (absolute) in efficiency.

Lastly, by sampling over this 2 to 8 minute period, the local species concentrations and efficiencies reported are temporal averages of these quantities. Multiple tests at the same flow conditions and locations confirmed that the averages reported were stationary and therefore representative of the true mean.

5.3 SPECIES CONCENTRATIONS MAPS

To create a two-dimensional map of local efficiencies within the plume downstream of a flare, many single-point measurements of the composition of the plume were required. Collecting this amount of data with a single probe would be impractical. To accelerate the collection of these data, a linear array of twenty probes was employed. The probes were placed 2 cm apart in a vertical arrangement. This spacing allowed the array of probes to cover the full height of the plume being measured, while still providing acceptable spatial resolution.

The twenty probes were connected to a parallel set of twenty equal-length tubes and twenty Tedlar sample bags. These bags were hung within a single large rigid vessel and a single vacuum was used to fill all the bags at the same time in the manner described previously for the single bag (Figure 5.1). A set of solenoid valves allowed the content of the individual bags to be sent to the gas analyzers in series to measure their composition (CO₂, CO, HC, and O₂). While the twenty bags were being analyzed the flare was turned off and the tunnel air was purged and refilled with fresh ambient air. The vertical array of probes was then moved

horizontally 2 cm to prepare for the next set of samples. In total, 300 single-point samples could be collected and analyzed in approximately 11 hours to create a single compositional map of the plume.

The results reported here for the local mean-species concentrations are for a flare stack with a diameter (d_i) of 22.1 mm burning natural gas. The flare gas exit velocity (V_j) was held constant at 1 m/s and the crosswind speed (U_∞) was fixed at 2, 4 or 8 m/s. These combinations of velocities show all the important features of how the various species are distributed throughout the plumes for each of the different plume shapes discussed in Chapter 4.

In each case, the two-dimensional mean-concentration maps for CO₂, CO, and HC have been normalized. This normalization scales the background concentration to zero and the highest concentration encountered in the sampling plane to unity. Instead of showing a concentration map for O₂, this information is presented as the volume fraction of products (Y_p) collected at the sample location but reported in the figures as a percentage (i.e., $100 \cdot Y_p$). This volume fraction of products is the portion of the gas sample that is not air (79 % N₂, 21 % O₂) and provides a measure of how dilute the products have become due to the entrainment of tunnel air before sampling. If desired, the dilution ratio is easily calculated ($= -1 + 1/Y_p$). For example, if $Y_p = 0.05$ then the sample consists of 19 parts air to 1 part of oxygen free products. The location of the sampling planes and the approximate flame length for the reported experiments are listed in Table 5.1.

Table 5.1: Test conditions for mapping species composition in the plume of a flare where $V_j = 1.0$ m/s and $d_i = 22.1$ mm

Wind Speed, (m/s)	Approximate Flame Length (cm)	Sample Plane, x (cm)
2	80	110
4	75	140
8	50	110

Results for the case of $U_\infty = 2$ m/s are shown in Figure 5.3. For these particular flow conditions, the shape of these mean species concentration plumes belong to the kidney-shape

family of plumes as discussed in Chapter 4. The similarities seen between the mean thermal plume and the CO₂ plume would be expected since the production of CO₂ is also associated with the release of chemical energy and the Lewis number (the ratio of thermal diffusivity to mass diffusivity) for these gases is near unity. It is important to note that the concentration contours for CO₂ differ slightly from those for CO and HC. While the 90% contour of the CO₂ is visible on the centerline and out in the two tips of the kidney, the same contour appears only on the tips of the kidney for both CO and HC. Those latter species only reach 60-70% of their own maximal concentrations at the centerline. The existence of CO and HC in the plume, a consequence of an incomplete combustion, in a pattern different from CO₂ is evidence that the efficiency is not homogeneous over the entire plume.

The volume fraction of products (Y_p) strongly correlates with the CO₂ plume because that is the most concentrated of the product species. In this particular flow, the highest volume fraction of products measured was 6.4 %, which represents a dilution of 14.6:1. Care should be taken when interpreting the contour plots of Y_p . When thinking in terms of the overall efficiency, the first instinct is to give greater importance to regions of the flow with the highest mean concentration of products. The problem is that these regions with the highest mean concentration of products are also the regions of highest mean temperature and consequently the lowest mean density. Therefore, in terms of mass flux of products, both the species concentration and density must be considered when weighing their importance.

Results for the case of $U_\infty = 4$ m/s are shown in Figures 5.4. These species plumes are similar in shape to when $U_\infty = 2$ m/s, but now measurable amounts of CO₂ and CO can be found below the main kidney-shaped plume. These fingers of products highlight the effect of the wake vortices being shed from the stack and their ability to extract products downward from the main plume. For the same flow conditions, these structures were not evident in the mean temperature maps discussed in Chapter 4 because of the relative higher sensitivity of the gas analyzers compared to thermocouples. As with the lower wind speed case, the detailed structure of the different species plumes shows that the products are not homogeneous and raises a caution regarding the relevance of a single-point measurement to characterize the overall efficiency of the flare.

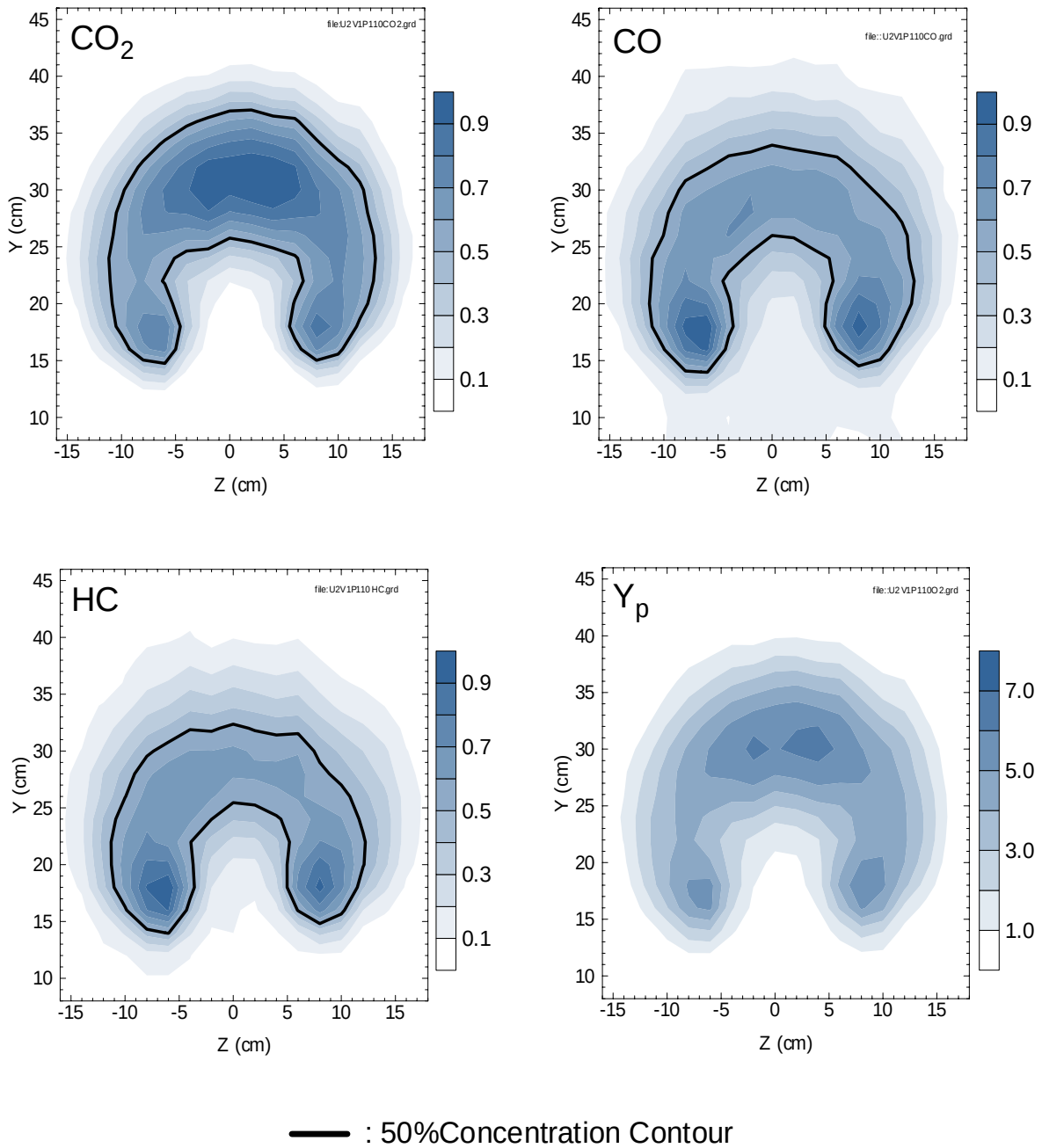


Figure 5.3: Concentration maps of CO₂, CO, HC, and volume fraction of products (Y_p). Test conditions: $d_i = 22.1$ mm, $V_j = 1$ m/s, $U_\infty = 2$ m/s, $x = 110$ cm .

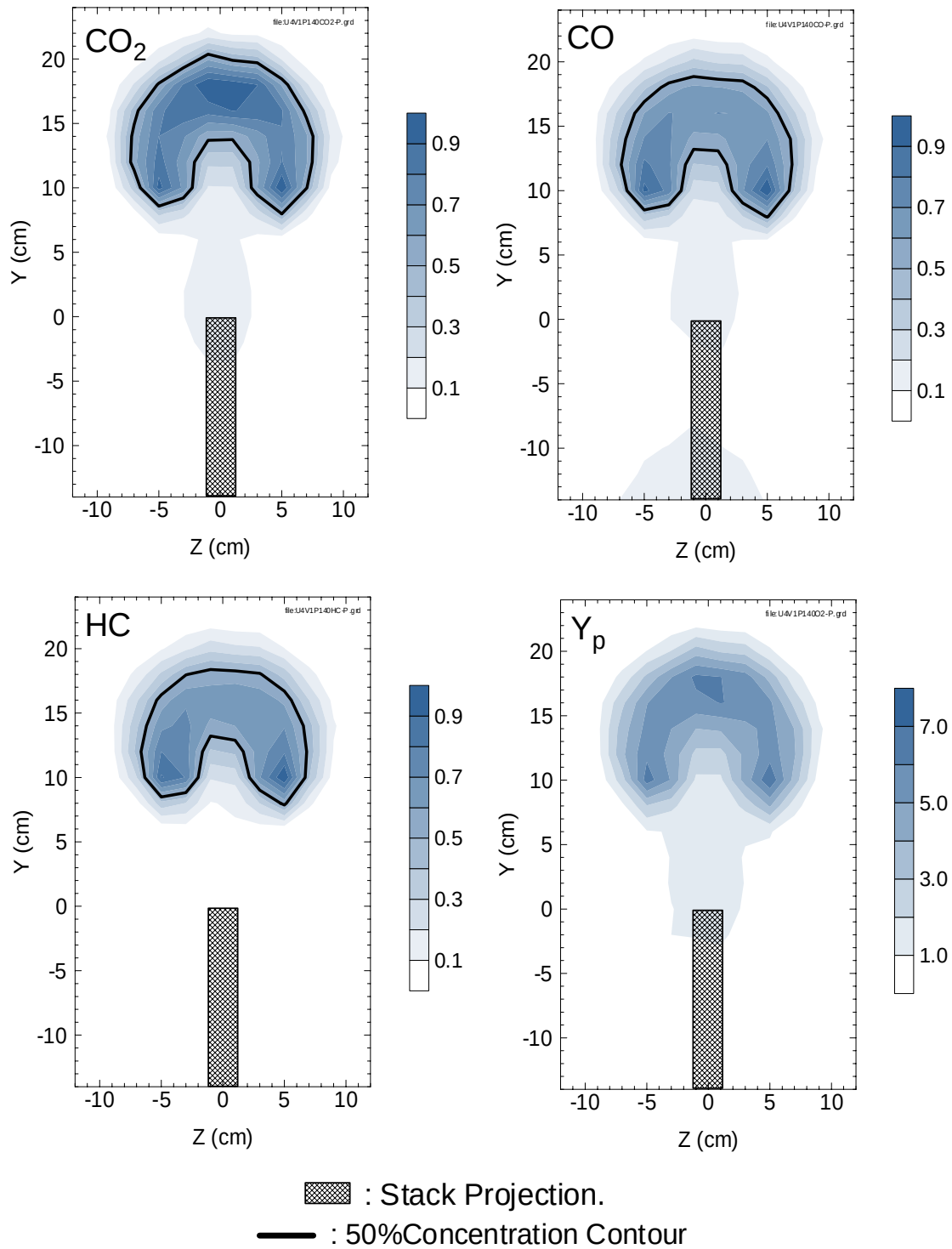


Figure 5.4: Concentration maps of CO_2 , CO, HC, and volume fraction of products (Y_p). Test conditions: $d_i = 22.1$ mm, $V_j = 1$ m/s, $U_\infty = 4$ m/s, $x = 140$ cm

Results for the case of $U_{\infty} = 8$ m/s are shown in Figures 5.5. These higher wind conditions show a strong influence of the stack and its wake flow on the products of combustion. The displacement of products is now so strong that products are divided into two regions. One region is above the stack tip height and the second is below. The differences between the mean concentration maps for CO_2 , CO , and HC have become more pronounced. The maximum concentrations of CO_2 and CO occurs in a region above the stack tip, which is directly downstream of the tip the flame. A significant portion of these gases also appears in a region below the stack tip height where their concentrations were measured to be between 40 and 50% of their maximums above the stack. HC has its maximum concentration region spread between the flame tip region and the region exactly downwind of the tip of the stack.

Combining results from the compositional maps, the flow structure data from Chapter 4, and the measured composition of the combustion products (Chapter 3) allows important conclusions to be made regarding the origins of the inefficiencies of non-sooting flares. The effectiveness of the flame in fully oxidizing the flare stream is not spatially uniform. The hydrocarbon emissions at higher wind speeds result from flare gas being stripped downward into the wake flow of the stack

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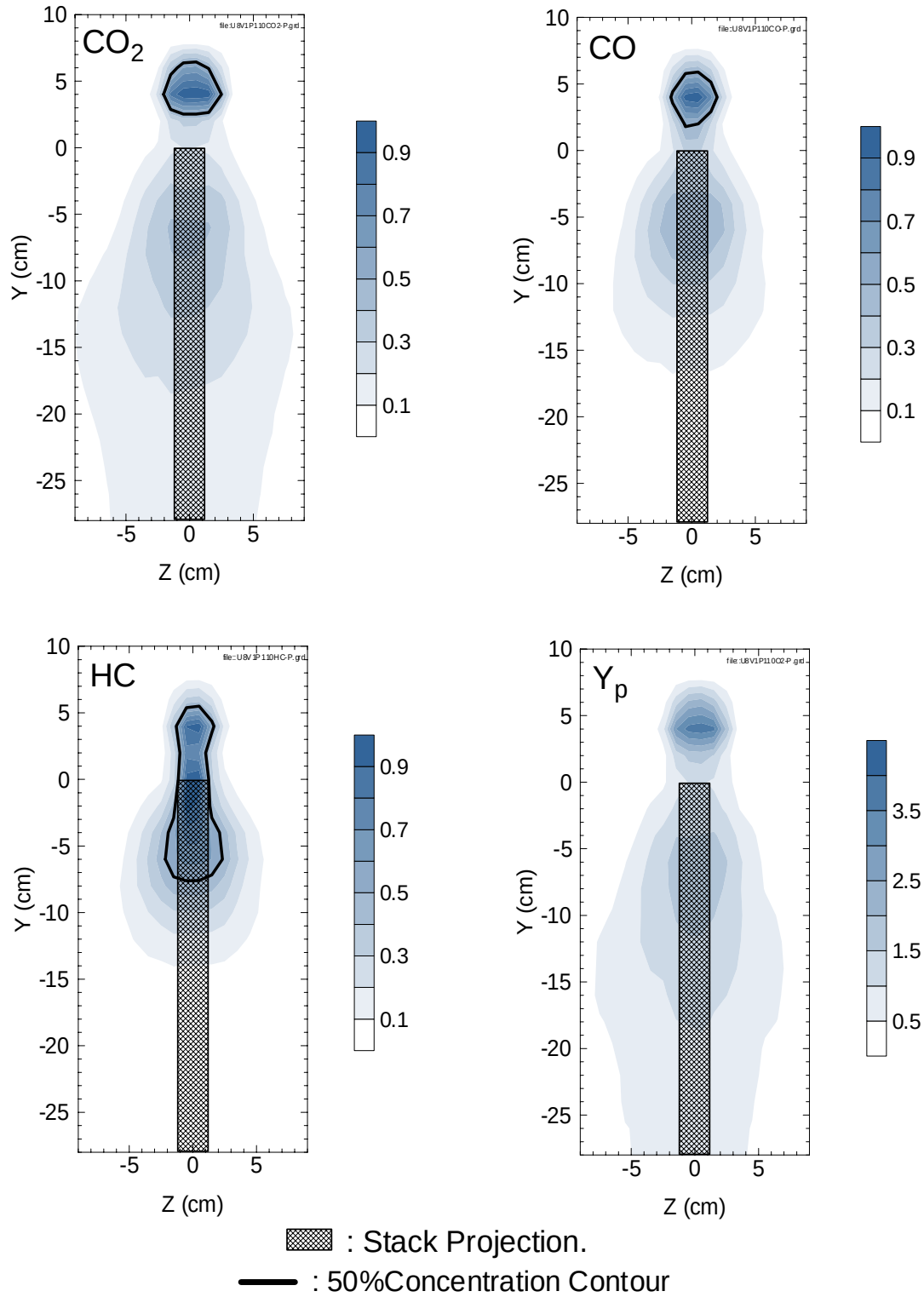


Figure 5.5: Concentration maps of CO₂, CO, HC and volume fraction of products (Y_p). Test conditions: $d_i = 22.1$ mm, $V_j = 1$ m/s, $U_\infty = 8$ m/s, $x = 110$ cm

5.4 TWO-DIMENSIONAL EFFICIENCY MAPPINGS

Figures 5.6 – 5.8 show the local mean efficiencies calculated in the flow region that contains more than 10% of the highest product concentration. This region is used here to define the plume of combustion products. At lower product concentrations (i.e., very high dilution), the composition approaches the background levels of CO_2 , CO , and HC , and the calculation of local efficiency approaches an unstable singularity. Also shown in these figures are the 50% mean temperature contours used in Chapter 4, which provide a physical reference to the thermal plume.

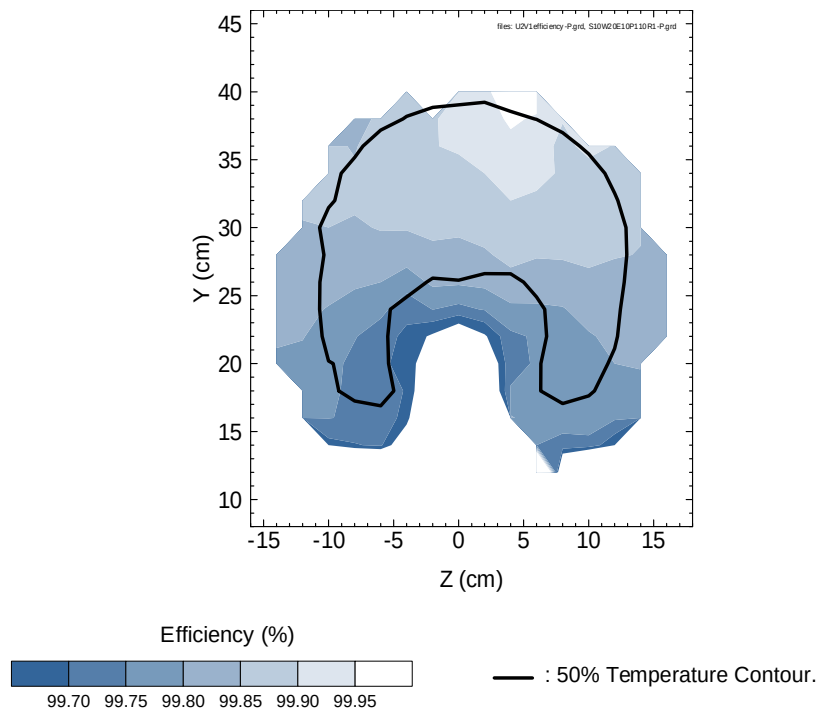


**Figure 5.6: Efficiency map for test conditions: $d_i = 22.1$ mm, $V_j = 1$ m/s
 $U_\infty = 2$ m/s, $x = 110$ cm**

For the case of $U_\infty = 2$ m/s (Figure 5.6), the local efficiency ranges upwards from 99.7%, where the lowest efficiency appears in the lower half of the kidney. This range of local efficiency measurements is not within the uncertainty of the measurement technique and, as a result, the local efficiency is essentially uniform throughout the plume. Hence, any single point measurement taken within the plume under these conditions would provide a good

estimate of the overall efficiency. The overall efficiency for this flare was measured in Chapter 3 as approximately 99.8%.

When the wind speed is increased to $U_{\infty} = 4$ m/s (Figure 5.7), the local efficiency ranges upwards from 98.3%. Again, the variations in local efficiency are small throughout the plume and any two single point samples have a maximum difference of only 1% .

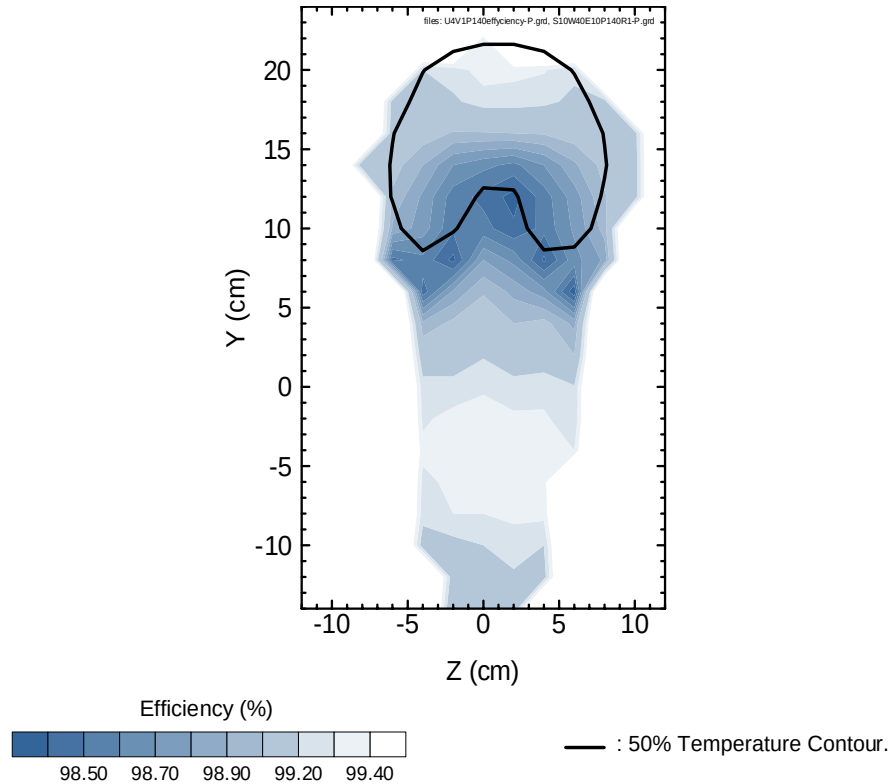


**Figure 5.7: Efficiency map for test conditions: $d_i = 22.1$ mm, $V_j = 1$ m/s
 $U_{\infty} = 4$ m/s, $x = 140$ cm**

For the case of $U_{\infty} = 8$ m/s (Figure 5.8), the local efficiency ranges upwards from 65 %, where the lowest efficiency appears in the same location as the highest concentration of HC. This range of efficiency highlights the potential problem of single point sampling techniques. For a 4 cm shift in the sampling point from $y = 0$ to $y = 4$ (along $z = 0$) the measured local efficiency changes from 70 to 94%. The measured overall efficiency of this flare was given in Chapter 3 as approximately 95%.

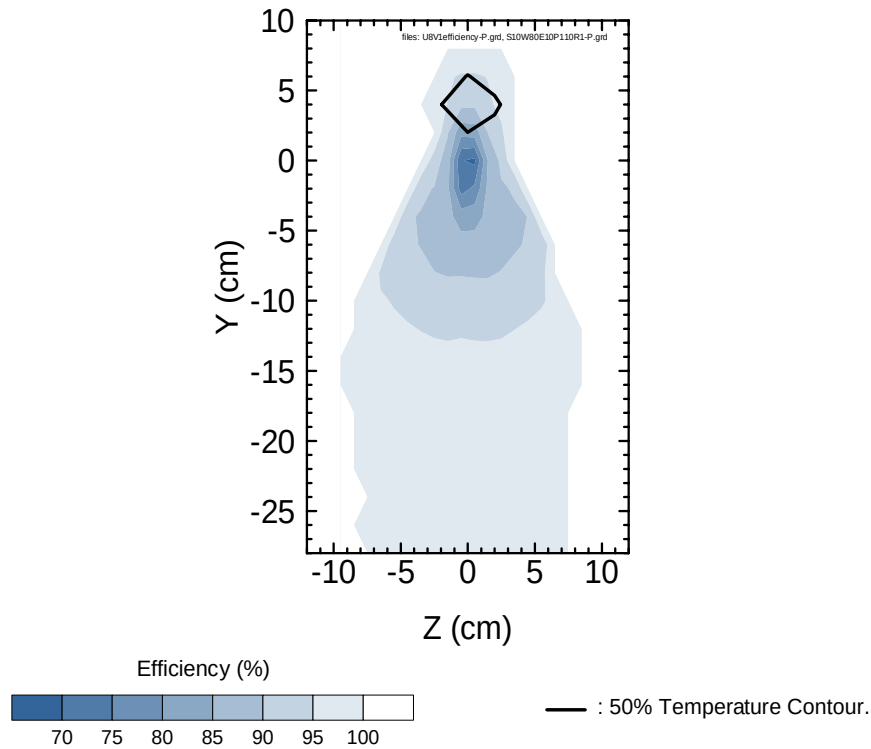


**Figure 5.8: Efficiency map for test conditions: $d_i = 22.1$ mm, $V_j = 1$ m/s
 $U_\infty = 8$ m/s, $x = 140$ cm**

5.5 ESTIMATING THE OVERALL EFFICIENCY

By integrating the data collected from the many single point measurement locations across the plume, the overall efficiency of the flare can be estimated. This integration was performed by assuming that a uniform velocity exists in the plume at the sample plane, and by weighting the calculated local efficiencies by product concentration and density. These estimates of overall efficiencies are shown in Table 5.2 and are in good agreement with the measured overall efficiencies given in Chapter 3.

For Table 5.2, the integration of single-point measurements, to calculate the overall efficiency, was performed using a cut-off set at 10% of the maximum measured product concentration. This limit was arbitrary and the stability of the integration with respect to the chosen cut-off is shown in Table 5.3. By increasing the cut-off, less of the plume is used in the integration.

Table 5.2: Comparison of Measured Overall Efficiencies (Chapter 3) and Integrated Efficiencies (Chapter 5)
($d_i = 22.1$ mm, $V_j = 1$ m/s)

Wind Speed (m/s)	Integrated Efficiency (%)	Measured Efficiency (%)
2	99.8	99.7
4	99.0	99.3
8	93.4	95.0

Table 5.3: Effects of Changing the Limits of Integration when Estimating Overall Efficiency

Product Concentration Cut-off (%)	Integrated Efficiency (%)		
	$U_\infty = 2$ m/s	$U_\infty = 4$ m/s	$U_\infty = 8$ m/s
10	99.82	98.96	93.42
30	99.82	98.91	90.83
50	99.83	98.91	93.11
70	99.84	98.95	92.66
90	99.86	98.90	92.05

Table 5.3 shows that the estimated overall efficiency from the single point data remains stable and representative of the measured overall efficiency even though the integrated area was reduced to include only the region of the flow where the product concentration was above 90% of its maximum. In fact, the local efficiency at the point of highest product concentration (i.e., a cut-off of 100%) provides a good estimate for the overall efficiency. This observation raises the possibility of using a single point measurement to estimate the overall efficiency of a flare, but care would be needed in choosing the correct sampling location or large errors would occur. The generality of this conclusion has not been fully examined and is based only on the data presented.

5.6 CONCLUSIONS

A methodology to measure the combustion efficiency at a point in the plume of a flare in a crosswind has been developed. This methodology is based on a mass balance between carbon dioxide, carbon monoxide, and hydrocarbons collected from an aspirating probe. By taking multiple point samples, 2-dimensional concentration maps of these gases can be constructed to determine their spatial distribution within the plume. In order to apply this technique, it was necessary to consider non-sooting flares.

The spatial distributions of carbon dioxide, carbon monoxide, and hydrocarbons within the plume varied significantly. As a result, the combustion efficiency was not uniform across the plume. The region of lowest combustion efficiency occurred at wind speeds high enough to cause a strong interaction between the flow of flare gases with the wake flow caused by the stack. Therefore, the overall wind-driven inefficiencies measured in Chapter 3 were a result of a portion of the flare stream being drawn into the wake flow and displaced away from the flare so that this part of the fuel does not have an opportunity to burn.

In one case the spatial variations in measured combustion efficiency were seen to range from 65 % to near 100 % within a single plume. Hence, caution must be taken in interpreting the combustion efficiency originating from any single-point measurement since it may not be representative of the overall efficiency of the flare. Results presented here suggest that analyzing the core of the plume around the point of minimum dilution with air has the potential of providing a good estimate of overall combustion efficiency.

6 MINOR SPECIES EMISSIONS FROM NATURAL GAS AND PROPANE FLARES

In Chapters 3 and 5, the performance of flares was characterized in terms of their efficiency of combustion, a measure of a flare's ability to convert the carbon mass of the fuel in the flare stream to CO₂. To obtain an accurate measurement of this efficiency, it was necessary to track the amount of the major carbon-containing species in the products of combustion. For the natural gas- and propane-based flares considered, the major carbon containing species were dominated by CO₂ and CO, and HC (i.e, fuel stripped from the flare stream without burning). Inherent to this approach was the realization that that soot was not an important emission in terms of its total carbon mass. For natural gas, this assumption was based on its very low propensity to soot at ambient conditions [19]. The amount of soot emitted from propane flares was also expected to be a small amount (less than 0.5 %) of the carbon mass emitted [9, 18]. Hence, soot or other carbon-based compounds not found in the fuel stream (e.g., cyclic or polycyclic hydrocarbons) but emitted from the flare were considered minor in terms of the total carbon mass and were negligible in terms of the efficiency calculation. However, for flare streams composed of heavier HCs such as alkenes, alkynes, or liquid fuel droplets, a significant amount of carbon-mass may be emitted in the form of soot and this assumption would not be appropriate. Throughout this chapter the terminology "minor species" will refer to these carbon-based compounds emitted from the flare.

In this chapter, the focus shifts from the combustion efficiency to the minor species that can be emitted from natural gas and propane flares. Despite the fact that these minor species represent only a small mass fraction of the combustion products, they are important because of their potentially toxic or carcinogenic properties. No comments are made in this report regarding the specific health concerns of any of the compounds or particulates found in the products of combustion. These health effects can be found within published epidemiological literature [c.f., 44]. The objective of this research is to provide a better understanding and engineering quantification of the emission rates of some of the important minor species

emitted from natural gas or propane flares. The data collected are for selected compounds and are used to help characterize the potential toxicity of flare emissions. No attempts were made to identify and catalogue the full range of chemical compounds that could exist in the products of combustion from these flares.

The following research regarding minor species emissions from flares is divided into two sections based on the phase (i.e., vapor or solid) in which these minor species are emitted. The first section considers minor species emissions in the vapor phase, while the second section considers solid phase (soot) emissions. Separating the emissions into phases provides an enhanced understanding of the issues of minor species emissions. As will be seen later in this chapter, the soot emissions are dominant and therefore more attention is given to the collection and measurement of the particulates emitted from the flare. This understanding also helps direct discussion toward appropriate monitoring and mitigation strategies.

6.1 EXPERIMENTAL SETUP AND METHODOLOGY FOR MEASURING MINOR VAPOR PHASE EMISSIONS

There are no standard test procedures for determining the vapor-phase emission rates of minor chemical compounds from a flare in general, nor for the particular case of the flare burning in a closed-loop wind tunnel. Therefore, a methodology for estimating these rates had to be developed as part of this research. The approach taken was to build on the methods for sampling ambient air as recommended by the U.S. National Institute for Occupational Safety and Health (NIOSH) which allow low levels of selected compounds to be measured by concentrating them within a solid sorbent tube. The particular sorbent used in the tubes depends on the compounds being measured (c.f., NIOSH analytical methods 5506, 2539, 1501, etc.). The compounds tested in the vapor phase were 17 poly-nuclear aromatic hydrocarbons (PAHs); benzene, toluene, ethyl-benzene, and xylene (known collectively as BTEX); and 12 aldehydes.

The experimental procedure involved burning a flare at a steady set of operating conditions (i.e., fuel composition, wind speed, flare diameter, and flare gas flow rate) for a specified

period (e.g., ~10 minutes). During this burning period, emissions from the flare were allowed to accumulate within the tunnel. After the set burning period was completed, the flare was shut-off and the gases within the tunnel were thoroughly mixed to create a homogeneous sample within the tunnel. Then, to estimate the amount of the selected compounds that were emitted from the flare, these well-mixed tunnel gases were sampled, analyzed, and scaled appropriately to convert their concentrations to a mass emission rate.

Based on the NIOSH Standards, the process of sampling the tunnel air and concentrating particular species in a sorbent tube could take up to 8 hours as the maximum permissible flow rates through the tubes are low. Since the wind tunnel is not perfectly sealed, it would exchange a considerable amount of air with both the building and the outdoor environment over an eight-hour period, so the composition within the tunnel would change significantly. To overcome this problem, a portion of the tunnel gases were transferred to Tedlar bags immediately after they were mixed, thereby creating a relatively stationary and representative gas volume from which sampling could take place over a period of several hours.

Figure 6.1a is a schematic of the method used to transfer approximately 0.8 m^3 of tunnel gases to a set of five 200-litre Tedlar bags. The Tedlar bags were hung within a sealed rigid container and connected through a manifold to a sample port in the tunnel by a 50 mm diameter stainless steel sample tube. A high flow rate vacuum was used to extract air from the rigid container causing the bags to inflate and draw tunnel gases into the bags. This system allowed the full 0.8 m^3 sample to be extracted from the tunnel in less than two minutes without passing it through any mechanical air handling equipment. Extracting the sample from the tunnel by this method avoided any possible contamination due to hydrocarbon vapors from oils that are typically used in air handling equipment.

Once the Tedlar bags were filled, the vacuum was shut-off and the rigid container was opened to the atmosphere so that the tunnel gases could be sampled from the bags. A schematic of the system that sampled the gases from the bags is shown in Figure 6.1b. The gases in the bags were first drawn by the sample pump through a $1 \text{ }\mu\text{m}$ filter at the recommended NIOSH flow rate. In the next step of this analysis, these gases were passed

through the sorbent tube and then a total volume meter. Once the sample was collected and concentrated in the sorbent tubes, it was sent to a commercial analytic laboratory and processed according to the NIOSH standard. This procedure allowed for the determination of the mass of compounds of interest in the sample. The total sample volume drawn through the sorbent tube was used to relate the analyzed mass to the concentration in the tunnel at the time of testing. With the concentration of the products of combustion known, the total mass of the emitted species could be estimated. Once the sampling was completed, the Tedlar bags were purged with N₂ and evacuated in preparation for the next set of test conditions.

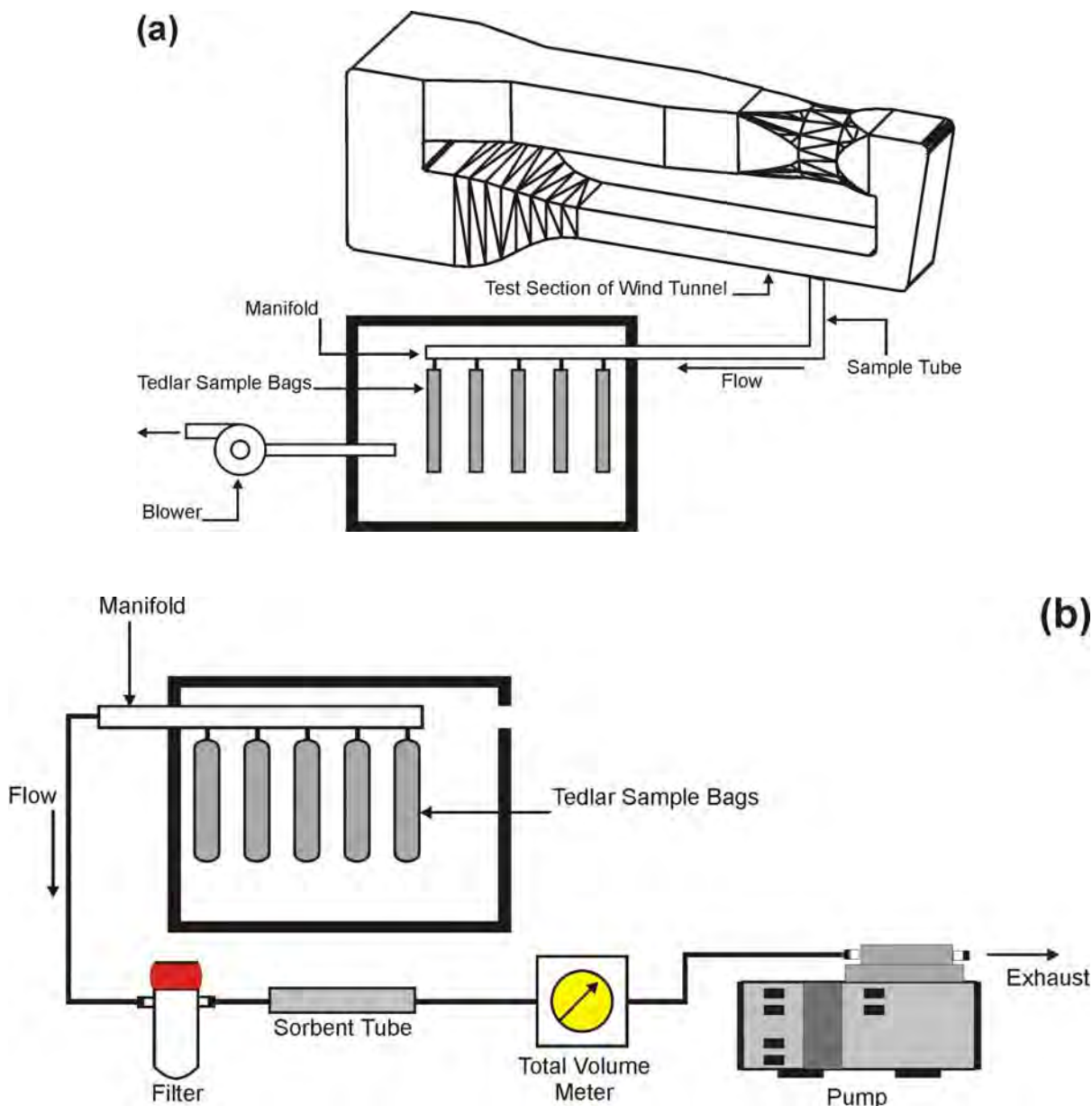


Figure 6.1: Schematic of (a) sampling gases from tunnel and (b) re-sampling these gases to concentrate vapor component of species

Using a closed-loop wind tunnel raises potential concerns about destroying some of the products of incomplete combustion by having them return to the flame as part of the tunnel air on subsequent passes around the tunnel (i.e., re-burning). This issue has been discussed in Chapter 3, where it was noted that the products of combustion are fully mixed into the bulk of the tunnel air before being recirculated back to the flame. Once mixed with the air, the total amount of the re-burning of emitted hydrocarbons can be estimated from the

depletion in O₂ in the tunnel air. Based on this calculation, approximately 1 % of the emitted products are returned to the flare when a 70 slpm (standard litres per minute) natural gas (or 30 slpm propane) flare was burned for 10 minutes. Given the uncertainties in the analysis of the sample, any effects of re-burning are entirely negligible.

Before presenting results of the tests based on the above methodology, a brief discussion is also needed regarding the limitation of using the alternate method of single-point sampling from the plume near the end of the flare. Initially, a single-point technique seems attractive because the concentration of the products of combustion would be highest and most readily measured in the near-plume. Though these samples are straightforward to collect and analyze, their interpretation is complex. Tests of this form only provide data regarding the mass of a particular species per unit volume of gas sampled (e.g., µg of benzene/m³ sampled). From Chapter 5, it is clear that the various products of combustion, in general, do not have the same concentration across the plume. Species concentrations also vary with distance downstream from the flare. Hence, the concentration of any species measured by a single-point sample is very dependent on where the sample was taken, and cannot be uniquely related to the total amount of that species being emitted. The extrapolation of single-point data to the total emissions rate could not be justified. Even attempts to quantify relative measures of emissions rates between flow conditions would be flawed due to the changing plume shapes seen in Chapters 4 and 5.

By contrast, the method used in this research can provide quantitative estimates of the total vapor mass of a chosen species emitted from the flare. By measuring the overall combustion efficiency of the flare and the concentration of CO₂ in the Tedlar bags, the net production rate of CO₂ by the flare can be estimated by the definition of combustion efficiency (Equation 3.1). The ratio of the concentration of CO₂ to the concentration of a minor species allows the production rate of CO₂ to be converted to the production rate of the minor species. Since the rate of flare gases being burned was also recorded, the source strength of various minor compounds can be calculated in terms of mass produced per unit mass of fuel burned (e.g., µg of benzene emitted/kg of gas flared). The estimated uncertainty in this calculation is

+/- 30 %, thus this approach provides an order-of-magnitude estimate of the rate at which these compounds are emitted in the vapor phase.

6.2 EMISSION RESULTS OF THE VAPOR PHASE

The compounds considered first were the PAHs listed in Table 6.1. The test conditions at which these samples were collected are listed in Table 6.2. Included in these tests were natural gas and propane flares operating at low and high wind speeds. All of these tests were performed using the 24.7 mm diameter (d_o) flare stack burning approximately 40 slpm of flare gas. A fifth sample was taken of the background air in the tunnel to confirm that the facility was not contaminated with vapor-phase PAHs.

The analyses of these five samples showed that all the selected PAH vapors emitted by the flares were below the detectable limits for this method. The detectable limits provided by the commercial laboratory for the compounds tested were 0.05 μg in the sample collected and are reported in Table 6.1 as their detectable concentrations within the tunnel gases.

An alternate way to express these detectable limits is in terms of their production rates that would have created these detectable limits. Using the case of a 40 slpm propane flare being burned for 10 minutes, the maximum production rate for each compound that could still fall below its detectable limit stated by the commercial laboratory is approximately 31 μg of each PAH per kilogram of fuel consumed. The third column of Table 6.1 lists these detectable production rates as the volume of each compound emitted per unit volume of gas flared.

Table 6.1: PAHs analyzed and their detectable concentration limits in vapor phase

Chemical Compound	Detectable Concentration Limits in Tunnel (ppt)	Detectable Volume Emitted/Volume Flared
Naphthalene	12.8	1.12×10^{-8}
Acenaphthene	10.7	9.4×10^{-9}
Acenaphthylene	10.8	9.4×10^{-9}
Fluorene	9.9	8.6×10^{-9}
Phenanthrene	9.2	8.1×10^{-9}
Anthracene	9.2	8.1×10^{-9}
Fluoranthene	8.1	7.1×10^{-9}
Pyrene	8.1	7.1×10^{-9}
Benzo(a)anthracene	7.2	6.3×10^{-9}
Chrysene	7.2	6.3×10^{-9}
Benzo(b)fluoranthene	6.5	5.7×10^{-9}
Benzo(k)fluoranthene	6.5	5.7×10^{-9}
Indeno(1,2,3-c,d)-pyrene	5.9	5.2×10^{-9}
Benzo(a)pyrene	6.5	5.7×10^{-9}
Dibenz(a,h)anthracene	5.9	5.2×10^{-9}
Benzo(ghi)perylene	5.9	5.2×10^{-9}

The conclusion drawn from these four tests is that the vapor emission rates of PAHs appear to be more than eight orders of magnitude less in mass than the flaring rate. Using this order of magnitude as an upper bound to the emission rates, the highest expected concentration of these species can be calculated. From the stoichiometry of the combustion of natural gas and propane, the volumes of air involved are respectively 9.5 and 24 times the volume of fuel gas. Dispersing the upper bounded emissions rate into the total volume of products of combustion, the concentration of any of the PAHs in vapor form would be, at most, in the order of 1 ppb. Using a representative molecular weight for these compounds suggests that they would appear in amounts less than $5 \mu\text{g}/\text{m}^3$ even before any entrainment of ambient air into the plume occurred.

Table 6.2: Experimental conditions for PAH measurements in vapor phase

Test	Fuel	Flare Exit Velocity (m/s)	Wind Speed (m/s)	Overall Efficiency (%)
1	Natural Gas	2	4.0	99.7
2	Natural Gas	2	12.1	90.4
3	Propane	2	4.0	99.9
4	Propane	2	12.0	98.7

Similar tests to those described above were conducted to measure the emission rates of BTEX and selected aldehydes (formaldehyde, acetaldehyde, propionaldehyde, acrolein, butyraldehyde, iso-butyraldehyde, crotonaldehyde, n-valeraldehyde, iso-valeraldehyde, hexanal, heptanal, and furfural) in the vapor phase by using different sorbent tubes. All of these results were also below the respective detectable limits. The detectable limits for these compounds were approximately 40 times that of the PAHs but still represent very low emission rates.

Based on these results for PAHs, BTEX and aldehydes, no further investigations were made into the vapor-phase emissions rates for these compounds until work on the solid-phase emissions was completed. The results in the following section show that the emission of minor species can be much more prevalent in the solid phase than in the vapor phase. Consequently, no more experiments are planned for these compounds in the vapor phase.

6.3 EXPERIMENTAL SETUP AND METHODOLOGY FOR MEASURING PARTICULATE-PHASE EMISSIONS

The basis of the method to measure the particulate material emitted from a flame was to separate the particles from the gas flow using filters. The mass of particles could then be determined by gravimetrically measuring the change in mass of the filters. Although this method appears straightforward, several issues needed to be resolved to ensure an accurate estimation of the total mass of particulate emitted. Due to the practical limitations of the filter size, it was not feasible to filter the entire plume of the flares tested. Alternatively, the

extraction of small portion of the plume (i.e., a single-point measurement) would not be representative of the whole since the particle concentration was not expected to be uniform as shown in Chapter 4 and 5 or gas phase emissions. Furthermore, multi-point measurements cannot be integrated without complementary data of the velocity field so that the mass flux of particles can be calculated.

In order to overcome these difficulties, a new technique of measuring the total mass of emitted particles was developed. The development of this technique was divided into two parts. First, the particle plume had to be located and collected in its entirety. Second, the total mass flow rate of the collected particles needed to be estimated.

6.3.1 Locating the Particle Plume

When the number density of the particles emitted from the flare was low, there was often no visible indication that a soot plume was present even though particles were being emitted. This was most often the case for the flares considered where the total mass of soot produced represented only a small fraction of the total mass of combustion products. Thus, locating the particle plume was non-trivial.

Three techniques were considered for locating the particle plume of the flares. One method was to sample the tunnel air downstream of the flame at multiple points and filter each sample to determine if particulate was passing through that point. However, for a reasonably useful measurement, numerous (>100) filters would be required to accurately sample the entire particulate plume at each of the test conditions. Such a technique was judged too time consuming to be effective for use in this study. A second potential method was based on a laser-scattering technique to measure the density of non-gaseous material. In this approach, a laser sheet would be passed through the plume and the laser light would be scattered by particles in the flow resulting in an image of the particle plume. Given the expected low particle number density and the high ambient light levels from the flame, this technique was deemed unacceptable. Instead, a third method was developed that used a soot measurement probe constructed using a modified dual channel fast flame ionization detector (FFID) [45].

A flame ionization detector (FID) is typically used to determine the concentration of hydrocarbons in gas samples. A fixed volumetric flow of sample is passed through a hydrogen flame that has a small ion detector surrounding it. When the hydrocarbons in the sample are oxidized, the detector responds to the produced ions. If properly calibrated, the ion current can be used to measure the concentration of hydrocarbons in the gas sample.

To convert an FID to an FFID the sampling lines are shortened, smaller diameter tubes are used, and the size of the hydrogen flame combustion chambers is scaled down. The result of these changes is a device that can respond rapidly to changes in hydrocarbon concentration making it an ideal device for detecting the ion bursts associated with burning soot particles passing through the hydrogen flame. Normally, the sample tubes and capillaries of FFIDs are designed to prevent particles from passing through the hydrogen flame so some redesign was required to use the device as a carbon-particle detector. Since the goal was to detect the presence of soot particles not to measure the mass of soot, the difficult task of calibrating the FFID for burning particles was not a problem. Details of the required modifications to the original FFID system can be found in [46].

The modified FFID was capable of detecting both particulate and gas-phase hydrocarbons on two separate modules. In order to discriminate between carbon-containing particles and gaseous hydrocarbons in the sample required two FFID modules. One of the FFID modules was used to analyze a filtered (particulate-free) portion of the sample [47], while the other module was left unfiltered and responded to both carbon particulate and hydrocarbons in the sample. The signal from this filtered FFID module corresponded to gaseous hydrocarbons only and was subtracted from the signal generated by the unfiltered FFID module. The two module system used in this study is shown in Figure 6.2.

The smallest particle believed to occur in soot is a single spherule, which has a diameter of 20 – 50 nm. Based on this assumption, a Whatman Anodisk filter with a pore size of 20 nm was selected to filter the gas stream within the FFID module. The introduction of this filter into one of the sampling lines significantly unbalanced the flows to the two FFID modules and, therefore, a matching dead volume was added to the line going to the unfiltered FFID

module. This dead volume served to correct for the time lag induced by the addition of the filter to the sampling line.

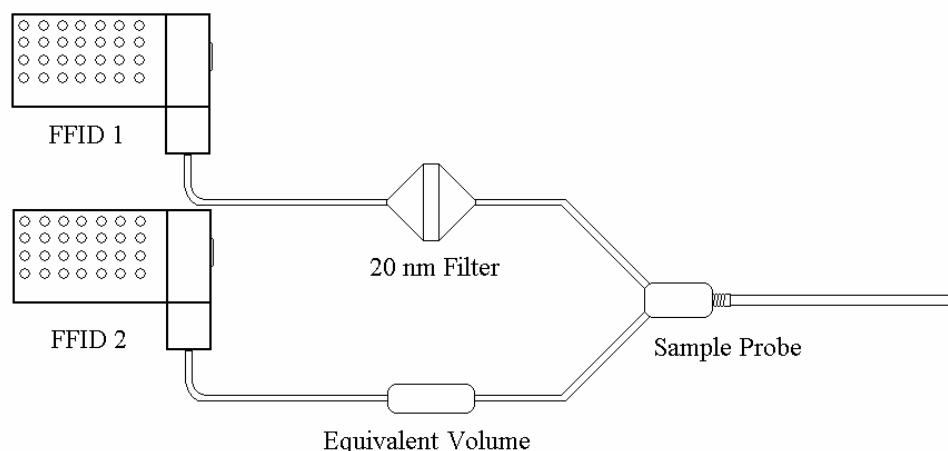


Figure 6.2: Dual FFID modules mounted in a parallel arrangement to analyze both filtered and unfiltered samples

Figure 6.3 shows the resulting output from the dual FFID system after the separate signals have been resolved, subtracted from one another, and a threshold for noise (~ 10 on the scale shown in Figure 6.3) has been applied. The spikes that remain are attributable to particulate matter in the sample flow and the magnitude of the spike is a function of the carbon mass in the particle. By counting the spikes and dividing by the sampling period, the mean particle frequency at the sampling location can be calculated. During testing the sample period was set to 60 seconds at each point to collect enough particles for an accurate estimate of the mean particle frequency.

6.3.2 Particle Plume versus Thermal Plume

By mounting the dual FFID system onto the computer controlled traverse system that was described briefly in Section 2.1.1.1, the mean particle frequency was measured on a square pattern grid with 2 cm spacing. Contour plots of these particle frequencies were generated to help visualize the particle plumes. Figure 6.4 shows a mapping of particles produced by a propane jet with an exit velocity of 0.5 m/s burning in a 4 m/s cross flow. The sampling plane was located 2.3 m downstream from the stack, while the flame length was

approximately 2 m. The flare stack used in this experiment was 64.5 cm tall and the point of maximum particle density is approximately 25 cm above the top of the stack.

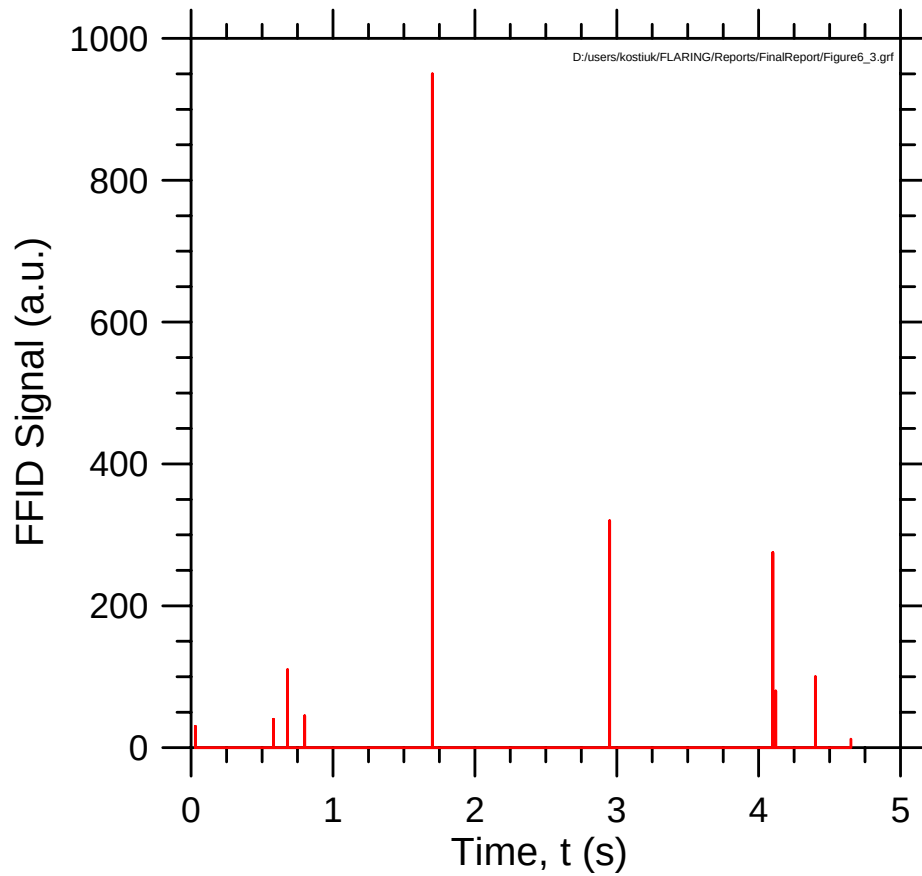


Figure 6.3: Processed output of dual FFID system which allows individual soot particles to be identified

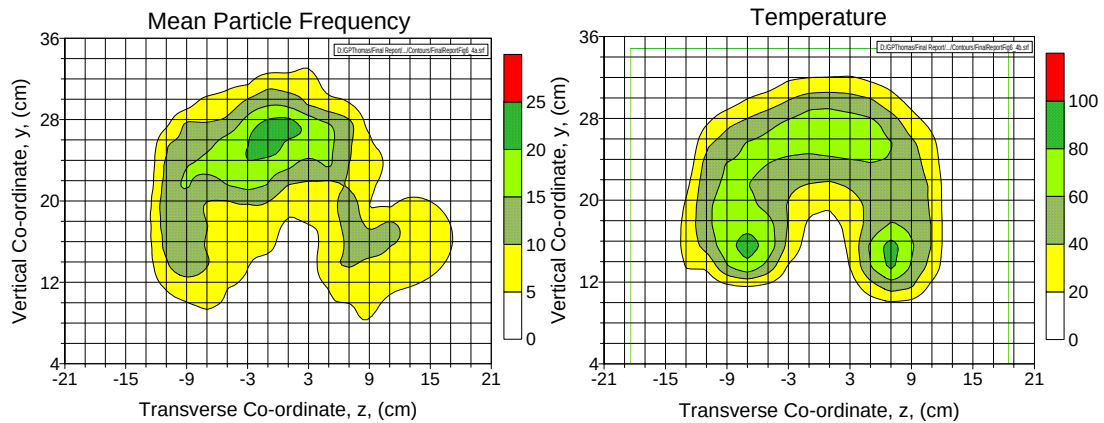


Figure 6.4: Measured mean particle frequency (Hz) and temperatures (°C) of a propane flare with an exit velocity of 0.5 m/s in a 4 m/s crossflow.

For comparison, the measured thermal plume for the same flare is also shown in Figure 6.4. The thermal plume was mapped using a Type-K thermocouple mounted next to the sampling probe. Both the particle and temperature contours correspond to a “kidney” shaped plume that is characteristic of low crosswind speeds as discussed in Chapter 4. However, the peak values of the two scalar quantities (i.e., mean particle frequency and temperature) in the plumes do not coincide. The maximum temperature in the plume is located within the core of the counter rotating vortices (c.f., Section 4.2), while the maximum density of particles is located in the center of the kidney directly downstream of the tail of the flame.

Section 4.2 also showed that changing the crosswind speed changes the shape and size of the thermal plume. Figure 6.5 shows the particle contour and thermal plume plots for a 0.5 m/s propane jet in a 6 m/s crosswind. The probe in this case was located 2.2 m downstream from the stack, which was approximately 50 cm beyond the flame tip under these conditions. At this higher crosswind speed, the thermal plume is reduced in width and expanded into the wake region directly behind the stack. The particle plume had corresponding changes, mimicking the shape of the thermal plume. However, the maximum peak frequency was still located directly behind the flame tip. This result implies that this region is responsible for a majority of the particulate material emission regardless of the crosswind speed.

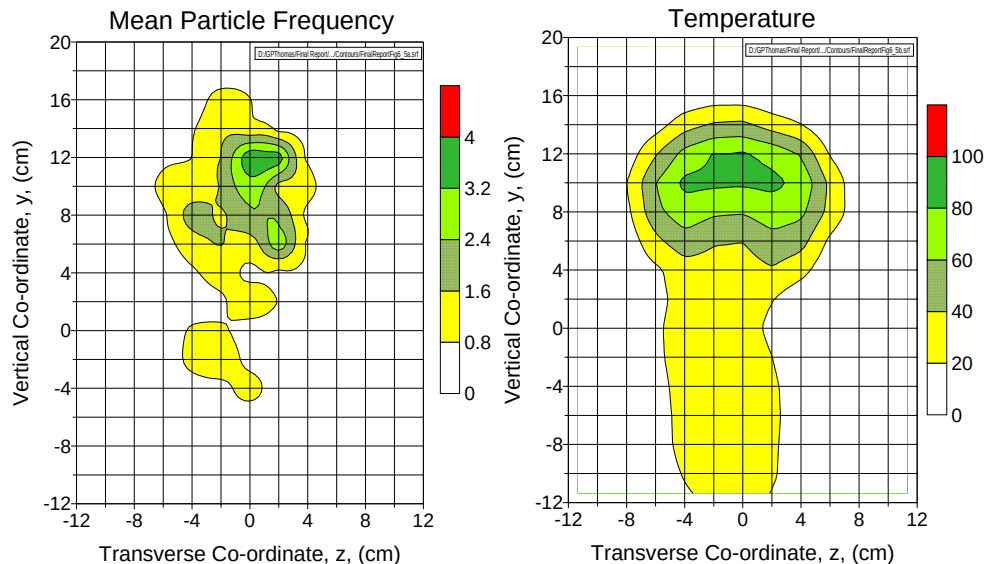


Figure 6.5: Measured mean particle frequency (Hz) and temperatures (°C) of a propane flare with an exit velocity of 0.5 m/s in a 6 m/s crossflow.

It is important to stress the implication of the particle plume being inhomogeneous and the fact that its shape changes with different flow conditions. Due to these factors, single-point measurements of particle emissions cannot be scaled up to total emissions. Moreover, single-point measurements cannot even be used to make relative comparisons between different flaring conditions. These findings are similar to those of Chapters 4 and 5 that considered thermal and compositional plumes and the associated inefficiencies of flares using single- and multi-point sampling. The issue of thermal and compositional plumes related to inefficiencies of large-scale flares will be explored in Chapter 8.

Figures 6.6 - 6.8 show both the particle plumes and the thermal plumes at different downstream distances from a 24.7 mm flare burning propane at an exit velocity of 0.5 m/s in a 4 m/s crosswind. As the plume moves away from the flare stack, both the thermal and particle plumes expand due to the entrainment of air into the plume. Of primary importance is the fact that the boundaries of the particle plume continue to correlate well with the thermal plume throughout all of the possible collection locations in the wind tunnel downstream of the flare stack. Thus, within this range of downstream locations, collecting the entire thermal plume would coincidentally collect the entire particle plume.

6.3.3 Collection and Measurement of Particulate Emissions

Once the particle plume was shown to correspond with the thermal plume, the focus of the research shifted to developing a methodology for collecting the thermal plume. The thermal plume could be sampled and that material would be used to quantitatively measure the particulate emission rates of the flames. During the process of locating the particulate plume, it was noted that the particle plume does not have a uniform spatial distribution. Thus, to measure the total amount of particles emitted, the entire plume needed to be iso-kinetically collected into a sampling duct and subsequently mixed into a homogeneous mixture. A sample was then extracted from this now-uniform flow for filtration so that the mass of the particulates collected could be related to the total particulate emission rate. This total emission rate is expressed as a mass emission rate of particulate matter normalized by the mass of fuel flared, and given as

$$Y_{PM} = \frac{\dot{M}_{PM}}{\dot{M}_{fuel}} \quad (6.1)$$

where

- Y_{PM} - Normalized emission of particulate matter from the flare
- $\dot{M}_{PM}$ - Total mass flow rate of particulate matter emitted from the flare.
- $\dot{M}_{fuel}$ - Mass flow rate of flare stream.

Based on the methodology described above, and once a homogeneous plume has been created, which will be discussed later, the rate of particulate matter emitted from a flare can be estimated from

$$\dot{M}_{PM} = \frac{\Delta m_{filter}}{\Delta t} \cdot \frac{\dot{Q}_{duct}}{\dot{Q}_{filter}} \quad (6.2)$$

where

- Δm_{filter} - Change in filter mass during experiment.
- Δt - Test duration.
- $\dot{Q}_{duct}$ - Flow rate through the sampling duct.
- $\dot{Q}_{filter}$ - Flow rate through the filter.

Designing a system to measure the mass emission rate of particulate material involved a number of challenges. With the location of the particulate plume known, a system was designed to collect it in its entirety. Next, the gas flow containing the plume needed to be mixed to create a homogenous mixture without loss of particulate matter. A filtration and mass measurement technique was also developed, taking into account the expected properties of available filters and particulate material. Finally, a means of filter storage and mass measurement was required. The system constructed to meet these challenges is shown in Figure 6.9. Only a brief description of this system is provided here to show how the important quantities in Equation 6.2 were measured (i.e., Δm_{filter} , $\dot{Q}_{duct}$ and $\dot{Q}_{filter}$, where $\dot{M}_{fuel}$ is already known and Δt is trivial).

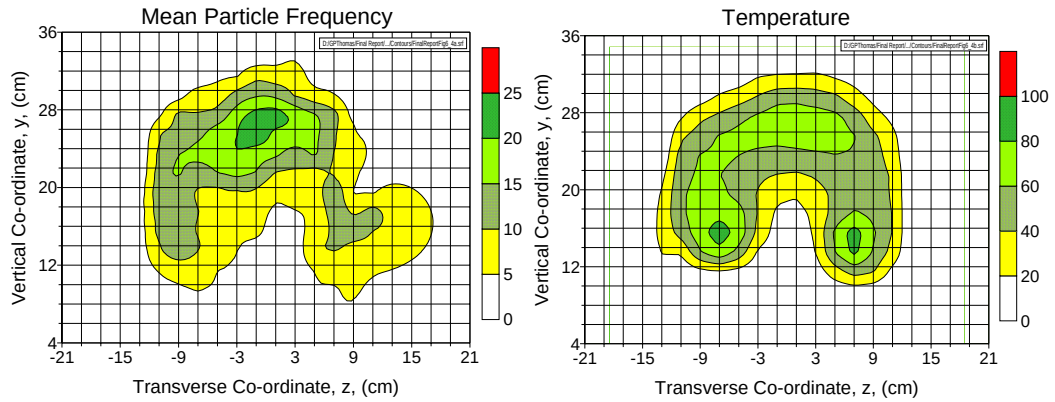


Figure 6.6: The mean particle frequency (Hz) contour (left) and the thermal (°C) contour (right) at a distance of 230cm downstream of the flare stack.

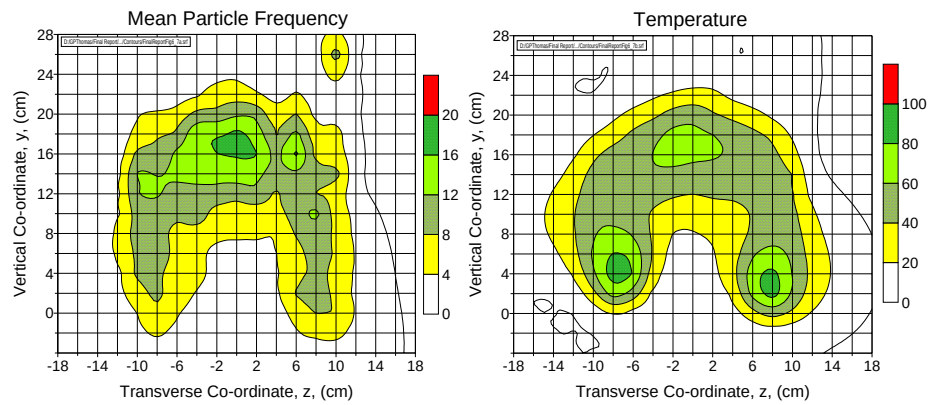


Figure 6.7: The mean particle frequency (Hz) contour (left) and the thermal (°C) contour (right) at a distance of 250 cm

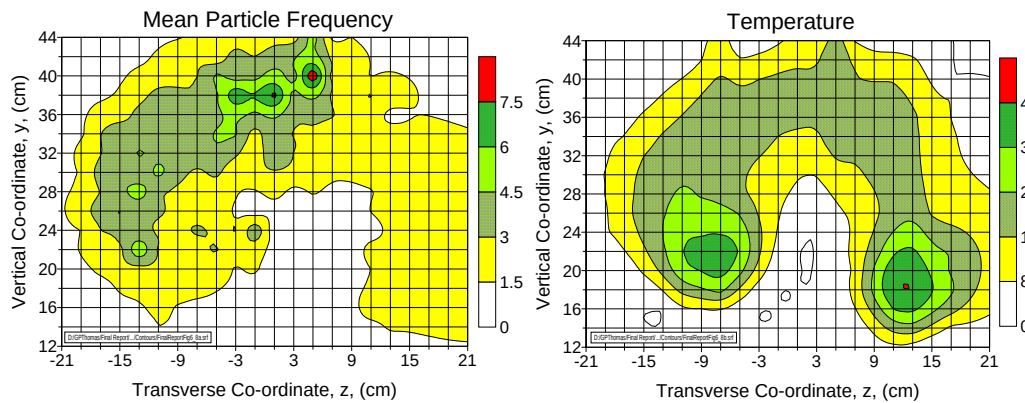


Figure 6.8: The mean particle frequency (Hz) contour (left) and the thermal (°C) contour (right) at a distance of 350 cm downstream of the flare stack.

A 0.6 m diameter duct was installed on the roof of the combustion wind tunnel. As shown in Figure 6.9, this duct had 3 main sections. The entry section collected the plume, the mixing section made the plume composition homogeneous, and the measurement section controlled flows and collected the particulate material.

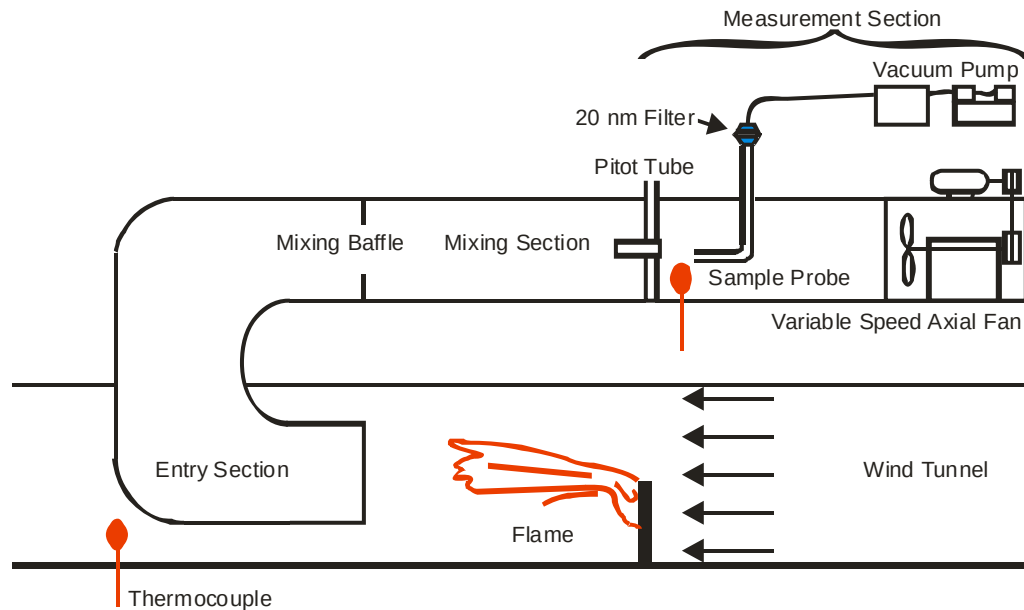


Figure 6.9: Schematic of the particle plume collection and sampling system.

The entry section was mounted into the wind tunnel so that the collection plane was 1.7, 2.3, 2.9, or 3.5 m from the flare stack and therefore could accommodate the various sized flames and plumes. To ensure that the entire thermal plume (and by implication the entire particle plume) was being collected, a shielded thermocouple was installed outside the duct and could be repositioned to different locations around the outside edge of the collection plane as needed. This externally-mounted thermocouple was used to detect increased temperatures that indicated the thermal plume was outside the entry section of the duct. If higher temperatures were detected then the duct was repositioned in order to collect the entire thermal plume.

The mixing section had a length of 9.2 m (a length to diameter ratio of over 15:1) and was needed to create a homogeneous mixture of both the plume and the air collected from the wind tunnel. Early tests indicated that the flow rate in the mixing section did not generate

enough turbulence to fully mix the gas flows, resulting in the stratification of the different gases. In order to promote mixing, a mixing baffle was installed at the beginning of the mixing section. The mixing baffle was designed to maximize mixing while minimizing flow blockage and thus avoiding large surface areas where particles could deposit. The ability of the mixing section to mix the flow of gas into a homogenous blend was tested by adding tracer gases to the gas flow and then traversing the sampling section with on-line gas analyzers to confirm whether or not the gas was mixed homogeneously across the duct. The FFID particle detector was also positioned at locations across the end of the mixing section to ensure the particles were also well mixed.

The measurement section of the mixing tunnel contained a variable speed fan, sampling probe, and velocity measurement equipment necessary to control and monitor the operation of the mixing tunnel. The measurement section was 1.0 m long and was constructed from the same 0.6 m diameter galvanized ducting as the rest of the sampling tunnel. The fan was driven by a 2 HP variable frequency drive motor that controlled the volume flow rate through the mixing tunnel to ensure near iso-kinetic velocity at the plane of collection in the wind tunnel. To measure the volumetric flow rate, an area-averaging Pitot tube was constructed and installed in the sampling section of the mixing tunnel. This Pitot tube was constructed to ASHRAE Standard 51-75 and, once installed, was calibrated to measure $\dot{Q}_{duct}$.

The flow rate, $\dot{Q}_{filter}$, through the 4 mm diameter sample tube and particle filter could have been difficult to measure and maintain at a constant flow rate if not for flow characteristics of the filters used. The filters used in these experiments were Whatman Anodisc 47 with 20 nm pore size membranes. The flow characteristics of these filters are very weakly dependent on the amount of material collected and make sampling straightforward as the suction pressure can be fixed for any desired flow rate. The flow through the filter was then set and known by fixing the pressure downstream of the filter with a vacuum pump and digital vacuum controller. The main reason for choosing these filters was that combustion-generated particles are comprised of many spherules that can be clustered together into larger particles called aggregates. A spherule is typically between 20–50 nm in diameter particle [49] and, as a result, the chosen filter could collect individual spherules. Also important in choosing

these filters was their flatness. This characteristic allowed the filters to be used to image particles collected in order to measure their size (see section 6.4.2).

When developing a sampling system intended to handle particulate matter and keep particles suspended, care must be taken to avoid significant deposition onto surfaces prior to measurement. Methods are available for estimating the loss of particles due to deposition but these calculations require a good description of particle size and density in order to be performed. As a result, when these quantities are not known *a priori* they must be estimated and checked later when this information has been obtained experimentally. Based on the particles collected and measured for size and composition (data presented later) 99.5% of the particles emitted from the flame are estimated to survive in suspension until removal by the collection filter. The details of this calculation are provided in Appendix B of [46].

The final quantity in Equation 6.2 that needs to be measured is the change in mass of the filter, Δm_{filter} , which requires the mass of the filter (and any mass collected on it) to be determined both before and after the particulate matter is collected. The actual mass of particulate material emitted by the flame was expected to be small and therefore a sensitive scale was required. A scale with a 10 μg resolution was used to measure the mass of all of the filters. As the sensitivity of the scale resulted in a slow response and settling time, it was connected to a computer and the mass was recorded over a period of time to determine when a stable mass reading had been achieved.

When dealing with a mass resolution of 10 μg , the environmental conditions and the handling of filters become important. To maintain a stable environment for the filters, both the scale and the filters were stored in a static-environment chamber, as shown in Figure 6.10. The chamber was maintained at a constant temperature and humidity for the equipment. The temperature was set to 25°C and 50% humidity since NMAM 5515 (NIOSH Manual for Analytical Methods) indicates that refrigeration is not required for filter samples. The filters had to be protected from UV light during storage and allowed to stabilize for a minimum of 24 hours in the environmental chamber prior to mass measurement.

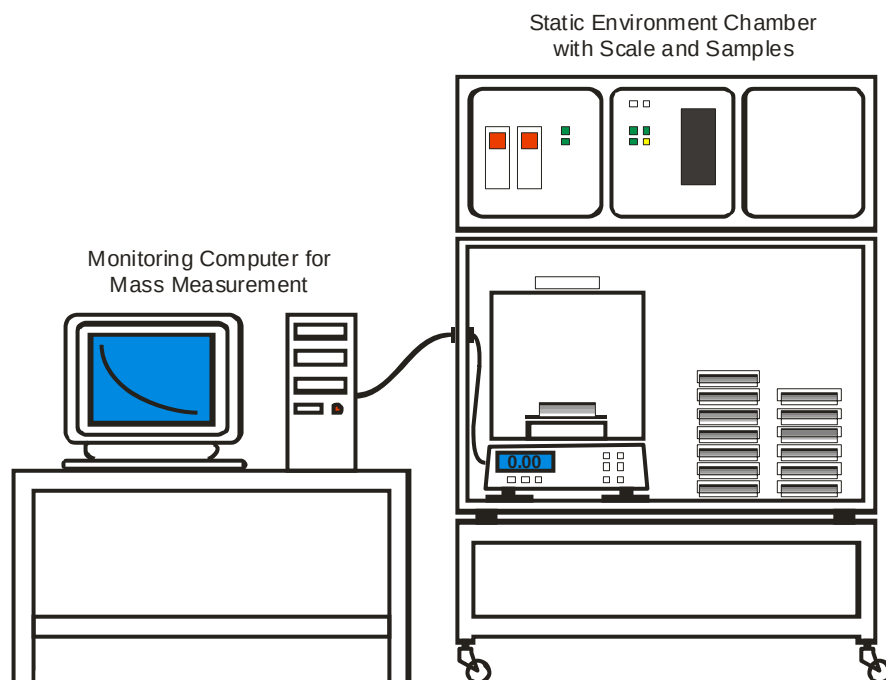


Figure 6.10: The assembly used for storage and measurement of filters. The environmental chamber maintains the environment while the computer monitors the scale readings through an RS 232 connection.

Due to the small masses involved, special precautions were taken when handling the filters:

- Filters were kept in individual Petri dishes. Each dish was sterile and clean before the filter was placed in the dish. Each filter had its own dish, and the dishes were not reused. Each dish was labeled for identification purposes. These dishes protected the filters from contamination from dust and airborne particles.
- Cotton gloves were worn at all times when handling the filters and filter dishes. This prevented skin oils from contaminating the filters.
- The filters were only removed from the environmental chamber for short periods of time. Once the mass of particulate was collected on the filter, it was returned to the environmental chamber to stabilize.
- Filters and dishes were transported in a closed container when not stored in the chamber. This allowed for easier handling and protected the filters from contamination.
- Control Blanks (filters that never left the chamber) and Test Blanks (filters that were moved, but not experimented upon) were maintained to monitor any system drift.

Multiple samples were collected for each set of experimental conditions. This testing protocol allowed for the identification of any contaminated filters by statistical analysis of the data collected.

6.4 EMISSION RESULTS OF THE PARTICULATE PHASE

The particulate matter collected by the above method was analyzed in three ways. First, the total mass of the particulate phase emitted from the flare was quantified and presented as the normalized emissions of particulate matter, Y_{PM} , as described by Equation 6.1. Second, the particles collected on the filter were imaged to provide an estimate of the particle size range as emitted from flares. Finally, the material collected on filters was chemically analyzed to determine the composition of the particles.

6.4.1 Mass of Particles Emitted from Flares

Particulate mass measurements were conducted over a range of test conditions. The fuels used in these tests were propane, natural gas, and natural gas blended with octane droplets where the octane comprised up to 40% of the mass of fuel being flared. Details of the method for adding octane droplets to the flare stream and characterizing the droplet sizes are presented in Chapter 7. The flares used were the standard 12.1 and 24.7 mm diameter tubes (d_o). In addition, a 29.9 mm outside diameter flare was used that had an internal flow area 50% larger than the 24.7 mm flare. The plumes of flares with a diameter greater than 29.9 mm were too large to be captured with the present experimental set-up. The gas exit velocity was varied from 0.15 to 2 m/s, and the crosswind was either 0 m/s or varied from 1 to 5 m/s.

In order to make measurements at zero crosswind speed, the working section of the wind tunnel was modified. A 50 cm diameter section of the tunnel floor and the horizontal part of the entry section of the collection tunnel were temporarily removed so a flare could be burned directly under the vertical part of the entry section. A nominal 1 m/s suction velocity

was established in the sampling tunnel to fully capture the associated plumes and collect the emitted particles.

The potential problem of ambient particles affecting the results was considered by collecting background particulate samples during tunnel operation without a flare burning. All of these background tests showed that the ambient particulates in the wind tunnel were below the detectable level of the measurement system. Based on a typical 15-minute test, the detectable limit for the measurement system was conservatively estimated to be 1.7 mg/m^3 of air. Taking the density of soot to be 1700 kg/m^3 [48], the detectable limit for soot would be 1 ppb in the particulate sampling tunnel.

From the data collected, the amount of particulates emitted from flares burning natural gas and natural gas / octane blends fell below the detectable limit. This result is further validation of the work in Chapters 3 and 5 wherein the calculation of efficiency neglected the presence of soot in natural gas flares. This omission was deemed valid since the soot was thought to be a small fraction of the mass of carbon in the combustion products. As discussed at the start of this chapter, natural gas is composed mostly of methane (C_1 alkane), which has a very low propensity to form soot at atmospheric pressure. In general, as the number of carbons in the alkane structure is increased so is the fuel's propensity to form soot [19]. As will be discussed in the following sections, propane (C_3 alkane) does produce measurable amounts of soot. However, when octane (C_8 alkane) is burned with natural gas (up to 40% of the fuel-mass flared being octane) no soot is emitted. Because this result was somewhat counterintuitive, separate measurements with the FFID particle detection system (described in Section 6.3.1) were completed to verify this absence of soot. In these additional experiments, samples were drawn directly off the tip of the flame and no carbon-based particles were detected. This issue will not be pursued further but leads to the hypothesis that methane, with its large number of hydrogen atoms, appears to suppress soot emissions.

Propane flares did produce measurable amounts of soot and these data will be discussed in the remainder of this chapter. As noted above, since the amount of any background particulate in the tunnel was below detectable limits, measurable particulate matter collected

on the filters were therefore emitted from the flare and will henceforth be referred to as soot. A chemical analysis of the material collected on the filters, including the physical structure of the particles, will be discussed later in this chapter which will lead to the identification of the particulate as soot.

Figure 6.11 shows the raw data for the mass of soot emitted (i.e., Y_{PM}) for the 24.7 mm diameter flare burning propane at a 1 m/s exit velocity (V_j). Despite the considerable noise in the data at higher wind speeds (U_∞), there appears to be a slight decrease in soot emissions from the flare as the crosswind is increased.

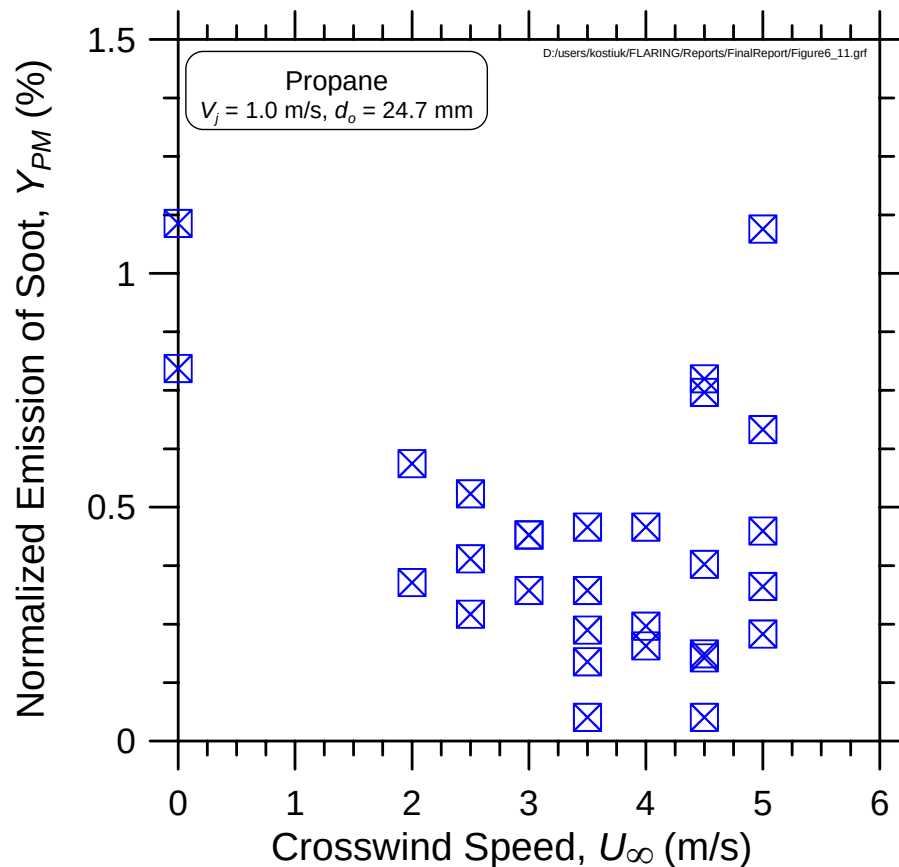


Figure 6.11: Data for 1 m/s exit velocity propane flame with the 24.7 mm diameter jet in a varied crosswind.

Figure 6.12 shows data acquired at a constant crosswind of 2 m/s with the jet exit velocity varied and indicates that soot emissions decrease with increasing jet exit velocity.

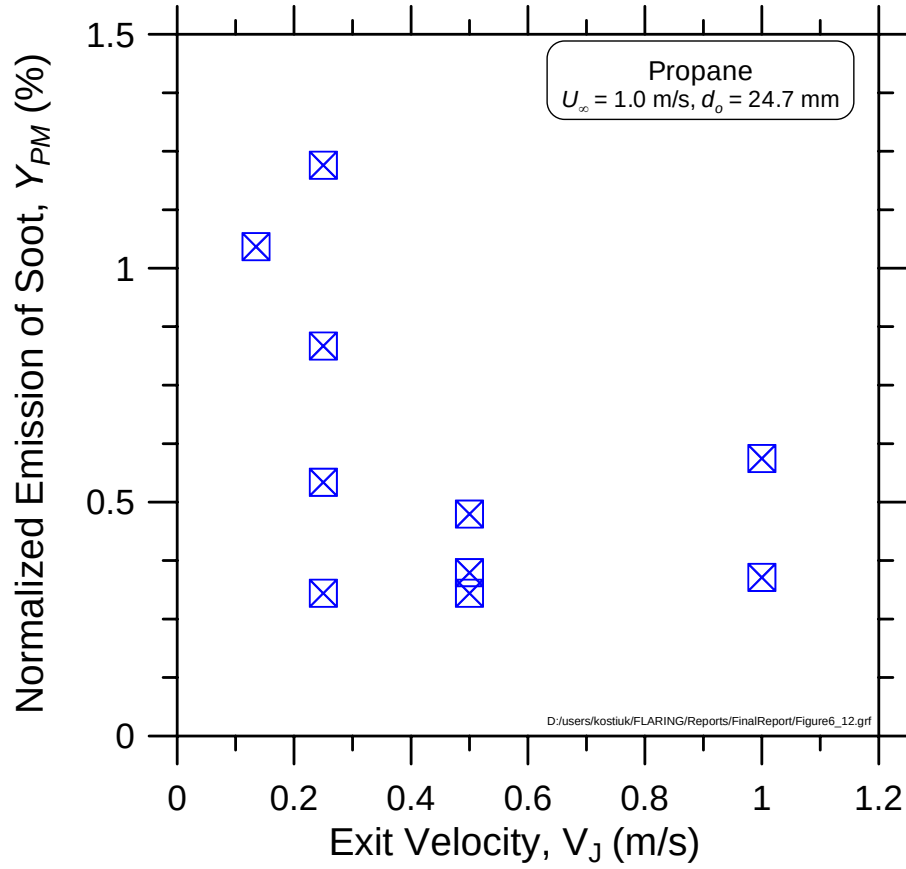


Figure 6.12: Data collected for a 24.7 mm diameter jet in a constant crosswind of 2 m/s with a varied jet exit velocity.

These trends of decreased soot emissions with either increased wind speed or jet exit velocity are consistent with previously published results from 6 mm diameter propane jets [18]. To correlate their data, they adopted the idea that the amount of fuel converted into particulate material was inversely related to the mixing ratio, defined as $U_\infty \cdot V_j$. This mixing ratio was proposed previously based the observation of the combined importance of the crosswind speed and jet velocity in mixing the fuel and air together for the combustion of jet diffusion flames in a crosswind. The model proposed [24] was

$$Y_{PM} = \alpha (U_\infty V_j)^\beta \quad (6.2)$$

where α and β are experimentally determined constants.

Figure 6.13 shows all the Y_{PM} data collected for the 24.7 mm diameter flare stack (65 experiments) plotted as a function of the mixing ratio.

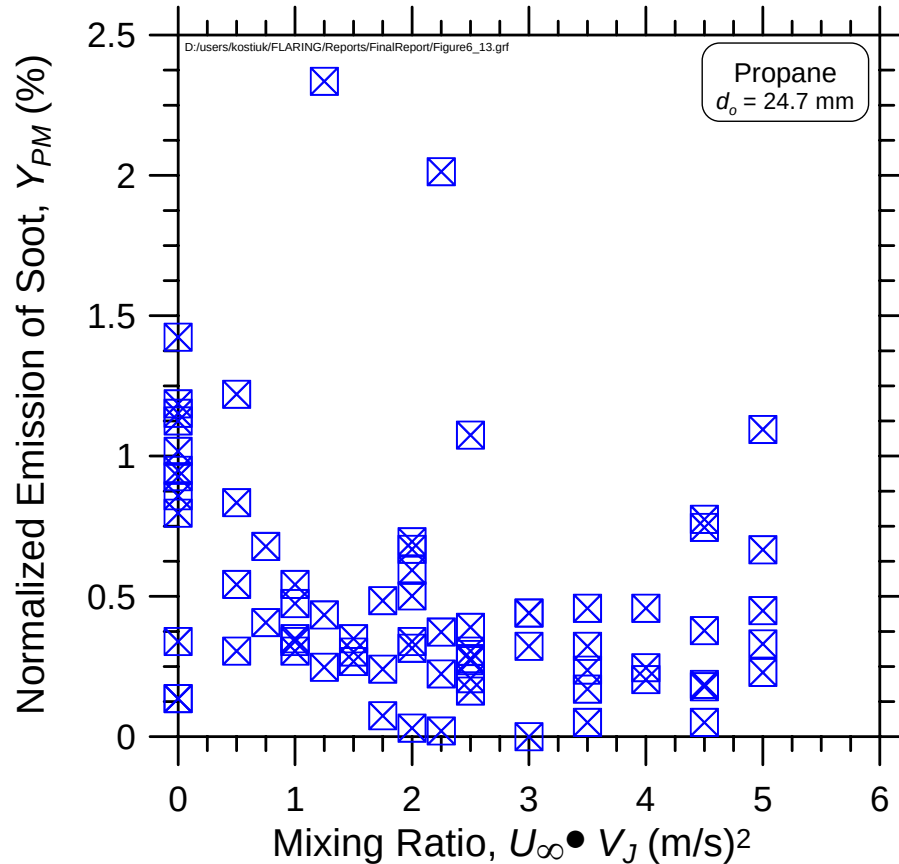


Figure 6.13: All data collected for the 24.7 mm diameter jet prior to the statistical analysis.

The particulate matter data shown thus far is quite noisy. The data in Figure 6.13 potentially shows two trends. The first trend shows a rapid drop in emitted soot as the mixing ratio is made non-zero. The second trend indicates a rise in the emitted soot as the mixing ratio is increased towards $5 (m/s)^2$. Further insight into these trends can be achieved through a statistical analysis of the data in order to focus on the data that is most sound. The analysis technique used to process this data needed to respect a few important constraints on the data. On the one hand, data would likely have a relatively small amount of naturally occurring variation since the test conditions were repeatable and well-controlled. On the other hand, contaminated samples would have a relatively large variation due to stochastic events. Also,

the filters could not lose mass. Consequently, a Gamma distribution was used to describe the expected data variation. Any data point that had a probability of <5% or >95% of occurrence was removed from the data set, which left 48 data points. The final processed data collected from the 24.7 mm diameter flare stack is presented in Figure 6.14.

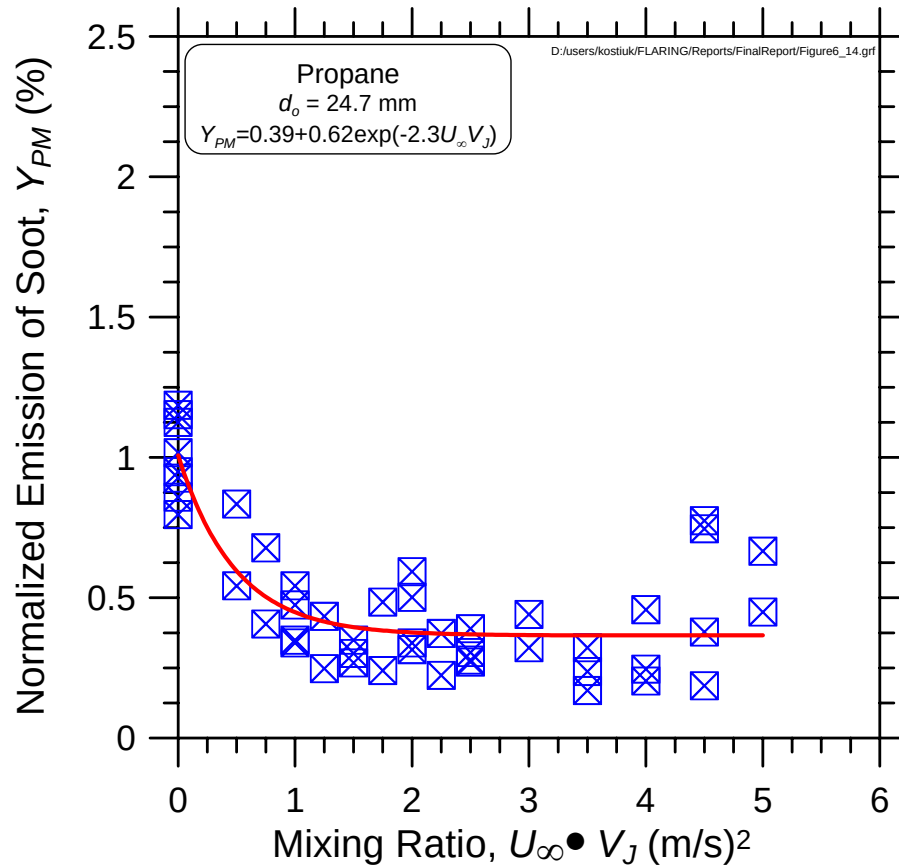


Figure 6.14: The data collected for particulate mass production using the 24.7 mm model flare stack.

The data in Figure 6.14 continue to show a rapid decrease in the production of particulate material as the mixing ratio is increased above zero. However, the effects of changing either the exit velocity or the wind speed are not observed as the mixing ratio is increased beyond 2 (m/s)^2 . The model proposed by Ellzey [18] could be fit to the data, but this model predicts the unrealistic result of an infinite amount of soot emissions when the mixing ratio becomes zero due to the negative exponential variable (β). Therefore, an alternate model based on an

exponential function is applied here (Eq. 6.3) where A, B and C are constants determined by the data.

$$Y_{PM} = A + B \exp(-C \cdot U_{\infty} \cdot V_j) \quad (6.3)$$

Also, based on the data in Figure 6.14, the 24.7 mm diameter jet had a mean soot emission of approximately 0.4 % of the fuel burned. It should be noted that this quantity of soot is small in the overall carbon balance of the flare. As such, the overall efficiency measurements presented in Chapter 3, which were based on gas-phase carbons only, are not significantly affected by soot emissions for either the natural gas or propane flares.

In order to determine if changing the stack diameter has any effect on the production of particulate material, a series of experiments were conducted using a larger-diameter stack ($d_o = 29.9$ mm) and the data for this larger stack is shown in Figure 6.15. The 29.9 mm diameter stack shows the same response in the amount particulate material emitted as the 24.7 mm stack with increasing mixing ratio. At mixing ratios above 2 (m/s)^2 , the larger stacks appear to convert approximately 0.3 % of the fuel mass into soot, which is approximately the same as the smaller stack. The main difference in the performance of the two stacks is that particulate material emitted for mixing ratios less than 2 (m/s)^2 is notably higher for the 29.9 mm diameter stack. Based solely on this data, there would be a considerable concern regarding the amount of soot emitted for full-scale flares when the mixing ratio was $< 2 \text{ (m/s)}^2$. However, published data [9] on propane flares as large as 300 mm are reported to emit ~0.5% of their flared mass as soot in quiescent conditions.

Due to limitations in the size of flame and plume that can be sampled within the wind tunnel facility, larger flares cannot be tested to see if this observation of increased particulate matter yield for the larger flare stack is a consistent trend that would be applicable to yet larger flares. Tests on smaller flares (e.g., $d_o = 12.3$ mm) were inconclusive due to problems in creating low mixing ratio flow with propane since the Reynolds number becomes small and turbulent flow in the stack could not be maintained. Details of the effects of the flow profile within the flare are discussed elsewhere [46]. It is important to note that only turbulent flow

results are relevant to industrial flares. From the results presented, the scale of the flare appears to have an important impact on the amount of particulate matter emitted, particularly at a lower mixing ratio (i.e., $U_{\infty} \cdot V_j < 2$).

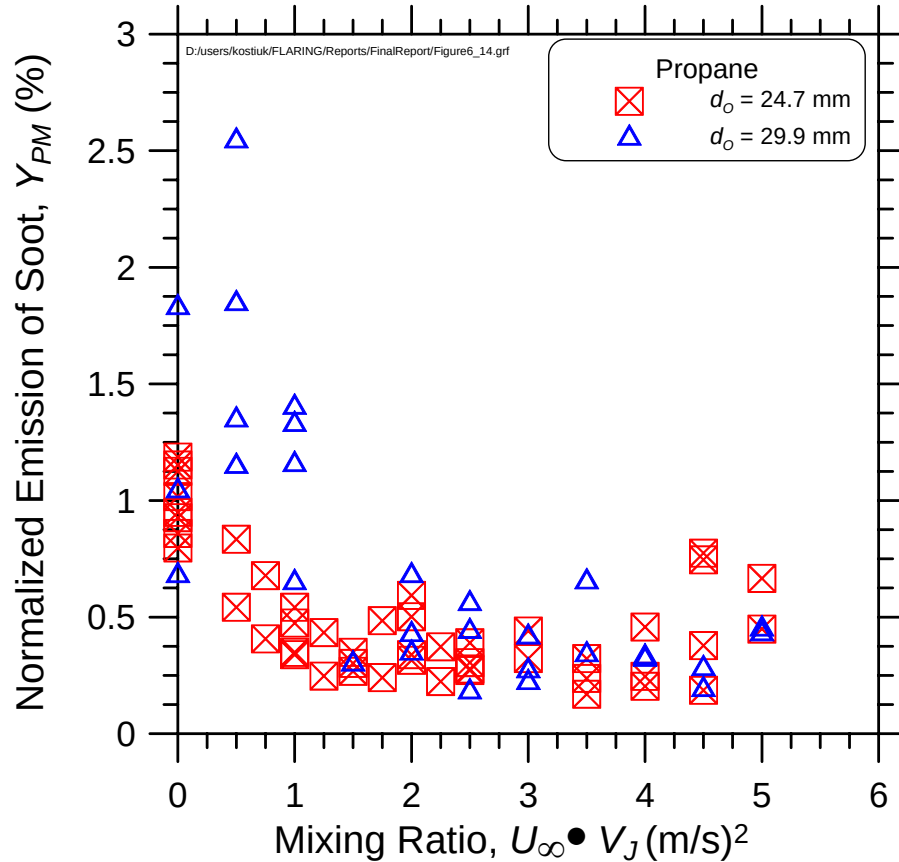


Figure 6.15: The particulate material production correlation for the 24.7 mm and 29.9 mm stacks.

6.4.2 Particles Imaging

There are two factors that are often used to determine the toxicity of a particle: its size and its chemical composition. Size is an important factor when considering toxicity because it determines how deeply the particle will be carried into the respiratory system; chemical composition is an important factor when considering toxicity since this affects the reactivity of the particle with the organism. In this section, particle imaging with a scanning electron microscope (SEM) is used to estimate the particle sizes collected on the filters described above. The chemical composition of the particulate matter is discussed in Section 6.4.3.

As discussed previously, the smallest sized particle expected from combustion and emitted as soot would be single spherules with diameters in the range of 20-50 nm. Larger particles of soot are aggregates of these individual spherules. The larger size limit of interest can be illustrated by the following examples: the nasal cavity and the upper respiratory system can effectively filter particles larger than 3 μm before entering the lungs; and the Cilia, the hair like fibrous cellular material that lines the lungs, can capture particles $\sim 1 \mu\text{m}$ in size, expelling them with mucus flow [50]. Therefore, the diagnostic system used to measure the particle sizes emitted from the flare must be capable of handling particles from as small as 20 nm to as large as a few micrometers in diameter. SEM is well suited to this task since it provides the necessary resolution with the added feature of being a non-destructive imaging technique.

To facilitate imaging, particles were captured on alumina membrane filters with a pore size of 20 nm. To verify this pore size, clean filters were imaged as shown in Figures 6.16-17. Figure 6.16 shows the filter face where the individual pores can be identified as approximately 20 nm across. A small amount of material appears to be on the surface of the clean filter. An x-ray spectrometer determined that these particles were pieces of alumina residue, probably deposited during the production of the filter. A side image of the filter is shown in Figure 6.17 that shows that the layer making up the 20 nm pores is only ~ 100 nm thick. Beneath this exterior layer, the filter is a collection of ~ 200 nm diameter channels.

Initially, the imaging of particles emitted from the flares was conducted on the filters used in the previous section to determine the mass emission rate of soot. However, too much material was collected on these surfaces to be able to identify what were individual particles suspended in the combustion products. The surface of these filters appeared to be a single mass of spherules and it was not possible to determine if these spherules were deposited separately or in large aggregates. Therefore, in order to image individual particles, the tests were repeated when only a small amount of soot was collected on any filter.

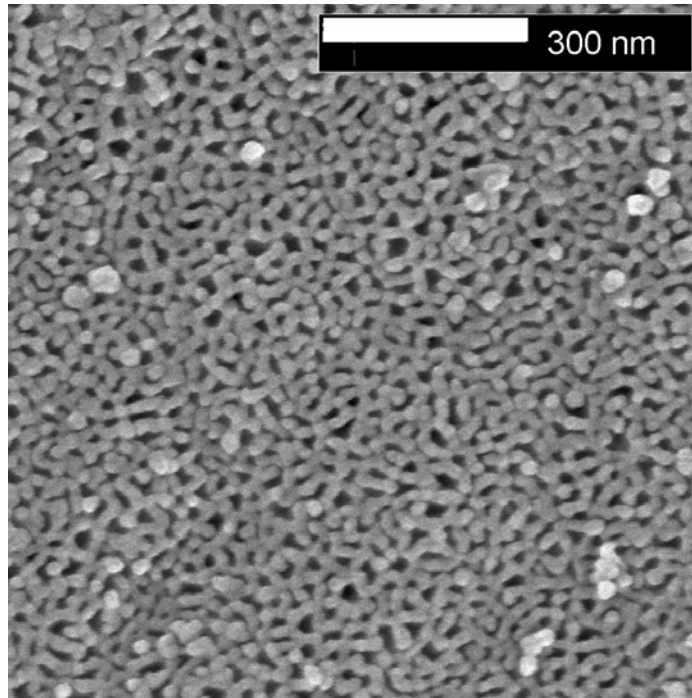


Figure 6.16: Magnification of the collection facing of the 20 nm alumina filter. Individual pores are ~20 nm in diameter as specified by the manufacturer.

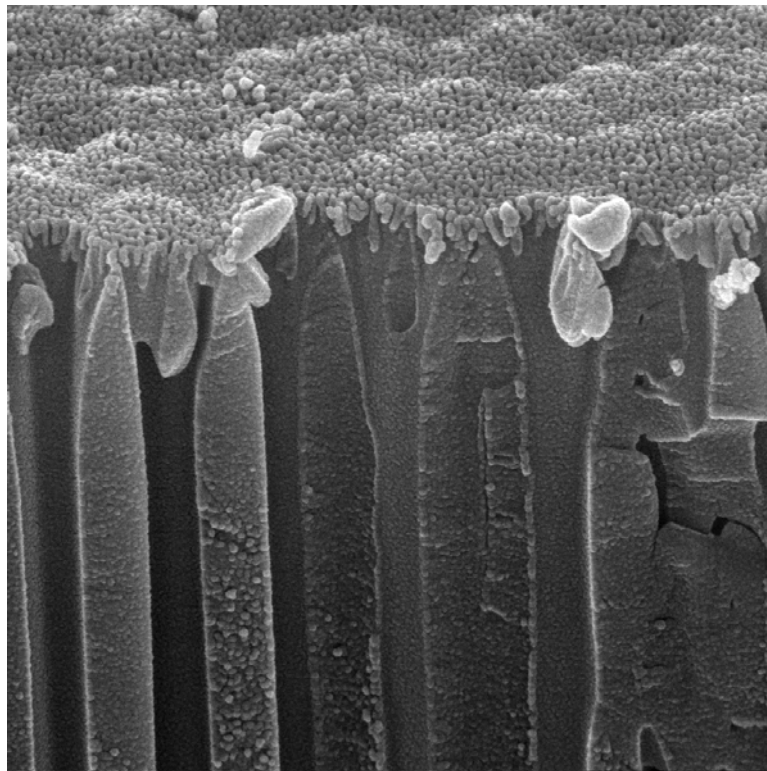


Figure 6.17: A side image of the filtration surface. The magnification is the same as Figure 6.16. The filtering surface is less than 100 nm thick, and then it becomes a 200 nm tube.

Filters were collected and imaged for both natural gas and propane flares. No particles were observed on the filters when natural gas was burned. This result confirmed the previous observation that natural gas flares of this scale do not emit soot. For propane flares operating over the full range of test conditions, samples were aspirated onto filters placed in the particle plume directly behind the flame tip. The SEM images of these filters showed a distinct similarity present amongst all the particles observed. Representative data is shown in Figure 6.18 for the case for a 24.7 mm diameter flare with an exit velocity of 1 m/s in a crosswind of 2.0 m/s. Large collections of highly irregular shaped aggregates are seen across most of the filter. These aggregates were seldom found outside the range of 100 to 400 nm in size. As explained above, particles of this size become of concern to the human respiratory system.

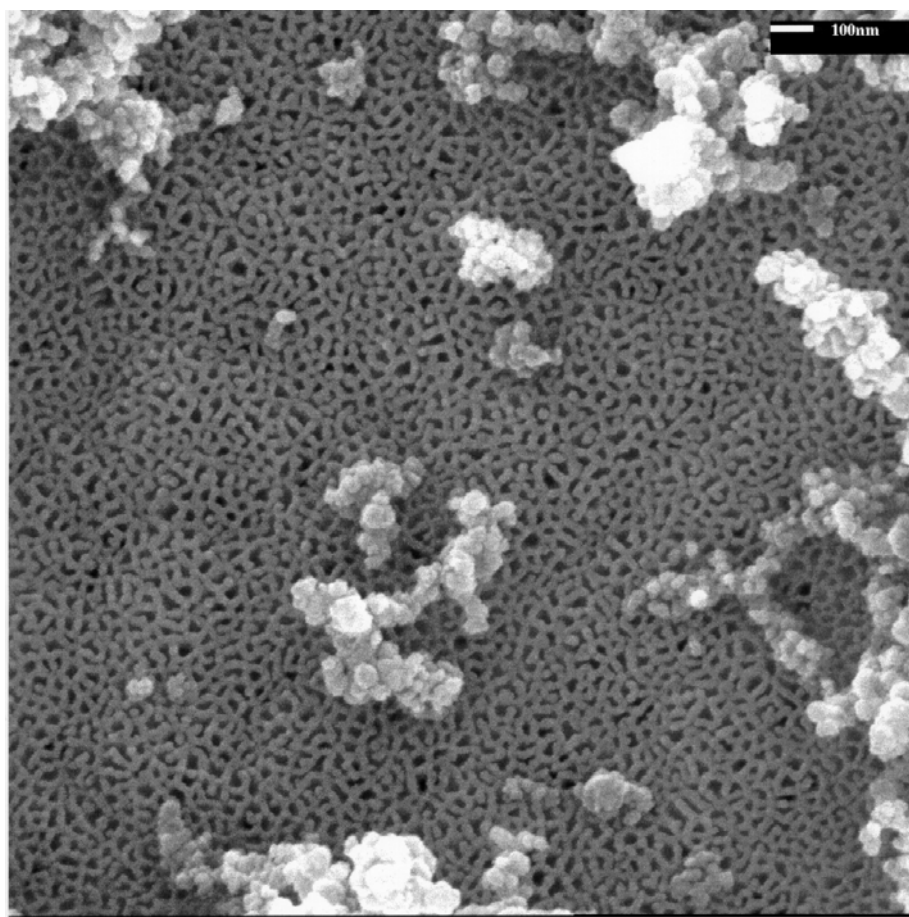


Figure 6.18: A large number of aggregates on a 20 nm filter. The large particles are aggregates that have collected together on the filter. Most individual particles are 100 – 400 nm in size.

Figure 6.19 shows the particles under greater magnification so that the individual spherules are more easily visible. Occasionally, under this magnification individual spherules were observed in isolation on the filter surface. This result underscored the need to use filters capable of collecting particles down to a single spherule.

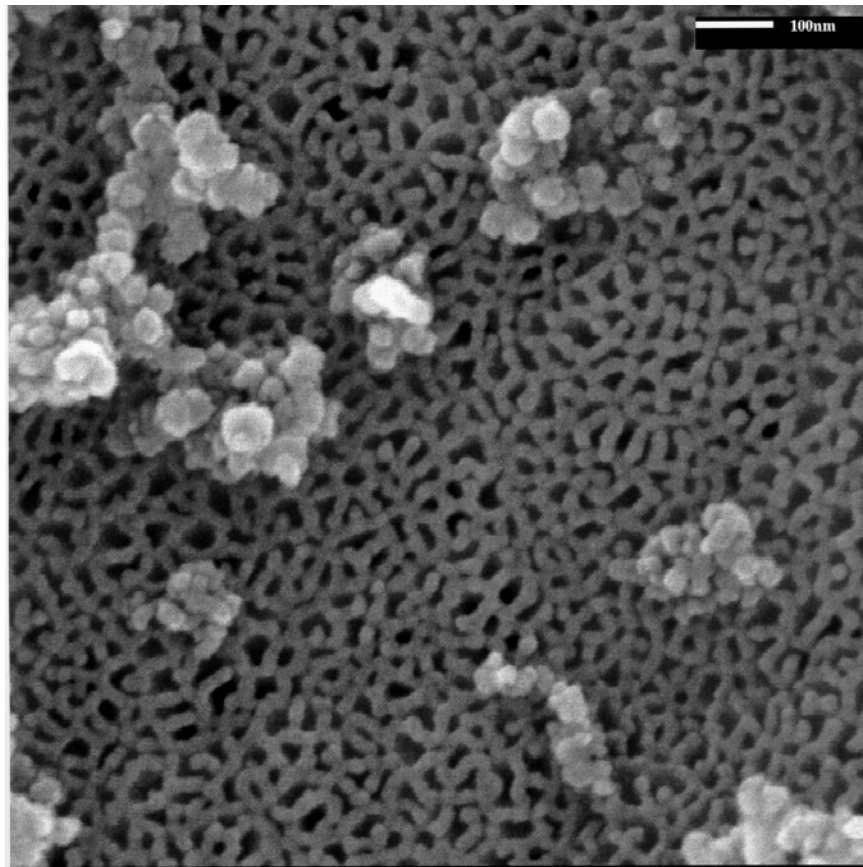


Figure 6.19: Individual spherules are identified within aggregates

At a very high magnification there were difficulties associated with focusing the image. The individual filter pores and the spherules had a very low surface roughness and did not provide any sharp edges on which to focus. By filtering the particulate matter with a flatter 200 nm alumina filter, a sharper image than those obtained with the 20 nm filter was produced. Figure 6.20 shows the material collected for the same set of test conditions as before, but with a 200 nm filter. Some of the sub-200 nm aggregates were able to escape, but

the larger aggregates were retained, and the sharper focus allowed for easy definition of the spherules. The spherules were approximately 30 nm in diameter and, consequently, the 20 nm filters (which are rated to collect 100 % of material larger than 20 nm) ensured complete collection of all sizes of material. The shape of the spherules and the aggregates they formed are consistent with soot particles [46].

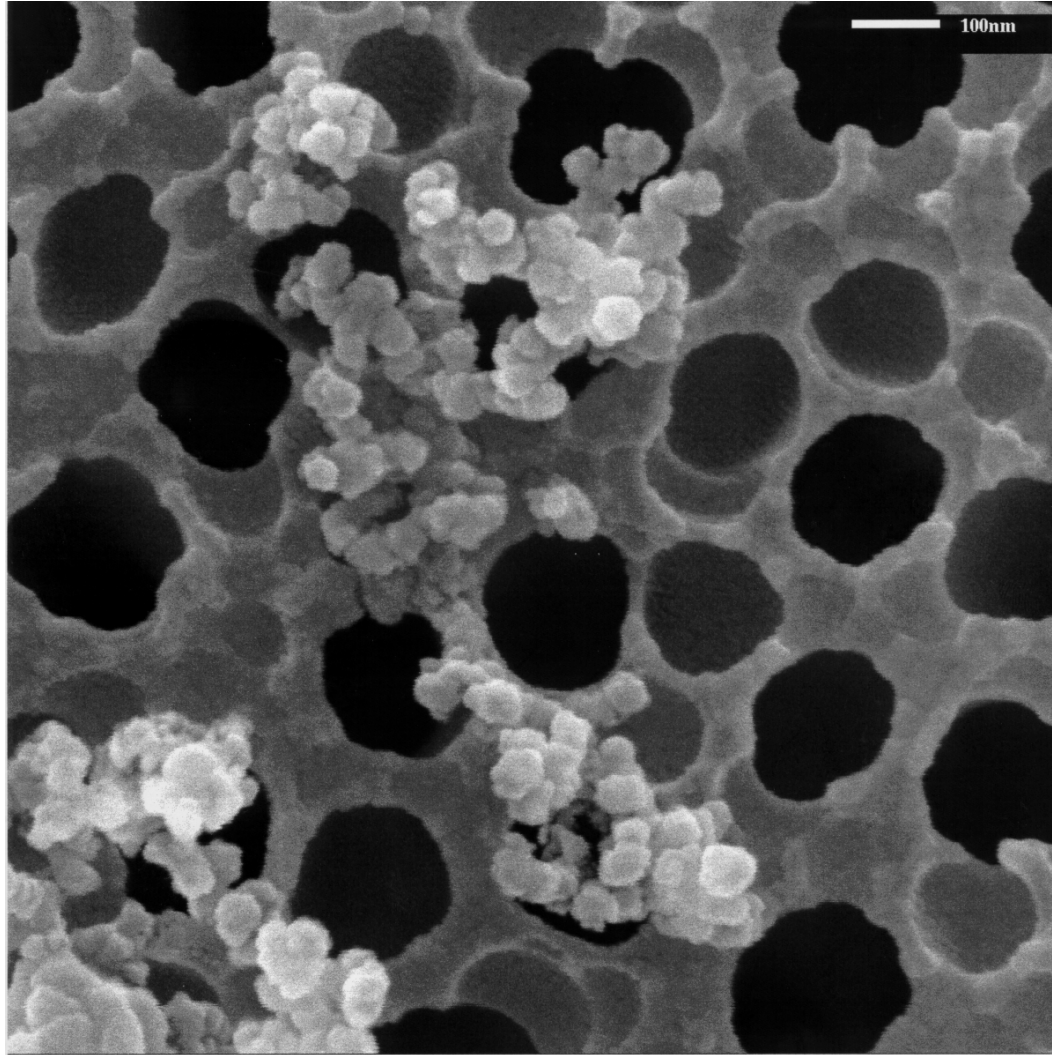


Figure 6.20: Particulate material collected on a 200 nm filter. The larger pores provide a better background for higher quality images.

It is interesting to note that the spherule size measured from soot emitted from flares is essentially the same as that emitted from other combustion devices such as diesel engines. By contrast, aggregate particle sizes from other combustion sources (e.g., diesel engines, which typically have aggregates larger than 1 μm [50]) are larger than those emitted from

flares. The reason for this difference in aggregate particle size is unclear since the base particle (i.e., the spherule) is the same. The two main differences between engines and flares are the fuel type and the conditions before and after combustion. Different fuels will produce different amounts of soot, especially at the elevated pressure of internal combustion engines, so the number density of spherules will be different. Furthermore, inside internal combustion engines the product gases and soot are confined, which increases the likelihood of particles agglomerating to form larger aggregates. In the case of flares, the product gases and emitted spherules are continuously part of a dispersive environment, which reduces the possibility of particles agglomerating to create larger aggregates.

6.4.3 Chemical Composition of Particles

The process by which soot is created involves the formation and condensation of many complex poly-nuclear aromatic hydrocarbons (PAHs). To address concerns over the toxicity of particulate emissions from flares, experiments were conducted to quantify the mass production rates of selected chemical compounds embedded in the emitted particles. Rather than try to provide an exhaustive catalogue of all detectable compounds, the purpose of these experiments was to provide quantified mass production information for representative compounds. The analysis technique used to measure the mass of 21 selected PAH compounds (listed in Table 6.3) was mass spectroscopy. The handling of the particle sample was conducted in accordance with NMAM 5515 (NIOSH sampling method) but with a 20 nm filter being substituted for an absorbent tube.

The general methodology used to collect the particulate matter for analysis was the same as that used to measure the total mass of particulates collected. By using this method, the mass of particles collected for analysis could be used to determine the total mass of particles emitted from the flare (see Section 6.3.3). Since the chemical analysis provided the mass of specific compounds in the sample collected, it was also possible to specifically quantify the total emitted mass of any species analyzed. The only difference between the methodology used in Section 6.4.1 to collect the particle samples and the methodology used in this section to collect particle samples is that the collection time was extended to 60 minutes in order to have sufficient PAH mass for analysis.

Only samples drawn from propane flares were chemically analyzed since flares burning natural gas did not emit detectable amounts of particles. As with the particle size data, the chemical composition from various tests showed similar results and only data from a representative test is presented. The data shown below are for the same experimental conditions as for the particle images presented in the previous section (i.e., $d_o = 24.7$ mm, $V_j = 1$ m/s, $U_\infty = 2$ m/s).

During the 60-minute test a total of 1.18 mg of particulate material was collected on the filter. The results of the chemical analysis associated with these tests are listed in Table 6.3. The collected particulate was analyzed for PAH compounds. Within these samples, the mass fraction of the PAHs that were tested for was approximately to 0.1 % of the total sample mass. Based on the correlations for these conditions, given in Section 6.4.1, the soot yield would be approximately 0.4 % (i.e., mass of particulate emitted to mass of fuel burned). Given this ratio, had the flame burned for 1 hour, it would have consumed 2360 g of propane and emitted 9.4 g of particulate material. This particulate material would therefore have contained 0.0094 g (or 9.4 mg) of the PAHs detected by the above method. The amount of individual PAH emitted varies considerably. For example, naphthalene represented 16.5 % of the PAH mass tested for in the sample. Alternately stated, 0.66 μg of naphthalene is emitted for each gram of propane burned. These production rates are at least two orders of magnitude greater than the maximum vapor-phase production rates shown in Section 6.1 and highlights why no further work was conducted on the vapor-phase PAH emissions.

Table 6.3: Quantities of PAH analyzed in particulate material sample.

Chemical Compound	Quantity in Sample (µg/mass fraction)	Detectable Limit (µg)
Naphthalene	0.2/0.00017	0.1
Acenaphthylene	0.3/0.00025	0.1
Acenaphthene	<DL	0.1
Fluorene	0.07/0.00006	0.05
Phenanthrene	0.27/0.00023	0.05
Anthracene	<DL	0.05
Fluoranthene	0.16/0.000136	0.05
Pyrene	0.21/0.00018	0.05
Beno(c)phenanthrene	<DL	0.05
Benzo(a)anthracene	<DL	0.1
Chrysene	<DL	0.05
7,12-dimethylbenz(a)anthracene	<DL	0.5
Benzo(b&j)fluoranthene	<DL	0.1
Benzo(k)fluoranthene	<DL	0.1
3-Methylcholanthrene	<DL	0.05
Indeno(1,2,3-cd)pyrene	<DL	0.1
Benzo(a)pyrene	<DL	0.05
Dibenz(a,h)anthracene	<DL	0.05
Benzo(g,h,I)perylene	<DL	0.05
Dibenzo(a,h)pyrene	<DL	0.1
Dibenzo(a,i)pyrene	<DL	0.1
Total	1.21/0.001	

6.5 CONCLUSIONS

In this chapter, the focus shifted from combustion efficiency to the consideration of minor species emitted from natural gas and propane flares. Despite the fact that these minor species represent only a small mass fraction of the combustion products, they are important because

of their potential toxic or carcinogenic properties. The objective of the research presented here was to provide a better understanding of the production rates of some of the important minor species emitted from flares burning natural gas, natural gas / octane droplet blends, or propane. The data collected were for selected compounds and were used to help characterize the potential toxicity of flare emissions. No attempts were made to identify and catalogue the full range of chemical compounds that could exist in the products of combustion from these flares.

The research presented here was divided into two parts based on the phase (i.e., vapor or solid) in which these minor species are emitted. There are no standard test procedures for determining either the vapor or solid phase emission rates of minor chemical compounds from a flare in general, much less for the particular case of a flare burning in a closed-loop wind tunnel. Therefore, methodologies for estimating these rates had to be developed as part of this research.

In the vapor phase, the compounds considered were 16 poly-nuclear aromatic hydrocarbons (PAH), 12 aldehydes, and BTEX. All of these compounds were below the detectable limits for the methodology used. Using a representative molecular weight for the PAH, the maximum concentration of these compounds that could have been produced would have been less than $5 \mu\text{g}/\text{m}^3$ even before the entrainment of ambient air into the plume. These emissions rates proved to be two orders of magnitude less than those found in the solid phase emissions of propane flares.

As a part of measuring the solid phase emissions from flares, a technique was also developed for mapping the soot plume of a flare using a modified dual channel fast flame ionization detector. An important observation from these experiments was that the particle plume emitted from flares corresponded to the size and shape of the thermal plume, although the soot particles were emitted at their highest frequency directly behind the flame tip. This last observation regarding the higher frequency of soot particles behind the flame tip suggests that this region of the flow is responsible for a majority of the particulate material emission, regardless of the crosswind speed. As a result of these tests the particle plume was found to

be inhomogeneous and, therefore, excluded the possibility of using single-point sampling to quantify the particle emissions rate.

Once the entire particle plume was located, it was characterized in three ways: the mass of the particulate phase emitted from the flare per unit mass of flare gas burned; the particles collected on the filter were imaged to provide an estimate of the particle size range emitted from flares; and the material collected on filters were chemically analyzed to determine the composition of the particles.

From the data collected the amount of particulates emitted from flares burning natural gas and natural gas blended with octane all fell below detectable limits. The detectable level was conservatively estimated to be 1.7 mg/m^3 of air or an average number density of 1 ppb in the plume.

For propane flares, the soot emissions from the flare were shown to decrease slightly as either the crosswind or jet exit velocity was increased. This result was characterized in terms of a mixing ratio, defined as $U_\infty \bullet V_j$. As a result of extensive testing, it was found that the emission of soot decreased as the mixing ratio increased. However, it was found that beyond a mixing ratio of $3 (\text{m/s})^2$ the mass fraction of soot emitted remained constant at approximately 0.4% of the fuel burned. This result was not a strong function of stack diameter (d_o), but it should be noted that the limitations of the facility allowed the testing of stacks ranging from only $d_o = 24.7$ to 29.9 mm. Despite this narrow range of the stack diameters, the larger stack resulted in a 47 % increase in internal flow area. Since the emission of soot is negligible compared to other carbon-based emissions, the overall efficiency measurements presented in Chapter 3, based only on gas-phase carbons, are not significantly affected and, therefore, remain valid for estimating the performance of flares. Below a mixing ratio of $2 (\text{m/s})^2$, the mass of soot emitted rose significantly and had a strong dependency on d_o such that with no crosswind the fraction of fuel mass converted to soot was 1% and 3% when $d_o = 24.7$ and 29.9 mm, respectively. This result suggests that soot emissions at low mixing ratios are more of a concern for larger stacks.

The particles emitted from propane flares were imaged with a scanning electron microscope (SEM) to estimate the size and shape of particles collected on filters. The soot particles consisted of large collections of spherules that combined to produce highly irregular-shaped aggregates that were seldom found outside the range of 100 to 400 nm in size. The individual spherules were approximately 30 nm in diameter and their shape was characteristic of soot particles as described in previously published research.

Mass spectroscopy was used to measure the mass of 21 selected PAH compounds in the solid phase. It was found that the amount of individual PAH emitted varies considerably. These chemical analyses allowed for the detection of numerous compounds in the soot such as naphthalene, acenaphthylene, fluorine, phenanthrene, fluoranthene and pyrene.

7 EFFECTS OF LIQUID DROPLETS ON FLARE EFFICIENCY

The flare streams considered so far in this report have been composed of gases and vapors. Specifically, the fuels used were either natural gas or propane diluted, in some cases, with carbon dioxide or nitrogen to reduce the energy density of the fuel. One common perception of flaring at solution gas sites that has not been considered with these experiments is the possibility of liquid droplets as part of the flare stream. The origins of these droplets are attributable to two sources. One possible source is the condensation of saturated hydrocarbon or water vapor in the flare stream. These liquids result as the flare stream cools from process conditions at the battery site to ambient conditions at the flare. The other possible source is liquid droplet carry-over from a separation process or a liquid knockout system located upstream of the flare stack [5].

Theoretically, the presence of even small volume fractions of droplets in the flare stream could be important because the density of the condensed phase can be several hundred times greater than that of the gas phase. Hence, a significant fraction of the mass being flared could originate from a relatively small volume of droplets. The effect of the droplets on the combustion and emissions will depend on the composition, mass, and volume of the individual droplets. Once a droplet emerges from the flare stack it is exposed to the thermal radiation of the flame that aids the evaporation process. Small droplets will evaporate before reaching the flame and these vapors will partially mix with the gas stream before burning. Larger droplets will partially evaporate and consequently arrive at the flame in the liquid state. Some of these larger droplets will evaporate at the flame surface while yet-larger droplets will persist well into the plume of combustion products or fall out of the flow.

If the droplets are composed of heavier hydrocarbons, the portion that evaporates before the flame may increase the propensity of the flare to emit soot and toxic compounds [19]. These same hydrocarbons droplets will also increase the energy density of the flare stream. In Chapter 3, high energy density flares were shown to be more robust and less susceptible to wind-driven inefficiencies. Droplets surviving to the flame may burn as isolated droplets within the plume of combustion products. There is very little known about droplet

combustion when the droplets are carried within a gaseous fuel stream. The net effect of having hydrocarbon droplets in the flare stream is difficult to predict.

If the droplets were pure water, the potential effects would be significantly different from those expected of fuel droplets. The energy extracted from the flame to evaporate the water would reduce both the final product temperature and the robustness of the combustion. Water that evaporates before the flame will dilute the fuel gases and reduce the energy density. Droplets surviving into the flame will locally quench combustion as they pass through the flame surface. If the water contains salts (e.g. NaCl), the chlorine could act as a chemical inhibitor to combustion, form a strong vapor-phase acid, or be emitted as a chlorinated hydrocarbon. The overall effect of having water droplets in the flare stream is also difficult to predict.

Very little is known about the composition, size distribution, or amount of liquid droplets present in solution gas flare streams. A recent field study that examined the materials being flared at solution gas battery sites suggested that the occurrence of liquid droplets in the flare stream might not be as common as previously believed [6]. In that study, a sampling system was developed to collect both the gas and liquid phases of the flare stream at the base of the flare stack to determine the relative mass fractions and compositions of the phases present. The liquid recovery system of the sampling process could trap droplets as small as 0.3 micrometers. Of the seven battery sites tested, which included smoking and smokeless flares, no droplets were found to be part of the continuous flare stream. Notwithstanding those reported results, it is important to understand the potential effects that liquid droplets could have on the overall combustion efficiency of flares. As part of the research presented in this chapter, samples were drawn from the liquid knock-out systems of two battery sites to provide some insight into the composition of the liquids being handled just upstream of the flare. The liquids in the knock-out drums were sampled by submerging a hollow vertical tube to the near-bottom of the drum. A flapper valve was then closed at the bottom so that a vertical segment of the liquid in the drum could be extracted. These liquids were found to be composed of two stratified layers: the lower section being composed of heavier brackish water and the upper section being composed of lighter hydrocarbons. Independent chemical

analysis of these layers showed that the water was mainly composed of NaCl and KCl salts and that the hydrocarbons were typical of what the energy industry refers to as *condensate*, a collection of mostly C6 to C12 compounds centered on C8-C9.

With this meager guidance from field studies, the laboratory experiments were approached to include a broad perspective on potential compositions, sizes, and mass fractions of droplets. The compositions of droplets considered here include the cases of iso-octane, diesel, or distilled water. The choice of liquids for these experiments was based on the following: iso-octane represents *condensate*, diesel represents the effects of heavy hydrocarbons (C12-C25) in a blended form, and distilled water represents liquids that extract energy in evaporating without contributing as a fuel source (salt water was not tested to avoid exposure to corrosive and toxic compounds). The size ranges considered are log-normal type distributions with approximate mass mean diameters of 4 and 200 micrometers. The amount of droplets added to the flare stream range from mass fractions of 0% to as high as 32 %. Only 24.7 mm diameter flares were tested with droplets and the variations in jet exit velocity and crosswind speed were restricted to 1 – 2 m/s and 2 – 9 m/s, respectively. In all cases, the gas phase of the flare stream is natural gas.

The following sections provide a detailed description of the experimental setup and the methodology used to test flare streams that contain droplets. This discussion includes: the method used to generate the droplets; the experimental procedure used to introduce droplets into the flare stream; and the diagnostics used to characterize the mass flow rates and size distributions of the droplets. An enhanced method for calculating the carbon conversion efficiency for flares that contain droplets is developed and discussed before results of overall efficiency are presented. The basic conclusions drawn from this research are that:

1. water has a nominal impact on flaring and causes a slight decrease in efficiency; and
2. iso-octane and diesel droplets cause improvements in efficiency.

It is also worth noting that no soot was emitted from any of the flares tested.

7.1 EXPERIMENTAL SETUP AND METHODOLOGY

7.1.1 Droplet Generation and Entrainment into Flare Gas

Many different droplet generation systems exist for producing and discharging liquids into a gas stream. The choice of droplet generation device for this research was designed to allow a range of droplets sizes to be available from approximately 15 μm in diameter to approximately four times larger. These limits on droplet size were arbitrary since there was no published work on measured droplet sizes in solution gas flaring systems. Also, in order to provide a mass flow rate of droplets independent of the gas stream flow rate, the droplet generation system could not use a jet of flare gas to form the droplets (e.g., blast atomizers or nebulizers). As a result, the addition of liquid droplets to the flare stream was done with commercially available ultrasonic droplet generators. These devices provide control over droplet size through a combination of liquid flow rate, liquid stream diameter, liquid properties, frequency of vibration of the generator, and power applied to generator to create the vibrations. Another important feature of this class of droplet generation system is the capability to use both flammable and non-flammable liquids. The measured size ranges of droplets and the physical structure of the apparatus for capturing the droplets within the flare gas stream are described below as part of the research conducted to measure the overall efficiency of flares with droplets.

The basic experimental set-up for measuring the efficiency of flares that contain liquid droplets was the same as described in Chapter 2. The wind tunnel was not altered for these experiments. The fuel delivery system remained unaltered (c.f., Figure 2.4) up to the base of the flare stack where some modifications were made to accommodate the introduction of liquids into the flare stream. Equipment to generate the droplets and introduce them into the flow of flare gases was added to the base of the flare stack. An ultrasonic droplet generator was used to create a spray of droplets. Once created, the challenge was to capture these droplets within the flow of flare gases so they could be convected to the exit of the flare stack.

Figure 7.1 shows a schematic of the base of the 24.7 mm diameter (d_o) flare stack used in the previous chapters. Mounted below the flare stack was the droplet generator that would spray the droplets upward in the same general direction as the flow up the flare stack. Two ultrasonic droplet generators, manufactured by Sono-Tek, were used. The spray pattern of droplets from the tip of the droplet generator was conical and, without intervention, there was a strong tendency for the droplets to immediately impact the sides of the flare stack. These impacting droplets would form a film on the inside walls of the stack and flow downward. In order to capture a greater fraction of the droplets created, the flare gases were introduced as an annular jet surrounding the tip of the droplet generator to redirect the droplets away from the stack walls. The gap size that created the annular jet was approximately 2.5 mm and the gases were directed slightly inwards (approximately 15° from the vertical). This method of capturing the droplets significantly increased the efficiency of the droplets actually becoming part of the flare stream and being carried to the exit of the flare stack. To further enhance the transport of droplets up the flare stack, the turbulence plugs described in Section 2.1.2.1 were not used in this set of experiments.

As mentioned previously, two droplet generators were available to produce droplets within two broadly defined size ranges. The mass-mean diameter of the droplets produced also depended on the liquid used. Table 7.1 provides data of the size of droplets tested. This range of droplets was essentially carried by the flow and did not immediately dropout at the stack exit due to gravity.

Table 7.1: Nominal Operating Parameters of Droplet Generators when the Liquid was Water, Octane, or Diesel

Generator Designation	Water Mean Diameter D_m, (μm)	Octane Mean Diameter D_m, (μm)	Diesel Mean Diameter D_m, (μm)
A	40 – 70	4 – 15	60 – 80
B	100 – 120	80 – 90	120 – 200

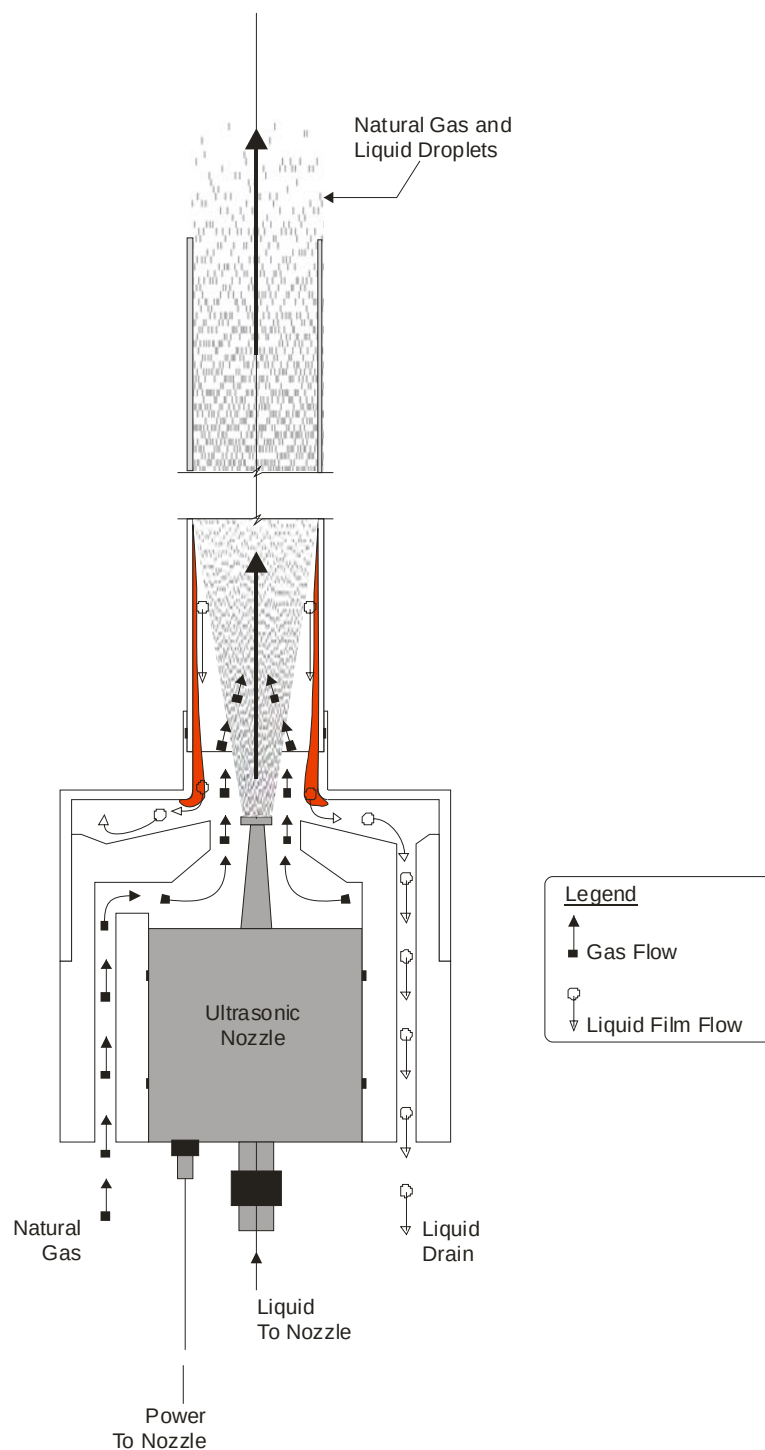


Figure 7.1: Sketch of the droplet generator and method for introducing the droplets into the flow

The configuration of the droplet generation system as integrated into the gaseous fuel supply system is shown in Figure 7.2. By using ultrasonic droplet generators, the supply rates of

liquid and gaseous fuels could, to the first order, be decoupled. Alternate systems for generating droplets, e.g., systems based on blast atomization, couple the flow rate of the gas with the production rate of droplets and would not allow independent control of the liquid and gaseous mass flow rates. Even with the ultrasonic generators, the flow rates of the two phases are not completely independent because increased gas flow rates improve the entrainment efficiency of the droplets into the flare stream.

7.1.2 Mass Flow Rate of Droplets being Flared

One of the main parameters that needed to be characterized, when measuring the efficiency of flares with droplets, was the mass flow rate of droplets that exited the flare stack and potentially participated in the combustion. The technique used to measure this flow rate is also shown schematically in Figure 7.2. A fixed flow rate of liquid was supplied to the droplet generator, but only some of this liquid was carried as droplets to the exit of the stack where it was flared. Some of the droplets would strike the walls and, since the stack velocities were low, would form a liquid film on the walls that would run back to the base of the stack. At the base of the stack this back-flowing liquid was collected as shown in Figure 7.1 and sent to the liquid return vessel. Lastly, some of the droplet mass would evaporate to form a saturated vapor that became part of the flare stream. By placing the liquid supply tank and return vessel on the same electronic mass balance, the rate of change in mass represents the total flow rate of liquid fuel (now either as liquid or vapor) that left the exit of the stack. The use of a sealed vessel and constant pressure nitrogen, i.e., the prime mover of the liquid fuel, was necessary to provide a steady flow of liquid fuel with very little disturbance to the mass balance.

The mass on the scale was recorded every second and the slope of the recorded mass during the steady-state operation period was defined as the characteristic mass flow rate for the flaring test conditions. Figure 7.3 shows a typical mass recording from the scale. The initial transient start-up period recorded by the scale was a result of the wetting of the walls of the flare stack and any accumulation of liquid at the base of the stack before the flow started to the return vessel. The fraction of liquid fuel that became vapor before leaving the stack was not considered separately from the droplet flow because of the low saturation vapor pressures associated with diesel, octane, and water at room temperature. If natural gas were used as the carrier gas of the flare stream, then approximately 1.0 % or 3.5 % of the volume of the gases would be either octane or water vapor, respectively. However, by mass this fraction would represent 6.4 % or 3.5 %, respectively. Given the further evaporation of the droplets once they leave the flare stack to become exposed to the radiation from the flame, the most relevant means to characterize the composition of the flow is to consider the total mass of what was liquid fuel irrespective of its phase either in the stack or just prior to combustion.

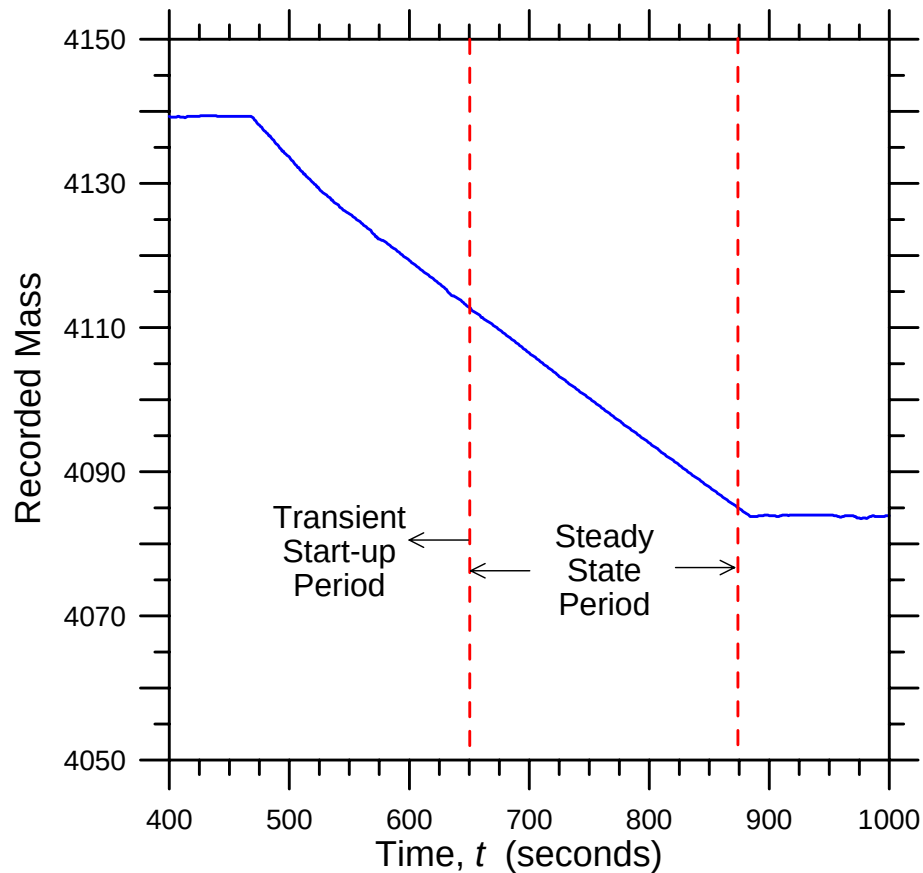


Figure 7.3: Typical mass recording from balance in order to estimate the mass flow rate of droplet exiting the flare stack

The mass flow rate of liquid fuel being flared was controlled by altering the supply flow rate of liquid fuel to the droplet generator, by altering the power to the ultrasonic nozzle, and by altering the position of the spray relative to the annular flare gas jet. Altering the flare gas flow rate also affected the efficiency of entraining and carrying droplets to the flare exit, but was a second order effect. The mass flow rate of droplets was measured during every experiment to ensure that parameters (e.g., mass fraction of droplets in the flare stream) were fixed for a series of tests.

7.1.3 Characterizing Size Distribution of Droplets

Another important parameter that was needed to characterize the test conditions was the particle-size distribution of droplets being flared. A droplet size analyzer manufactured by Sympatec Corporation (Helos BFS) was used to characterize the probability size distribution

of the droplets exiting from the flare stack. The basis for this measurement system is the analysis of the far field intensity distribution created by the diffraction of a laser that passes through a particle carried by the flow. The range of droplet sizes that could be measured with this device is from 0.5 to 875 micron.

A typical probability distribution function (pdf) for droplet sizes of a particular test is shown in Figure 7.4. The droplet distribution shown in Figure 7.4 was produced by droplet Generator A, which was spraying into a 97 cm long, 24.7 mm diameter flare stack (d_o) with a 2 m/s exit velocity (V_j). The total mass flow rate of liquid fuel leaving the stack was measured by the above method to be 7.56 g/min and the ratio of liquid mass flow rate to the carrier gas mass flow rate was 20% or $X = 0.20$.

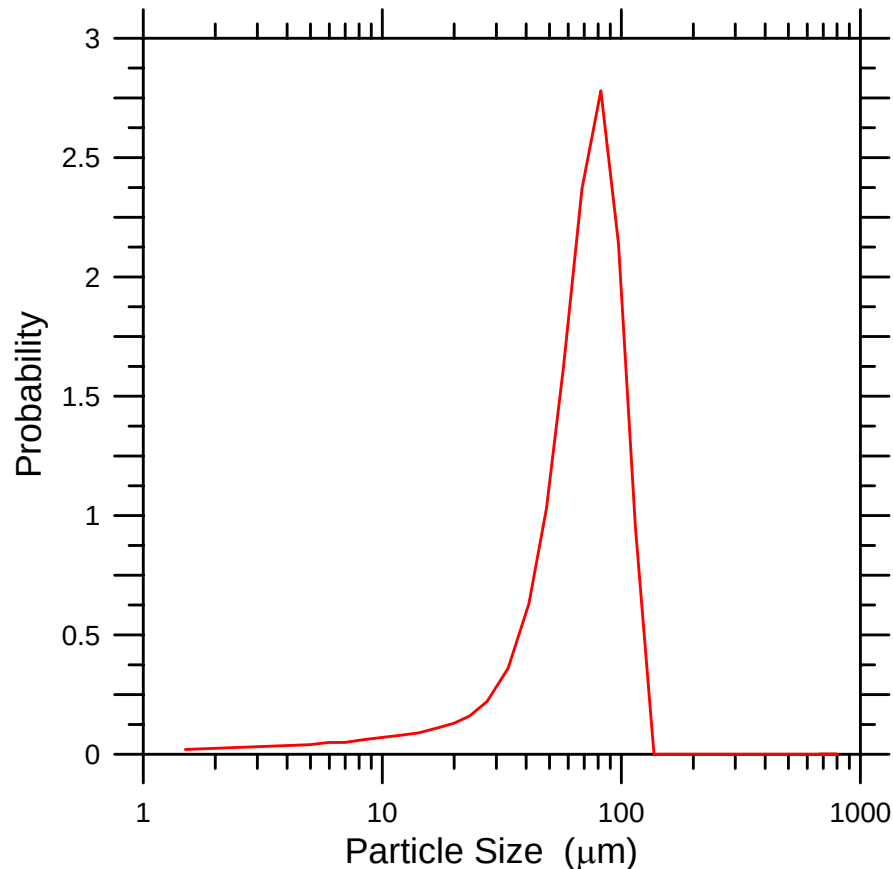


Figure 7.4: Typical particle size distribution of octane from droplet Generator “A” that was exiting the flare stack

A proper description of the pdf of droplet sizes, like the one shown in Figure 7.4, would normally require a few of its lower order moments (i.e., mean, standard deviation, skewness,

etc.) to be specified. For the simple characterization of the droplets needed here, only the mass mean diameter (the lowest moment) will be reported. For particles of the same density, the mass mean diameter, D_m , is calculated by the cubed root of the average of the particle diameters cubed. This form of averaging characterizes the droplet in terms of the mass contained within each droplet and not just its diameter. Thus, in using the mass mean diameter larger droplets are considered to be more important in the average than a smaller droplet because they contain more mass.

7.1.4 Method for Estimating Combustion Efficiency

In reviewing the methodology used to measure the overall carbon conversion efficiency in Chapter 3, some of the arguments invoked to simplify the developed expressions may not apply when fuel droplets are added to the flare stream. For example, if significant amounts of soot were emitted, then the carbon-mass balance used in Chapter 3 would no longer be valid. Since one of the expectations was that soot emissions will increase due to the addition of heavier hydrocarbons, a new method of estimating the combustion efficiency needed to be developed. In the case of adding water to the flare stream, the carbon-balance method developed in Chapter 3 remains valid and there is no reason to use an alternate methodology. Consequently, the same gas analysis system was used for these experiments as was shown in Figure 2.5.

To develop this new method formally, it is important to return to the definition of the carbon conversion efficiency given in Chapter 3, expressed here in terms of rates as

$$\eta = \frac{\text{Rate of mass of carbon in the form of CO}_2 \text{ produced by the flare}}{\text{Rate of mass of carbon in the form of hydrocarbon fuel supplied to the flare}}$$

$$= \frac{\dot{m}_{C, CO_2}}{\dot{m}_{C, FUEL}} \quad (\text{Eq. 7.1})$$

The denominator of Eq. 7.1, $\dot{m}_{C,FUEL}$, is readily calculated from the composition and flow rate of the fuel entering the flare. For the case considered here where both the liquid and the gaseous fuel may contain hydrocarbons expressed as either C_xH_y or $C_{x'}H_{y'}$, then

$$\dot{m}_{C,FUEL} = M_C \left(\frac{x \dot{m}_G X_{CxHy,G}}{M_{CxHy,G}} + \frac{x' \dot{m}_L X_{Cx'Hy',L}}{M_{Cx'Hy',L}} \right) \quad (\text{Eq. 7.2})$$

where $\dot{m}_G$ = mass flow rate of flare gases

$\dot{m}_L$ = mass flow rate of liquids exiting the flare stack

X_{CxHy} = mass fraction of hydrocarbon fuel in flare gases

$X_{Cx'Hy'}$ = mass fraction of hydrocarbon fuel in the liquid stream

M_C = molecular weight of carbon

M_{CxHy} = molecular weight of hydrocarbons in flare gases

$M_{Cx'Hy'}$ = molecular weight of hydrocarbons in liquid stream

x = mean number of carbon atoms on fuel molecules in flare gases

x' = mean number of carbon atoms on fuel molecules in liquid stream

The numerator of Eq. 7.1, $\dot{m}_{C,CO_2}$, is calculated from the rate that the mass of carbon in the form of CO_2 (m_{C,CO_2}) accumulates in the tunnel. Using the same arguments as developed in Chapter 3, the problem of tunnel air exchanging with ambient air can be avoided by considering the limit at which the volume fraction of CO_2 in the tunnel approaches the ambient conditions. The accumulation rate of carbon as CO_2 can be expressed as

$$\dot{m}_{C,CO_2} = \left. \frac{dm_{C,CO_2}}{dt} \right|_{Y_{CO_2} \rightarrow Y_{CO_2,\infty}} \quad (\text{Eq. 7.3})$$

where $\dot{m}_{C,CO_2}$ = rate of mass of carbon in the form of CO_2 produced by the flare

m_{C,CO_2} = mass of carbon in the form of CO_2 in the tunnel

Y_{CO_2} = volume fraction of CO_2 in the tunnel

$Y_{CO_2,\infty}$ = volume fraction of CO_2 in the ambient air

The total mass of carbon in the form of carbon dioxide can be estimated from the concentration of CO_2 in the tunnel and the application of the ideal gas law, so that Equation 7.3 can be rewritten as

$$\dot{m}_{C,CO_2} = \frac{d}{dt} \left(\frac{M_C}{M_{CO_2}} \frac{Y_{CO_2} PV}{R_{CO_2} T} \right) \Bigg|_{Y_{CO_2} \rightarrow Y_{CO_2, \infty}} = \frac{M_C}{M_{CO_2}} \frac{PV}{R_{CO_2}} \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \Bigg|_{Y_{CO_2} \rightarrow Y_{CO_2, \infty}} \quad (\text{Eq. 7.4})$$

where M_{CO_2} = molecular weight of CO_2

P = absolute pressure of tunnel gases

V = internal volume of tunnel

R_{CO_2} = specific gas constant of carbon dioxide

T = absolute temperature of tunnel gases

In principle, everything on the right hand side of Equation 7.4 is either known or measurable and the combustion efficiency can be calculated from Equations 7.1, 7.2, and 7.4. Unfortunately, there are problems associated with the accurate measurement of the effective internal volume of a complex structure like a wind tunnel. To eliminate the need to know the internal volume of the wind tunnel, the approach used to determine the mass flow rates of the products of combustion was to break the test into two parts.

In the first part of a test, no droplets were added to the flare stream. This part of the test was conducted in the same manner as an efficiency test described in Chapter 3. The experimental conditions (i.e., flare gas composition, flare gas flow rate, and wind speed) were fixed for a period long enough to get a good estimate of the carbon conversion efficiency. When the information collected during this part of the test was processed, it acted as a quantitative reference for the second part of the test when the fuel droplets were added. Since Equation 7.4 applies to both parts of the test, it can be used for both the no-droplet and droplet portions of the experiment resulting in two equations. These two equations can be written as a ratio shown as Equation 7.5.

$$\frac{\dot{m}_{C,CO_2}}{\dot{m}_{C,CO_2}^{REF}} = \frac{\frac{M_C}{M_{CO_2}} \frac{PV}{R_{CO_2}} \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \Bigg|_{Y_{CO_2} \rightarrow Y_{CO_2, \infty}}}{\frac{M_C}{M_{CO_2}} \frac{PV}{R_{CO_2}} \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \Bigg|_{Y_{CO_2} \rightarrow Y_{CO_2, \infty}}^{REF}} = \frac{\frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \Bigg|_{Y_{CO_2} \rightarrow Y_{CO_2, \infty}}}{\frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \Bigg|_{Y_{CO_2} \rightarrow Y_{CO_2, \infty}}^{REF}} \quad (\text{Eq. 7.5})$$

where REF = refers to the results from the first part of the test

Since the flare gas composition, flow rate, and efficiency are known in the reference test, the rate of carbon in the form of CO₂ produced by the flame can be calculated explicitly by Equation 7.6.

$$\dot{m}_{C,CO_2}^{REF} = x \eta^{REF} \dot{m}_G^{REF} X_{C_xH_y,G} \frac{M_C}{M_{C_xH_y,G}} \quad (\text{Eq. 7.6})$$

If the same flare gas flow rate is used for the two parts of the tests, then the combustion efficiency when droplets are part of the flare stream is given by Equation 7.7 which is developed by combining Equations 7.1, 7.2, 7.5 and 7.6.

$$\eta = \left[\frac{\eta^{REF}}{1 + \frac{\dot{m}_L}{\dot{m}_G} \frac{X_{C_xH_y,L}}{X_{C_xH_y,G}} \frac{M_{C_xH_y,G}}{M_{C_xH_y,L}} \frac{x'}{x}} \right] \frac{\left. \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \right|_{Y_{CO_2} \rightarrow Y_{CO_2,\infty}}}{\left. \frac{d}{dt} \left(\frac{Y_{CO_2}}{T} \right) \right|_{Y_{CO_2} \rightarrow Y_{CO_2,\infty}}^{REF}} \quad (\text{Eq. 7.7})$$

From an uncertainty perspective, some of the terms on the right hand side of Equation 7.7 are more problematic than others. As shown in Chapter 3, the measurement of the slopes associated with the concentration of CO₂ and the efficiency of the reference test have small uncertainties. The greater uncertainties lie in the accurate measurement of the flow rates of both the gas and liquid components being flared. These uncertainties are currently estimated to be approximately +/-1 %. A similar level of uncertainty is expected regarding the efficiency measurement for a flare with liquid fuel droplets as part of the flare stream.

From the form of Equation 7.7, it was decided that the second part of the test should be conducted immediately after the first part. This testing procedure insured an uninterrupted gas flow rate to avoid any problems concerning repeatable conditions. In practice, the curves of Y_{CO2}/T are straight lines (c.f., Figure 3.2), and therefore the notion of measuring their slope near ambient conditions is not significant.

Given the increased complexities and uncertainties associated with this methodology that leads to Equation 7.7, experiments were conducted to determine if these measures were really necessary. The reason for introducing a methodology separate from that presented in Chapter 3 was to account for soot emissions that may result from burning the octane and diesel droplets. This scenario would not produce a valid carbon-mass balance for calculating the efficiency of the flare. During initial tests of natural gas flares with either octane or diesel droplets it was noted that there was no visible smoke. This observation suggested that the fraction of carbon not present in the gaseous form may be small enough to ignore and that the simpler method of measuring combustion efficiency was valid for these situations. Detailed sampling of the plumes of natural gas flares with either octane or diesel was conducted using a dual fast flame ionization detection technique described in Section 6.3.1. This technique was capable of detecting individual soot particles and sensitive to the carbon mass in particulate form. In all of the cases tested, which included mass fractions of either octane or diesel up to 32%, no soot emissions were found. Therefore, the combustion efficiency results presented in the remainder of this chapter are based on the methodology developed in Chapter 3.

7.2 COMBUSTION EFFICIENCY OF NATURAL GAS FLARES WITH DROPLETS

The results presented in this section are divided into sub-sections based on the composition of the droplets added to natural gas flare streams. All the experiments were conducted with a 24.7 mm diameter flare stack and therefore scaling issues associated with the size of the flare stack were not explored within the context of adding droplets to the flare stream. (Chapter 3 considered the scaling of stack diameter in detail for gas-only flares.) For each droplet composition the operating conditions were varied to examine the underlying effect of adding droplets. Other experimental parameters were manipulated to produce corresponding responses in efficiency, these parameters include: crosswind speed ($2 \leq U_{\infty} \leq 9$ m/s); stack exit velocity ($1 \leq V_j \leq 2$ m/s); droplet size, D_m , range (see Table 7.1); and mass fraction of liquids in the flare stream ($0 \leq X \leq 32\%$). The combustion efficiency results for water, iso-

octane, and diesel droplets will first be presented independently and then comparisons will be made between the different droplet compositions.

In general, comparing the results of gas flares to flares with liquid droplets shows similar levels of scatter in the data. The conclusions drawn from these results are the following: water has a nominal impact on flaring but does cause a slight increase in inefficiency; iso-octane and diesel droplets cause modest improvements in the efficiency. Flares containing droplets respond to crosswinds in essentially the same way as gaseous flares such that the inefficiency rises exponentially with increases in wind speed. Flares with higher exit velocities were less susceptible to the effects of crosswind and any changes introduced by adding liquid droplets to the flare stream were less pronounced at higher stack exit velocities. The size of droplets had little or no measurable effect on the combustion efficiency within the range of conditions tested. Increases in the mass fraction of liquids introduced into the flare stream show a monotonic trend in the combustion efficiency as influenced by the different liquids.

7.2.1 Distilled Water Droplets

The gross physical structure of flares containing water droplets observed in these experiments were essentially the same as the gas-only flares described in Chapter 3. At low crosswind speeds the flame appeared wholly above the flare stack and attached to the rim of the stack exit. As the crosswind was increased, the flame detached from the front of the stack and was stabilized at a single attachment point on the leeward edge of the stack rim. At yet higher crosswind speeds, the flame became almost horizontal and a portion of the fuel would be drawn into the wake of the stack where it was burned. In this higher crosswind mode, the flame would have three distinct zones as described in Section 3.3. The three zones can be described as follows: in zone one a planar flame was stabilized in the recirculation zone directly behind the leeward side of the stack; in zone three an axisymmetric flame tail would extend downstream; and in zone two there is a small region that connects zones one and three of the flame. The similarity of flame structures that existed between the water droplet and no-droplet cases showed that there is no substantive difference

in the fluid mechanics resulting from the addition of the droplets. As a result, it is expected that the same mechanisms that created inefficiencies in combustion in the gas-phase-only flares were also working in flares with droplets. The visual appearance of flames themselves was altered slightly by the addition of water droplets. A natural gas flare that contains water droplets would be less luminous and more translucent than the corresponding natural gas flares with no droplets operating at the same flow conditions.

Figure 7.5 shows the inefficiency of two natural gas flares as a function of wind speed with exit velocities of 1 m/s. One of the flares was burning natural gas only while the other contained water droplets with a mass-mean diameter of 96 micrometers and a mass fraction of water of 14.3%. It was observed that the addition of distilled water droplets to the flare stream increased the inefficiency of the flares over the range of crosswind speeds tested. The effects of the water droplets was non-linear with wind speed such that the change in inefficiency between the droplet and no-droplet cases was neither an offset (i.e., does not cause a fixed increase in inefficiency for all wind speeds) nor linear. The differences in the efficiencies at low wind speeds ($2 \leq U_{\infty} \leq 3$ m/s) was barely measurable, while at higher wind speeds ($U_{\infty} = 7$ m/s) there was more than a 2% absolute increase (or approximately a 33% increase in non-CO₂-based carbon emissions) caused by the addition of these particular droplets.

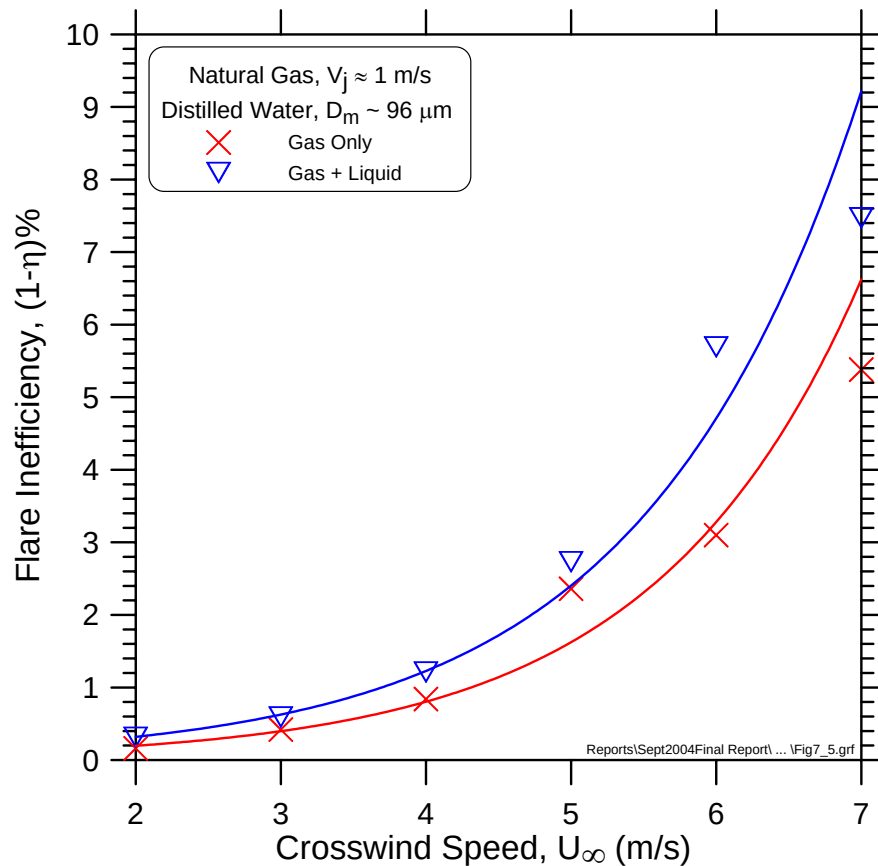


Figure 7.5: Effects of distilled water droplets on the inefficiency of a flare with low flare gas exit velocity in crosswind

The addition of non-combustible liquid droplets (i.e., distilled water) to the gaseous fuel stream affects the energy conversions that occur when gas-only fuel burns in an atmospheric environment. Without any droplets, the chemical energy that exists in the fuel is converted to thermal energy when it burns and heats the products of combustion to their flame temperature. The addition of a non-combustible liquid to the flow affects combustion processes by requiring some of the chemical energy from the flame to be transferred to the liquid. This energy transfer raises the temperature of the liquid. In the case of water droplets, this transfer of energy also results in the evaporation (boiling) of droplets which further extracts energy from the flame that would have been otherwise involved in increasing the gases to the final product gas temperature. As a consequence, the product gas (or flame) temperature is lower and the robustness of the flame is reduced. It is proposed that reduced robustness of the flame makes the flare more susceptible to the wind-driven mechanics that create the combustion inefficiencies. Another potential mechanism by which the addition of

non-combustible droplets can affect the combustion efficiency is that their vapours dilute the reactants prior to combustion. In this scenario, the dilution phenomenon is the same as that which results from nitrogen or carbon dioxide being added directly to the flare stream. The current research cannot address the question regarding the relative importance between the mechanism that involves energy extraction and fuel dilution. The main point being that, independent of mechanism, the addition of a non-combustible liquid to the flare stream reduces the robustness of the combustion process and increases the inefficiencies of the flare which can then be exacerbated by imposing a crosswind.

Figure 7.6 shows the inefficiency of natural gas flares as a function of crosswind speed with two different sizes of water droplets added to the flare stream. The exit velocity was 1 m/s and the distilled water was added to each flare stream such that their mass fractions of water were 21%, or $X = 0.21$. The droplet sizes were approximately 73 and 111 micrometers. The inefficiencies of flares having either size of droplets were observed to be almost the same except at higher crosswind speed (*i.e.*, 7 m/s). The difference in the inefficiency at this crosswind speed was approximately 3%, where the inefficiency of the flare with 73-micrometer droplets was higher than the flare with 111-micrometer droplets. The reason for this difference was unknown. This trend of droplet size having very little impact on the combustion efficiency is further supported with data from the iso-octane and diesel droplet experiments presented later.

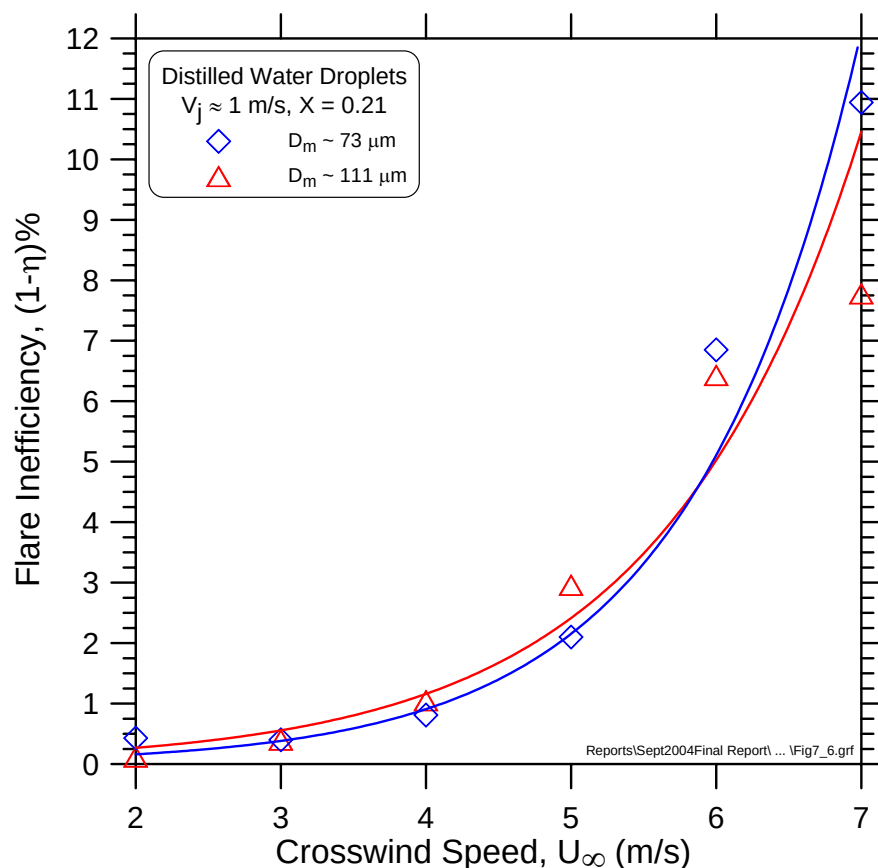


Figure 7.6: Effects of water droplet size on flare inefficiency in crosswind

Figure 7.7 shows the effects of varying flow rates of distilled water on the flare inefficiency in varying crosswind conditions. Varying amounts of droplets of distilled water were added to the natural gas flares with exit velocities of 1 m/s to create flows where the mass fraction of water ranged from 12 to 21% and the crosswind speed was varied from 2 to 7 m/s. (The droplet sizes are not reported since this parameter was shown to be insensitive to the results of combustion efficiency.) The results consistently show that increasing the mass of water in the flare stream increases the inefficiency of combustion. It is also worth noting that the water does not have a strong effect on the combustion efficiency for this range of mass loadings. Figure 7.8 shows the results from a similar series of experiments but with the exit velocity increased to 2 m/s. These higher-velocity results stress consistent behaviour: the greater the water content, the greater the effect. However, at flare exit velocities of 2 m/s the impact of the droplets is less pronounced regarding inefficiencies.

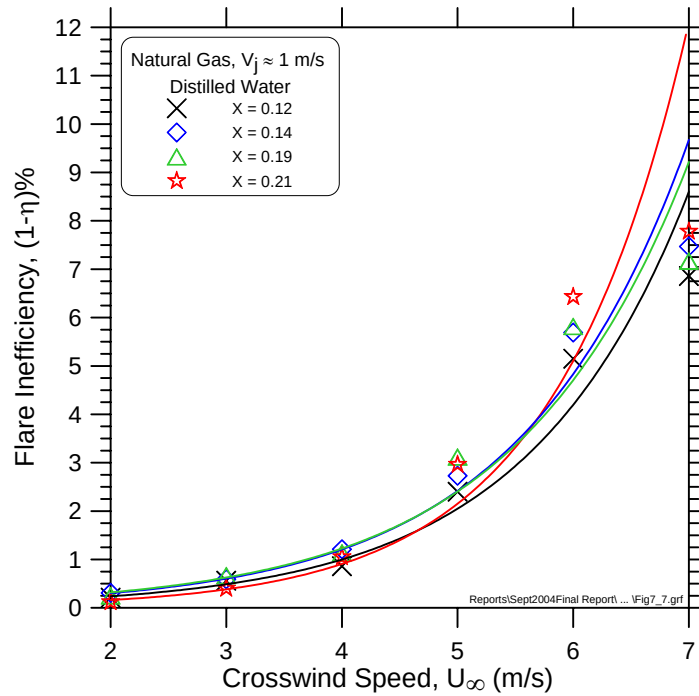


Figure 7.7: Inefficiency of flares having low jet exit velocities with varying flow rates of distilled water using Droplet Generator “A”

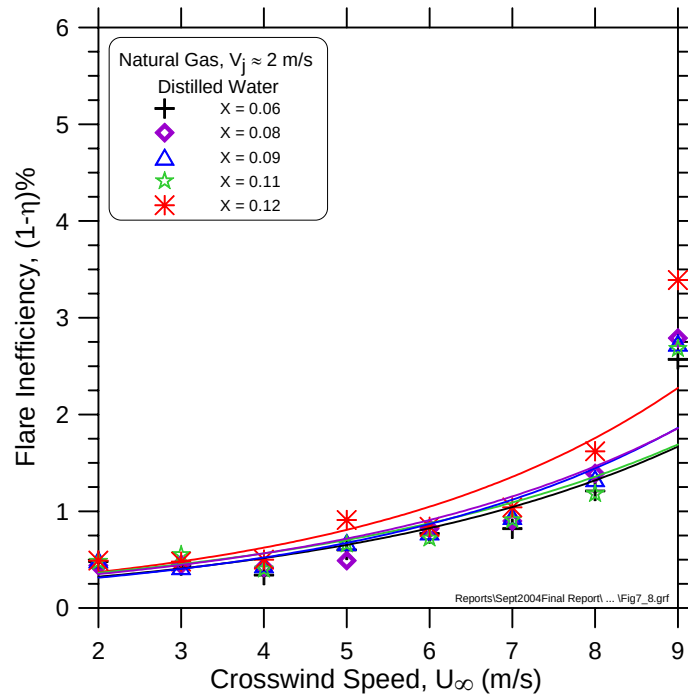


Figure 7.8: Inefficiency of flares having high jet exit velocities with varying flow rates of distilled water using Droplet Generator “B”

7.2.2 Iso-Octane Droplets

The flame structures of natural gas flares containing iso-octane droplets are the same as those observed for gas-phase-only flares as described in Section 3.3. The main visual effect of the iso-octane droplets was an increase in the luminosity of the flame. The gas-droplet flare had distinct yellow segments in place of the characteristic blue color associated with similar gas-only flares. There was no noticeable increase in flame size with the addition of fuel droplets, though detailed flame length measurements were not conducted. Under operating conditions that injected larger droplets into the flare stream, small streaks of light, similar in appearance to sparks, were observed appear at the flame surface. These light streaks, which extended for less than 5 cm, were concluded to be drops of iso-octane that did not fully evaporate before reaching the flame and continued to burn as isolated droplets while being carried downstream into the plume of combustion products.

Figure 7.9, shows the results of 24.7 mm diameter natural gas flares with exit velocities of 1 m/s exposed to crosswind speeds varying from 2 to 7 m/s and of flares with the same gas flow rate but with the addition of iso-octane droplets. The mass-mean diameters of the droplets were $\sim 10\text{ }\mu\text{m}$ and the mass fraction of iso-octane droplets was 13%. The addition of iso-octane droplet into the flare stream showed a positive effect on the combustion inefficiency. Iso-octane droplets lowered the inefficiency of the flares when tested under the same crosswind conditions as gas-only flares. At moderate crosswinds (*i.e.*, 2 to 4 m/s) the inefficiencies of both types of flares remained under 1% inefficiency. At higher crosswinds (*i.e.*, 5 to 7 m/s), the inefficiency of natural-gas-only flares rose up to 6% while the inefficiency of the flares with iso-octane droplets rose only up to 3%.

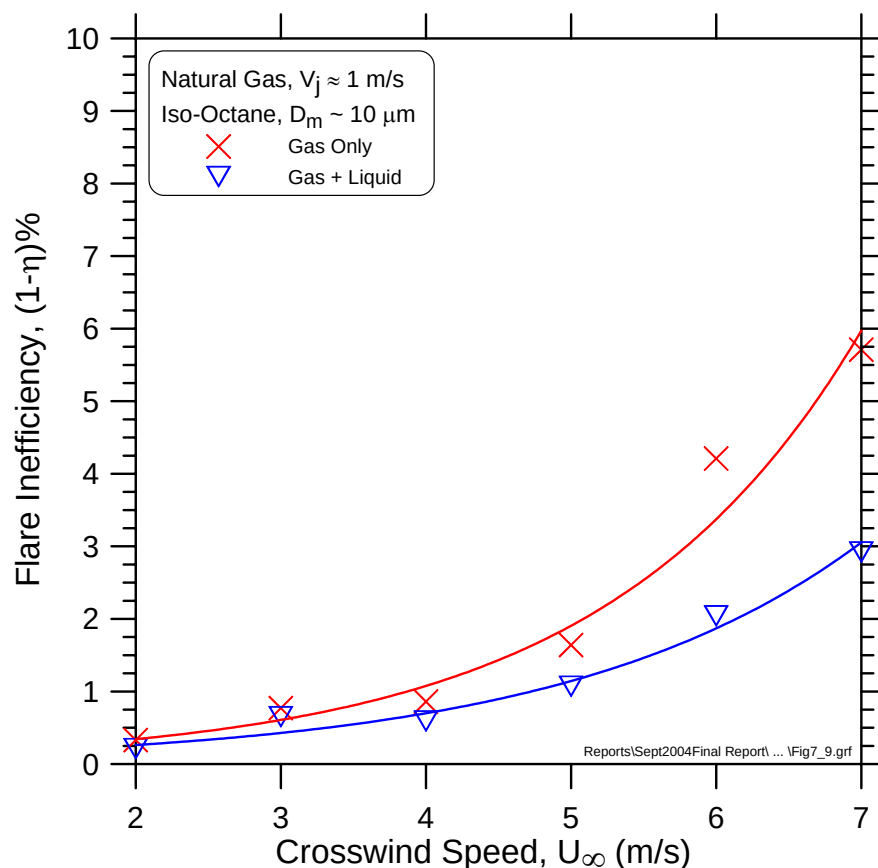


Figure 7.9: Effects iso-octane droplets on flare inefficiency in crosswinds

The reason for the improved combustion efficiencies associated with the addition of fuel droplets is related to the same phenomena that result in higher efficiencies in propane flares as explained in Section 3.5. The addition of iso-octane (C_8H_{18}) to natural gas creates an effective or average fuel composition of a heavier paraffin fuel in terms of both energy density and momentum flux. For example, the addition of a mass fraction of approximately 64% iso-octane (*i.e.*, 20% mole fraction) to natural gas would create a flare stream similar in mass and energy densities to propane. Since the mass fractions capable of being created in the present experimental setup were typically less than 20%, the observed effects on combustion efficiency are were not as great as comparing the results of natural gas flares to propane flares (*c.f.*, Section 3.5). The equivalence paraffin fuel composition (such that C_nH_{2n+2}) associated with a 20% mass fraction mixture of octane with the remainder being natural gas is approximately $C_{1.3}H_{4.6}$. It is important to note that since this fuel addition to

the natural gas comes in the form of droplets that require energy to evaporate these efficiency results cannot be directly compared to gas-only flares.

The effects of droplet size on flare inefficiency are shown in Figure 7.10 for two flares having the same mass fraction of 21% of iso-octane and an exit velocity of 1 m/s, but different sizes of droplets. The smaller droplets had a mass-mean diameter of approximately 5 micrometers while the larger droplets had a mass-mean diameter of approximately 66 micrometers. It was observed that the octane droplet size had no significant effect on the flare inefficiency. This result is not surprising since the arguments made previously were that the combustion efficiency is based on the effective or average composition of the flare stream. Since the bulk of the droplets evaporate prior to the flame, the droplet size exiting the stack is irrelevant. The important factors are the energy density and momentum flux, not the size of the droplets before evaporating. Figure 7.11 confirms that the size of the iso-octane droplets do not change the inefficiencies of the flares significantly. In this case, the exit velocity of the stack and the mass fraction of droplets were fixed at 2 m/s and 13%, respectively, and the droplet mass-mean diameter, D_m , was either 14 or 80 micrometers. Therefore, as long as the droplets are of a size range such that they evaporate prior to reaching the flame, the droplet size will have no profound influence on the flare inefficiency.

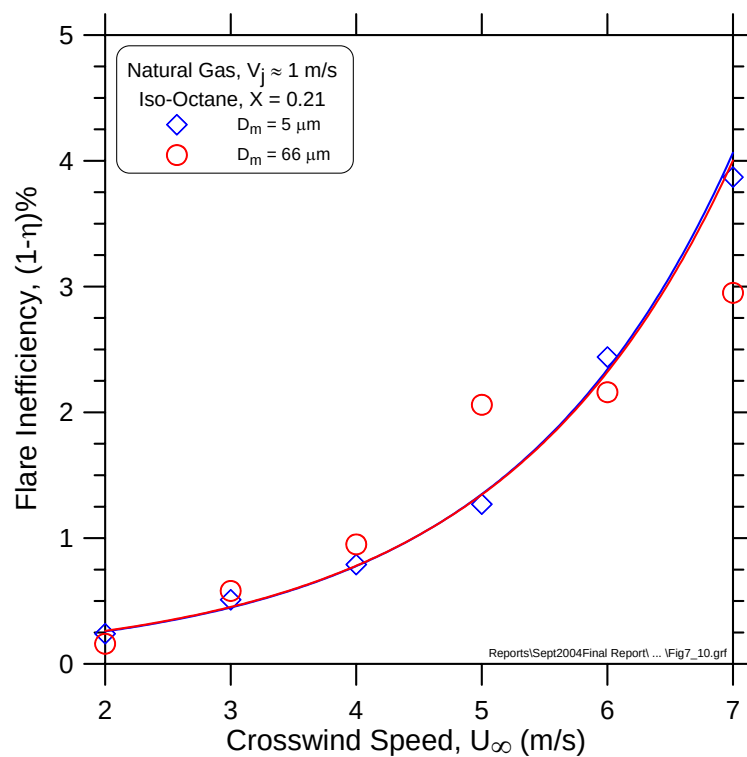


Figure 7.10: Effects of iso-octane droplet size on the inefficiency of flares with low flare gas exit velocities in crosswind

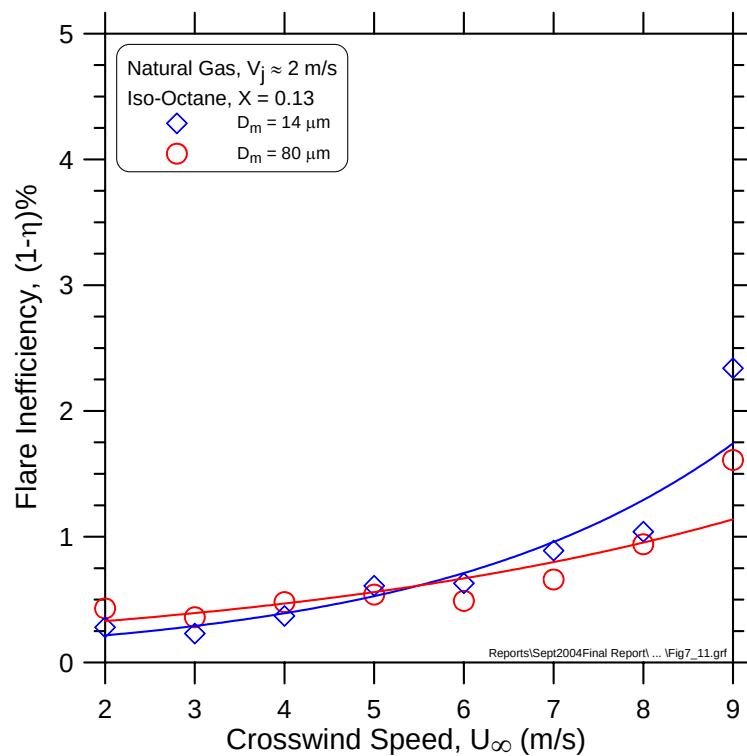


Figure 7.11: Effects of iso-octane droplets size on the inefficiency of flares with higher jet exit velocities in crosswind

In order to understand the effects of changing the mass flow rate of iso-octane on the flare inefficiency, experiments were conducted on natural gas flares with an exit velocity of 1 m/s and mass fractions changes from 17% and 30%. The droplet size in both cases was approximately 35 micrometers. Figure 7.12 shows that the measured inefficiencies of flares with a higher mass fraction of iso-octane were lower when compared to flares with a lower mass fraction of iso-octane. In this particular case, the observed inefficiency for the 32% mass fraction iso-octane flare was approximately half a percent lower than the 18% mass fraction iso-octane flare for the full range of wind speeds tested. Figure 7.13 shows the inefficiency of the flares as a function of mass fraction of iso-octane at 5 m/s and 6 m/s crosswind speeds. These tests were conducted by adding iso-octane while increasing their flow rate from a mass fraction of 19% to a mass fraction of 32%. These results showed, despite some scatter in the data, that the flare inefficiencies decrease with an increase in iso-octane mass fraction.

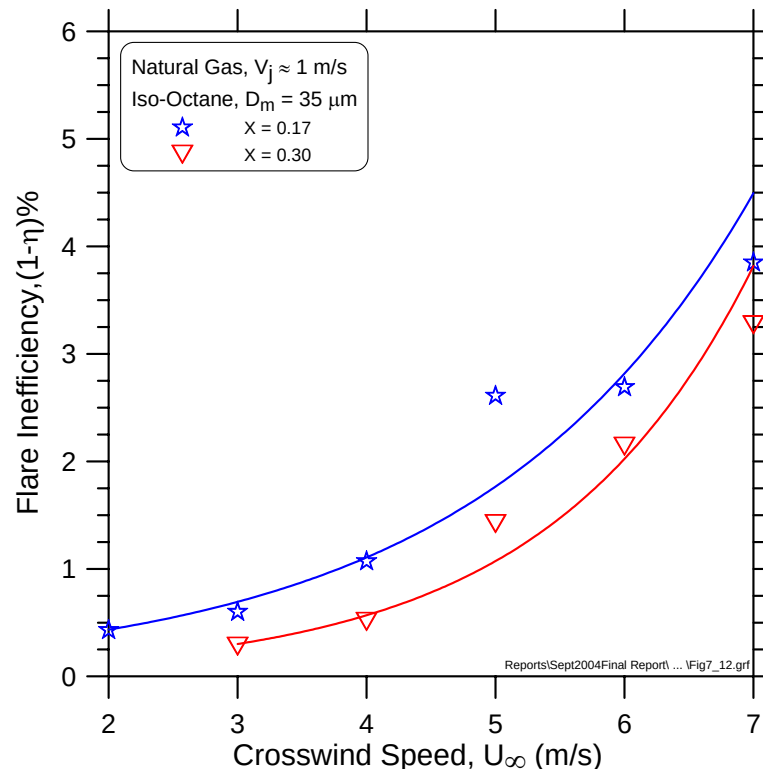


Figure 7.12: Effects of mass flow rate of iso-octane on flare inefficiency having same size of droplets in flare streams

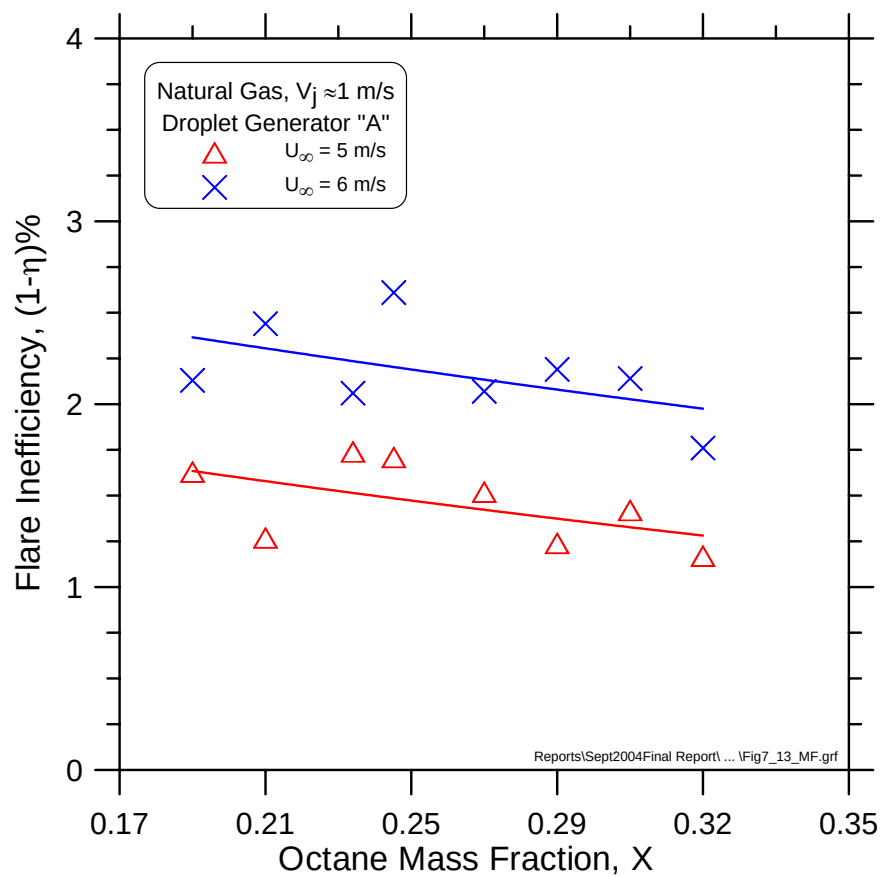


Figure 7.13: Flare inefficiency as a function of mass flow rate of iso-octane using Droplet Generator "A"

Figure 7.14 shows test results of flares with 2 m/s flare gas exit velocities when iso-octane was added to the flare stream such that the mass fraction ranged from 8% to 14% and the mass-mean diameter of the droplets was 15 micrometers. Again, there was no observed effect of different droplet diameter on the measured combustion efficiency.

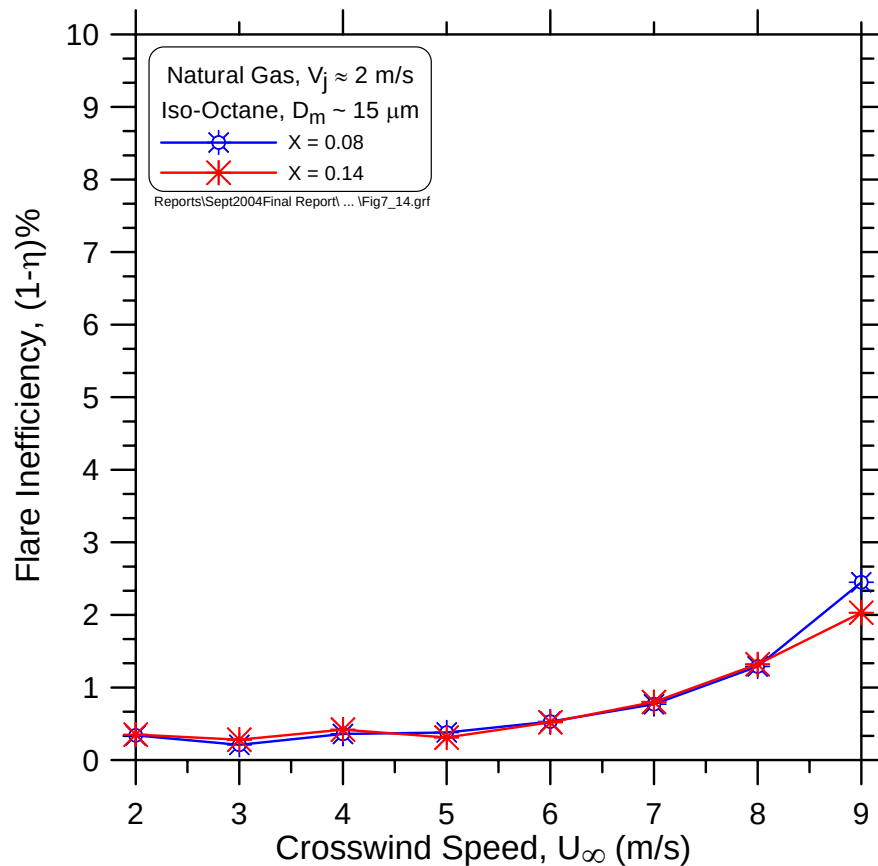


Figure 7.14: Effects of mass flow rates of natural gas and iso-octane on flare inefficiency with same size of droplets in flare stream

7.2.3 Diesel Droplets

Similar to the flares tested with water and iso-octane droplets, the visible flow patterns and flame structures of natural gas flares containing diesel droplets were unaffected by the presence and combustion of the droplets. The diesel droplets, like the iso-octane droplets, caused the flame to become far more luminous than the flames produced by burning natural gas alone. The occurrence of streaks of light starting near the flame surface was more common with diesel than with iso-octane droplets. As explained above, these streaks were associated with burning droplets that survive to the flame surface without fully evaporating. This observation is believed to be a consequence of the relative properties of diesel and iso-octane. The physical properties of components that make up diesel result in larger-sized droplets and a higher boiling point making these droplets harder to evaporate.

Figure 7.15 shows a comparison between the inefficiency of natural gas flares with and without diesel droplets added to the flare stream as a function of crosswinds. In this particular case, the exit velocity was 1 m/s, the mass-mean diameter of the droplets was 97 micrometers, and the mass fraction of diesel was 14%. As with all the flares tested, there was a characteristic and strong dependency of inefficiency on the crosswind speed with or without droplets. The addition of diesel droplets to the flare stream had a non-linear effect on flare inefficiency when compared to the natural gas flare. At low crosswind speeds (*i.e.* 2 to 4 m/s) the effect of the droplets was not measurable; at higher crosswind speeds (*i.e.* 5 to 7 m/s) the flare inefficiency decreased when diesel droplets were added to the flare stream.

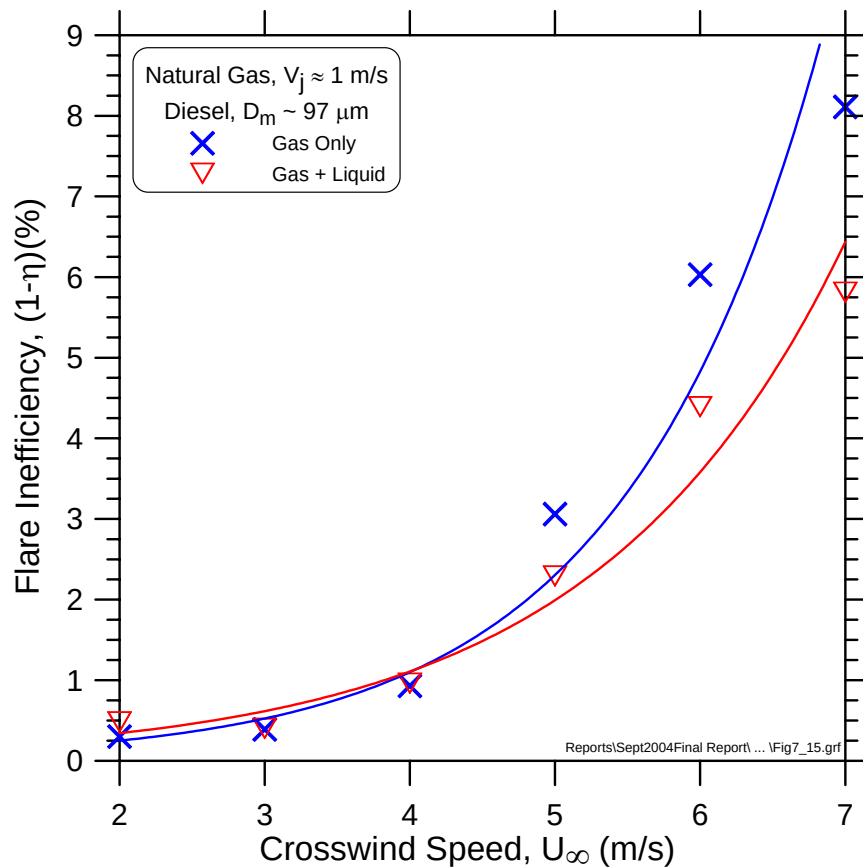


Figure 7.15: Effects of diesel droplets on the inefficiency of flares in crosswind

The effects of droplet size on flare inefficiency were examined by adding different size diesel droplets to the natural gas flares. Figures 7.16 and 7.17 show the results for flares with 1 m/s and 2 m/s exit velocities, respectively. At the lower exit velocity condition, the mass fraction of diesel droplets was held at 14%. At the higher exit velocity condition, the mass fraction of

diesel droplets was held at 11%. In both cases there was a small ($\sim 0.25\%$ when averaged over all the crosswind speed tested) but systematic reduction in the flare inefficiency that resulted from having smaller droplets in the flare streams. The poorer efficiency of flare streams with larger droplets is associated with the increased occurrence of droplets that do not evaporate prior to reaching the flame. Implied in this statement is the supposition that liquid-phase combustion converts less of the carbon in the fuel into CO_2 than gas-phase combustion of the same fuel. In the case of iso-octane, essentially all of the droplets evaporate prior to reaching the flame and, therefore, the original droplet size has essentially no effect on the combustion processes. When larger diesel droplets were tested, a greater proportion of them remained in droplet form as they passed through the flame where they were ignited, resulting in a reduced conversion efficiency.

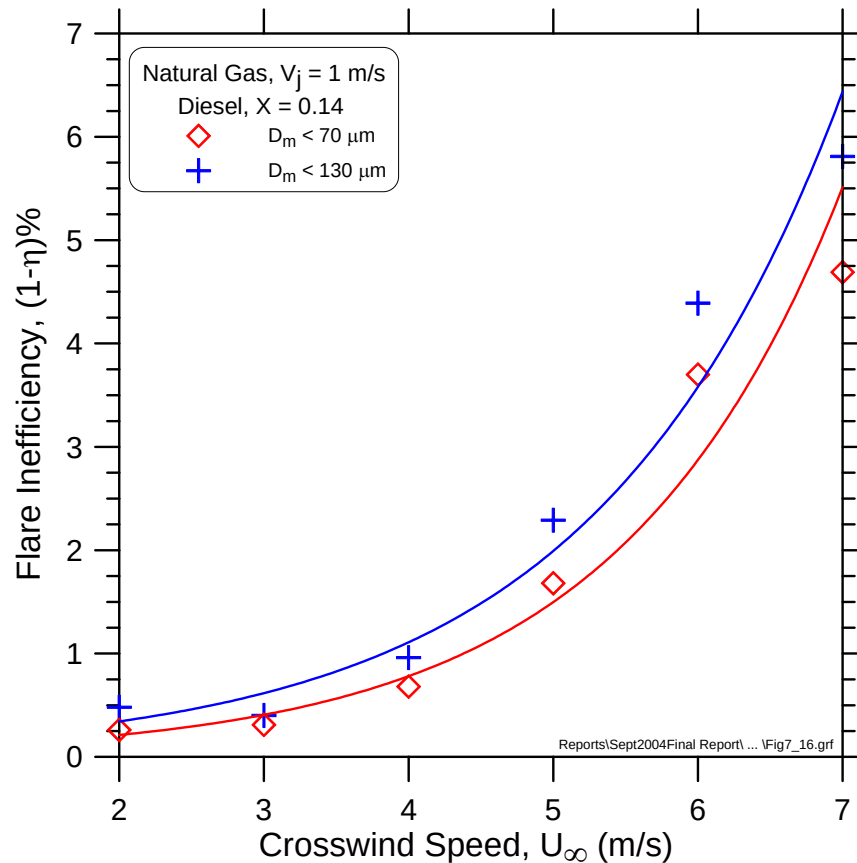


Figure 7.16: Effects of diesel droplet size on the inefficiency of flares with low flare gas exit velocity

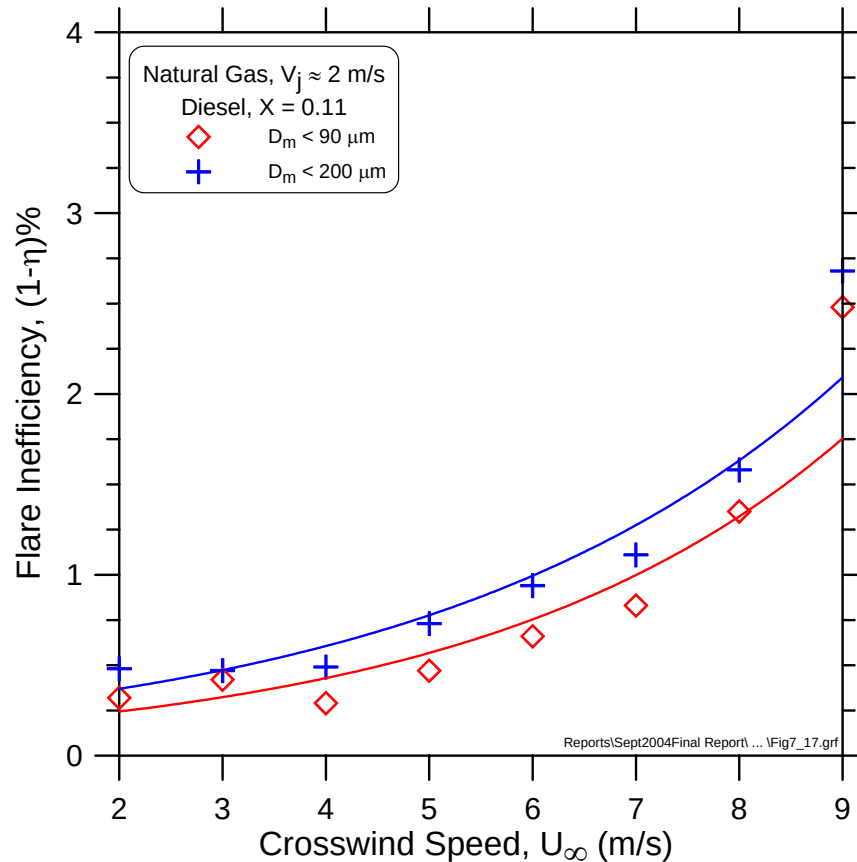


Figure 7.17: Effects of diesel droplet size on the inefficiency of flares with higher flare gas exit velocities

7.2.4 Comparison Between Droplets of Different Composition

Various liquids, combustible and non-combustible, have been considered separately in the above sections comparing the combustion inefficiencies of scaled down natural gas flares. This section will compare these liquids relative to each other. Other than the effect of water increasing the inefficiency and hydrocarbons decreasing the inefficiency, no comparisons have yet been made regarding the relative impact of the droplet composition on the combustion. Figures 7.18 and 7.19 emphasize this point by showing the inefficiencies of natural gas flares with the various droplets added to 1 m/s and 2 m/s flares, respectively. The mass fraction of liquids added to the flare streams were 14% for the 1 m/s flares and 8% for the 2 m/s flares. In all cases, the inefficiency associated with the flare streams was highest when water droplets were added and lowest when iso-octane droplets were added. The impact of having either combustible or non-combustible droplets in the flare streams has

been discussed previously and explains why the flares with water droplets would be expected to have higher inefficiencies. The observed differences between two different types of fuel droplets, i.e. hydrocarbon-based liquids, being added to the flare stream is less clear. Differences in the physical properties between iso-octane and diesel can be found in the latent heats of evaporation and in the chemical enthalpies of combustion. As a result of the different latent heats of evaporation, the energy needed to evaporate a given mass of diesel is higher than the energy required for the same mass of iso-octane. The chemical energy that is converted to sensible energy during combustion per unit mass of iso-octane is slightly higher than that of diesel. Therefore, the relative differences in the inefficiency curves shown in Figures 7.18 and 7.19 for the two fuel different fuel droplets are a result of the diesel requiring more energy to evaporate and provide less sensible energy back to the flow than the iso-octane. This imbalance in the energy makes flares with iso-octane droplets more robust than similar diesel droplet flares.

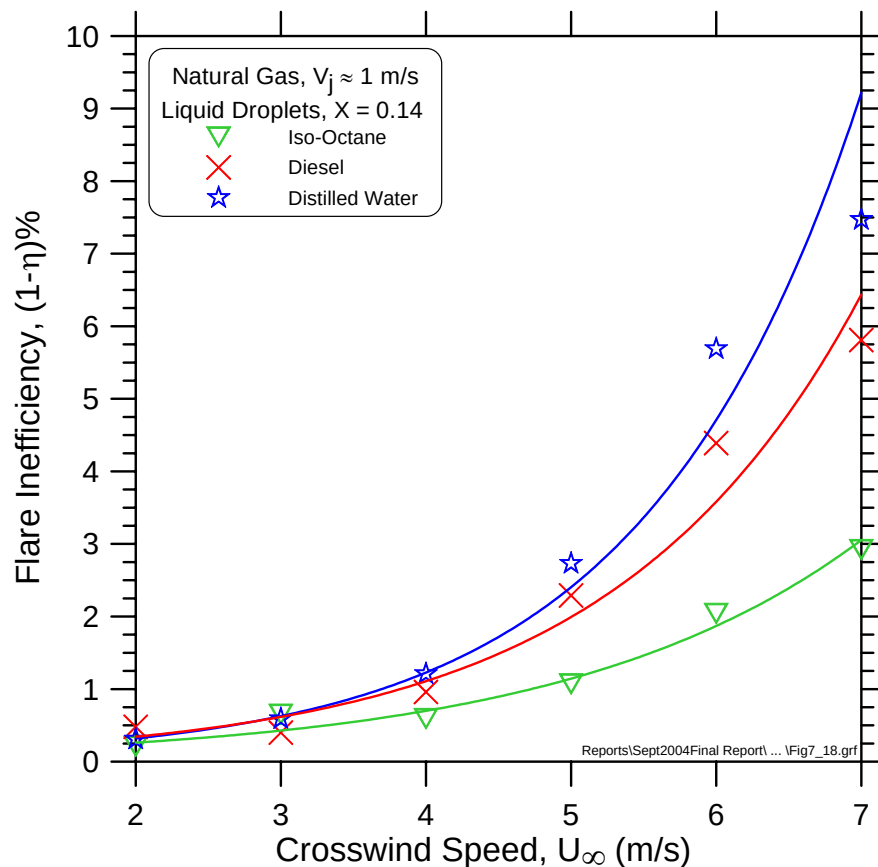


Figure 7.18: Effects of iso-octane, diesel, and distilled water droplets on the inefficiency of flares of low jet exit velocities in a crosswind

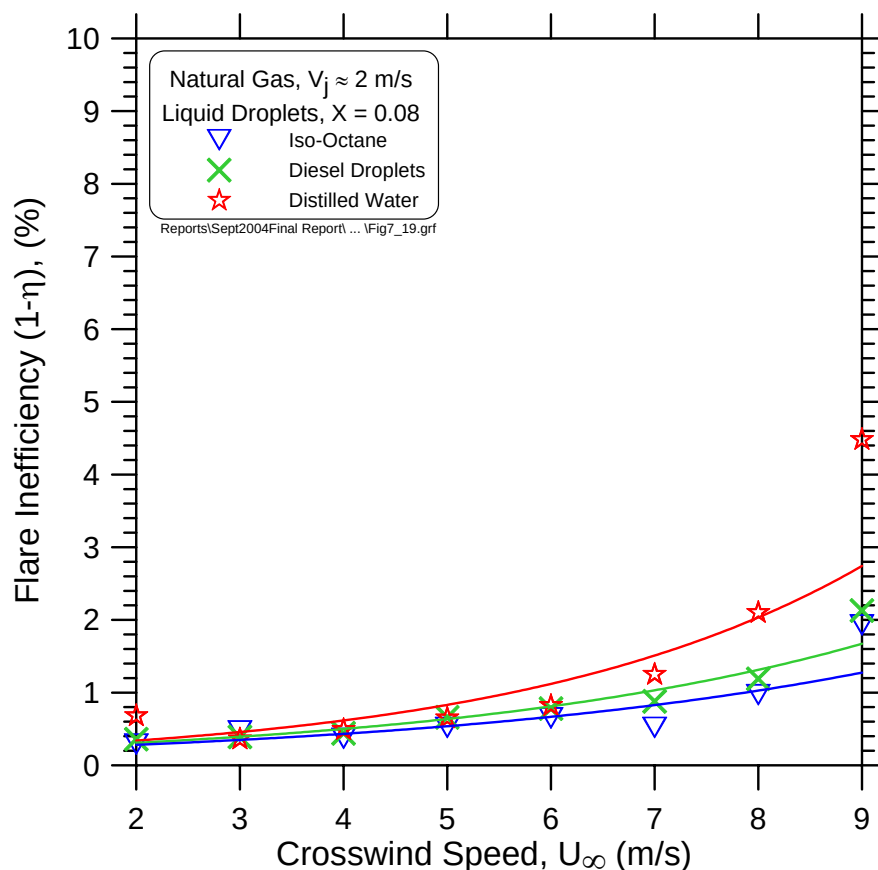


Figure 7.19: Effects of iso-octane, diesel, and distilled water droplets on the inefficiency of flares of high jet exit velocities in a crosswind

7.3 CONCLUSIONS

This chapter provided an experimental exploration of the effects of adding either combustible or non-combustible droplets to a natural gas flare. These experiments required the existing flare system at the U of A to be modified to allow droplets, produced by ultrasonic generators, to be introduced into the flare gas. With this method of droplet generation, it was possible to add droplets of varying sizes and mass fractions to the flare stream of natural gas. Droplets of water, iso-octane, or diesel were added separately to the flare stream in quantities up to a mass fraction of 32% and exposed to crosswind speeds from 2 to 9 m/s. The exit velocity of the 24.7 mm diameter flare stacks, used in these tests, was set to either 1 or 2 m/s. The droplet size diameters were measured and characterized as a mass-mean diameter and,

depending on the composition of the droplets, this characteristic diameter could be varied from 4 to 200 micrometers.

An enhanced method for measuring the combustion efficiency was developed in this chapter to allow for the emission of non-gaseous hydrocarbons (*e.g.*, soot). This methodology was not used in the presented results since detailed measurements to identify soot emissions showed that there were no particulate emissions from these flares. As a result, the simpler and more accurate method of measuring the efficiency of flares in a crosswind, described in Chapter 3, was used for these experiments.

It was observed that the addition of droplets in these quantities had no effect on the flame structures or patterns relative to gas-phase-only flares described in detail in Chapter 3. The luminosity of the flares carrying iso-octane or diesel was significantly increased; the luminosity of those flares carrying water droplets was unaffected. For conditions that produced larger iso-octane and diesel droplets streaks of light were observed at the flame surface and extended downstream for several centimeters. These streaks of light were most pronounced with larger diesel droplets and were associated with droplets not fully evaporating before reaching the flame where they were ignited and burned while being carried with the flow.

The results of these experiments showed that water droplets added to the flare stream increased the combustion inefficiency proportionate to the amount of water added. In contrast, the addition of fuel droplets resulted in decreased inefficiencies where iso-octane had a greater impact than diesel on a per mass basis. The explanation for these results was found in the energy balance and dilution effects associated with the various droplet compositions. Water droplets extract energy from the flow in order for evaporation to take place. The addition of these non-reacting vapors to the flare stream results in a flame that is less robust than a natural gas flare. Therefore, flares streams with water droplets were more susceptible to the mechanisms that create inefficiencies in a crosswind. For combustible droplets, energy is still required for evaporation but the vapors are a fuel that contributes to the total chemical energy being converted to sensible energy at the flame. The energy

associated with the combustion of a fuel far exceeds the energy associated with evaporation. Therefore, fuel droplets in the flare stream enhance the robustness of combustion and result in reduced inefficiencies.

The effect of altering the size of droplets carried out the stack exit was examined in these experiments. These results showed that if most of the liquid phase was converted to the gas phase before the flame, through evaporation, then the original diameter of the droplets had no influence on combustion efficiency. In practice, all of the water and octane droplets tested fully evaporated prior to the flame and, therefore, there was no observed effect of droplet size on the combustion efficiency. For the larger size diesel droplets a notable portion of these droplets were reaching the flame intact and resulted in a slight increase in the combustion inefficiency. The size of droplet that will be evaporated prior to reaching the flame is highly dependent on the following factors: the size and luminosity of the flame; the travel time of droplet between the stack exit to the flame; and the composition of the droplet. Therefore, no recommendation is made regarding an expectable size of droplet that can be emitted from a flare stack and not adversely affect the combustion efficiency.

8 TESTING OF LARGER SCALE FLARES

Up to this point in the report, the experimental data, the subsequent insights, and the developed models have come from work done at the University of Alberta Flare Research Facility. The salient points of this research are:

- the proposing and testing of a mechanism that leads to combustion inefficiencies of flares exposed to a crosswind;
- the development of a semi-empirical model for predicting the combustion efficiency for a range of flare gas compositions, jet exit velocities, flare stack diameters, and wind speeds;
- the establishment of the dominant fluid mechanic forces relevant to flares operating in a crosswind (i.e., the momentum of the crosswind and the buoyancy of the plume) as seen through both the evolution of the thermal plume and the measured combustion efficiency;
- the discovery that the predominant phase of minor, but toxic, chemical species was particulate and not gas; and
- the quantification of the effects of adding non-reacting liquids (i.e., water) or reacting liquids (i.e., iso-octane and diesel) to the flare stream on combustion efficiency.

Each of these aspects of the research was bound within a finite range of operating conditions within which the various parameters were explored. For example, there were bounds on the flare stream compositions, jet exit velocities, stack diameters and wind speeds that were tested. Some of these limitations arose by choice and representative of the problem being studied (e.g., flare gas composition and wind speed), while others (e.g., jet exit velocity and stack diameter) were constrained by the physical dimensions of the facility at the University of Alberta. In essence, as the size of the flare was increased, either by having a larger diameter or a higher exit velocity, the thermal load on the facility or the flame impingement on the ceiling became unacceptable.

This chapter presents results from a larger facility that allowed the bounds on stack diameter and jet exit velocity to be expanded. The broader objectives of this part of the research were, therefore, to explore experimentally parameter ranges that could not be investigated previously. These results will then be compared to the data and the models presented earlier in this report. The flare stack diameters considered in this chapter will be varied up to an outside diameter (d_o) of 114.3 mm, which is the size of a typical solution gas flare operating in Alberta. This flare is approximately four times larger than those regularly tested at the University of Alberta Flare Research Facility. The jet exit velocity on a 30.0 mm flare will be varied up to 40 m/s in order to simulate well-test or emergency flares and is nearly 20 times faster than the results previously considered in this report.

The grounds for comparison between the data presented here and those earlier in this report are the size and growth of the thermal plume downstream of the flare and the overall combustion efficiency. Comparing the size and growth of the thermal plume is important in establishing that the same basic fluid mechanics of air-fuel mixing and the subsequent combustion are consistent across the full range of physical sizes of flare stacks. Comparisons based on overall combustion efficiency were done to add confidence to the use of the models developed at the U of A to predict the efficiency of pipe flares up to full scale and to modify those models appropriately to include full-scale flares. By inference, if the efficiency data on the larger flare is consistent with the small scale data, this establishes that the underlying mechanism of fuel stripping is equally valid across all these scales. The basic conclusion of the results presented in this chapter is that the characteristics and performance of these larger flares are fully consistent with the data and models presented previously in this report. A more detailed discussion of larger diameter flares and the data collected at the NRC facility can be found in [51].

The organization of this chapter is to first briefly review the experimental setup and methodologies used in data collection for these larger flares. Characteristic thermal and efficiency data collected on larger diameter flares are then presented and compared to data and models from experiments performed at the University of Alberta Flare Research Facility. Lastly, efficiency data is presented for flares with higher jet exit velocities.

8.1 EXPERIMENTAL SETUP AND METHODOLOGIES

The experimental setup and methodologies used in this chapter have already been discussed in previous sections of this report (c.f., Chapters 2, 4, and 5). That is, the experimental methodologies developed at the U of A regarding efficiency calculations and plume mapping were adapted to this experimental work with larger-scale flares. All of the experiments were conducted at the Flare Research Facility at the National Research Council of Canada (NRC) in Ottawa. A description of this facility, including the wind tunnel that provides the crosswind for the tests and the diagnostic equipment used to analyze data, is provided in Section 2.2. The important features of this wind tunnel were that the test section was 6.10 m high, 3.05 m wide and 13.0 m long, and that its design was for a single-pass mode. Having a test section of this size allowed flares as large as 114.3 mm in diameter (d_o) to be tested without any direct effects on the flame being observed. In order to provide connectivity to tests conducted at the University of Alberta Flare Research Facility flares of 30.0 mm and 58.8 mm diameters were also tested. The single-pass design of the NRC wind tunnel also had important implications on the flaring research. In order to retain the integrity of these testing procedures, modifications were made to the operating protocols, the methods used to measure thermal plume structure or combustion efficiency, and the uncertainty associated with those measurements.

The method used to measure the mean thermal plume structures of the flares burning in a crosswind was the same as that described in Chapter 4. This method involved a rake of 27 Type E thermocouples with junction sizes of approximately 2 mm in diameter. To measure the mean temperature, the thermocouple voltage was sampled 500 times a second over a 10-second period. These 5000 sampled-voltages were converted to temperature, which were then averaged to calculate the mean temperature at the measurement point. After calculating the mean temperatures, the thermocouple rake was stepped incrementally across the plume using the computer-controlled traverse system.

The only material difference between the thermal plume measurement system described in Chapter 4 and that used at the NRC facility was the size of the rake and the steps taken across the plume. Since the flames at the NRC were generally much larger, the rake was redesigned to allow for thermocouple spacing up to 95 mm apart. Furthermore, to provide greater flexibility for the different sized flames, the thermocouple spacing could be changed to 50 mm spacing to better resolve the smaller plumes. The step size taken across the plume was also made variable to provide the necessary resolution of the thermal plume structures. Figure 8.1 is a drawing of the thermocouple rake used at the NRC facility.

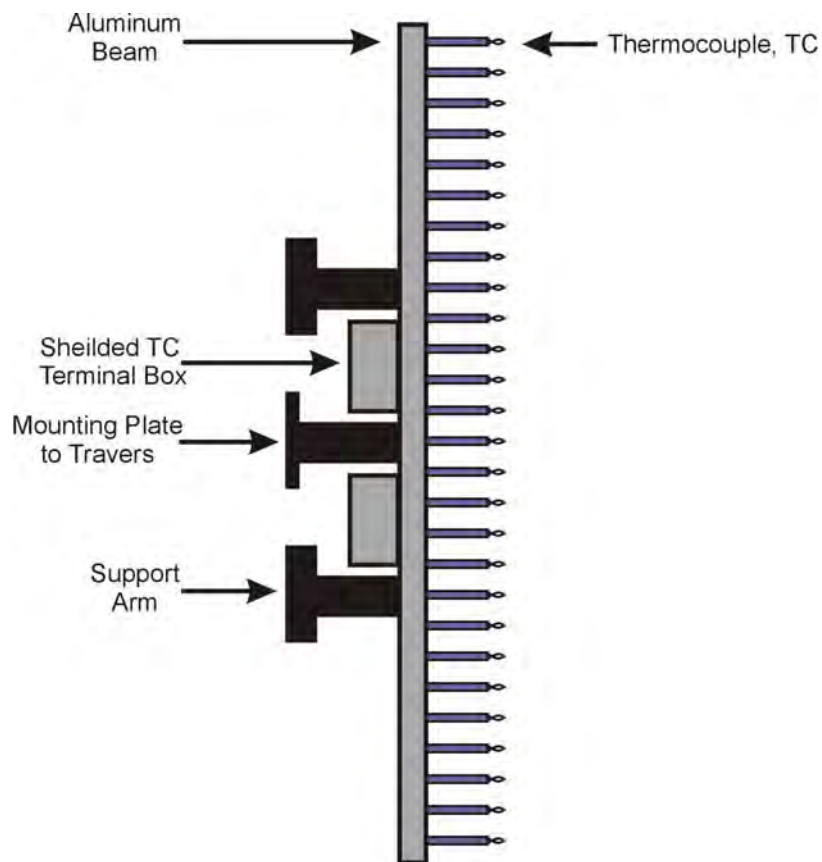


Figure 8.1: Thermocouple Rake (Top View)

The processing of the mean thermocouple data to calculate a characteristic mean plume dimension (d_p^*) was done identically to the method described in Chapter 4. The d_p^* used was defined as the square root of the cross-sectional area contained within the temperature

contour defined by the half-mean temperature rise relative to the ambient temperature (see Equation 4.1).

The basic method used to measure the overall efficiency of the flares burning in a crosswind is essentially the same as that described in Chapter 5. This methodology is based on making many point samples of the combustion products across the full plume of the flare. The stoichiometry of the major chemical species (i.e., hydrocarbons, carbon dioxide, oxygen, and carbon monoxide) was used to calculate the local combustion efficiency at the sample point (see Section 5.1). By integrating the data collected from the many single-point measurement locations across the plume, the overall efficiency of the flare can be estimated. This integration was performed by assuming that a uniform velocity exists in the plume at the sample plane, and by weighting the calculated local efficiencies by product concentration and density (see Section 5.5).

The main difference between the estimation of the overall combustion efficiency as described in Chapter 5 and that used at the NRC facility was the actual sampling process. At the University of Alberta facility an array of 20 sample probes was used to simultaneously transfer product gases to 20 Tedlar bags. The contents of those bags were then analyzed to calculate the combustion efficiency of the flare while the flare gas flow rate was shutoff and the tunnel was purged with fresh air for the next series of samples to be taken. This process was continued across the whole plume (i.e., 300 sample points taken) and took upwards of 11 hours to complete the experiment for each flaring condition tested. Since the NRC facility operated in a single-pass mode, the process of collecting samples does not have a purge stage and could only be done one point at a time. A single sampling probe would draw product gases from a fixed plane downstream of the flame. The sampled gases were measured with on-line analyzers (hydrocarbon, carbon dioxide, oxygen, and carbon monoxide) for a 30-second period and the concentration outputs were averaged to determine the mean species concentrations. Once the analysis at a point was completed, the traverse would move the probe to the next position in a pre-programmed grid pattern that was established across the product plume. Test times of this duration were problematic for a single-pass wind tunnel operating at wind speeds of the same order as the ambient winds. Since the tunnel was open

at both ends, wind gusts in the atmosphere or more gradual changes in wind speed and direction over the test period could alter the wind speed in the tunnel. In order to obtain reliable test conditions, vigilant monitoring of the wind speed in the test section was essential to compensate for any gradual changes in ambient conditions. The environmental conditions were monitored using a weather station located on the roof of the facility; the test section conditions were monitored and controlled using the equipment described in Chapter 2. On days of unstable winds, tests had to be postponed until favorable conditions prevailed.

8.2 CHARACTERISTICS OF LARGER DIAMETER FLARES

The experiments conducted at the NRC Flare Research Facility used sales-grade natural gas. The flares tested included stacks with outside diameters (d_o) from 30.0 mm to 114.3 mm, and flare gas exit velocities varied from 0.5 to 2.0 m/s. The wind speed was varied from 2.0 to 14.0 m/s. The data collected was processed by the methods described above for comparison with smaller scale flares in terms of thermal plume dimensions and overall combustion efficiency.

Before presenting and discussing the quantitative data regarding the thermal plume dimensions and overall combustion efficiency, it is worth considering the visual aspects of these larger flares. Figure 8.2 shows a selection of digital images of a 114.3 mm outside diameter flare burning natural gas flares. Due to the limited field of view of the camera lens and the sheer size of the flames, the images of these flares are cut off on the right side of each image. The size of the flames and the relatively poor optical access to the working section of the NRC wind tunnel made the collection of the images difficult, particular for the longer flames. The exit velocity (V_j) and wind speeds (U_∞) associated with these images were fixed at 0.4 m/s and 4.0 m/s respectively. The similarity of the flame shape and the stabilization mechanism between these 114.3 mm diameter flares and those tested as small as 12.1 mm (or smaller low-momentum jet diffusion flame reported in the literature [26, 27]) was readily observed. The reader is referred to Section 3.3 for a discussion of the effects of the crosswind on flame length, stabilization mechanism, and flame structure. The soot

deposition patterns on the stacks were also invariant with the size of stack. The implications of these soot observations were discussed previously in Section 2.1.2.2.



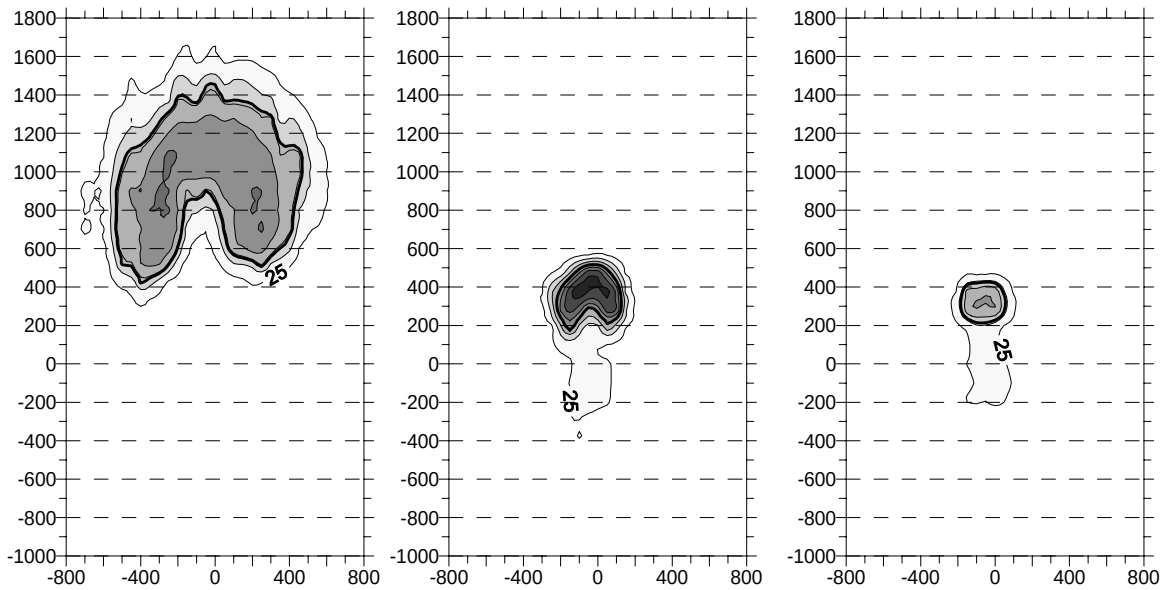
Figure 8.2: Visualization of 114.3 mm Flare Burning Natural Gas with an Exit Velocity of 0.4 m/s in a crosswind of 4 m/s.

8.2.1 Thermal Plume Data and Comparison

The main goal of the research in this section is to compare characteristics of the mean cross-sectional thermal plume structure from sub-scale flares (c.f., Chapter 4) up to full-size flare stacks presented in this chapter. That is, to show that the data collected for larger stack diameters burning natural gas at the NRC facility were consistent with those studied at the UofA (c.f., Section 4.3).

Typical mean thermal maps of the plume's cross-sectional structure for flares burning in the NRC facility are shown in Figure 8.3. These particular data are for a an inside stack diameter, d_i , of 52.6 mm and distance downstream of the stack, x , of 2.3 m, while V_j and U_∞ were varied to display a variety of plume shapes. As with the data presented in

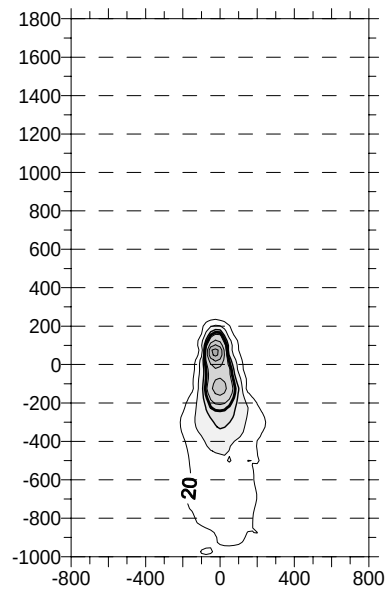
Chapter 4, the shape of the plume can be categorized into the modes that were described as kidney shaped, circular shaped, or downwashed. A detailed explanation of the existence of these modes is provided in Chapter 4. The important feature to note here is that these basic structural forms of the plumes, and the condition that led to their appearance, are consistent with flare stacks that have inner diameters ranging from 16.7 mm to 102.3 mm. This consistent behavior provides qualitative support for the conclusion that flares over this range of scales is part of the same flow regimes.



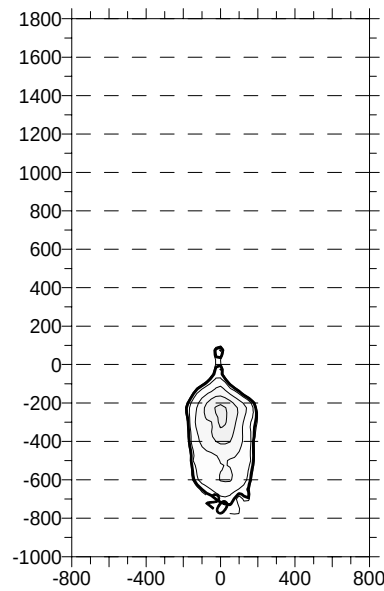
(a): $V_j = 2 \text{ m/s}$; $U_\infty = 2 \text{ m/s}$

(b): $V_j = 1 \text{ m/s}$; $U_\infty = 4 \text{ m/s}$

(c): $V_j = 0.5 \text{ m/s}$; $U_\infty = 4 \text{ m/s}$

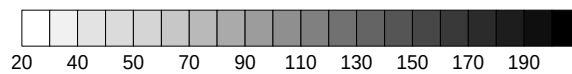


(d): $V_j = 1 \text{ m/s}$; $U_\infty = 8 \text{ m/s}$



(e): $V_j = 0.5 \text{ m/s}$; $U_\infty = 8 \text{ m/s}$

Temperature Scale (deg. C)



— : 50% Temperature contour

NOTE: X and Y axis in mm relative to flare stack tip

Figure 8.3: Varying Modes of Temperature Profiles for a Plume Cross-Section Behind a Natural Gas Flare for Constant Stack Diameter

Conditions: $d_i = 52.6 \text{ mm}$, $X_o = 2.3 \text{ m}$

flaresonMECE-HOME/Reports/.../Figure_8_3.srf

In Chapter 4, a model was developed based on the idea that the dominant fluid mechanic forces that establish the flow around flares are the buoyancy of the combustion products and the momentum flux of the crosswind. This modeling, that is based in the Richardson Number, leads to a relationship between a characteristic mean plume dimension (d_p^*), jet exit velocity, wind speed, distance downstream of the flare stack, and the inner diameter of the stack. This relationship is Equation 4.4 and repeated here for convenience, such that

$$d_p^* \propto g^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3} \quad (\text{Eq. 4.4})$$

Data presented in Chapter 4 for 129 natural gas flares of three flare diameters ($d_i = 16.7, 22.1, \text{ and } 33.3 \text{ mm}$) and varying the stack exit velocity ($V_j = 0.5, 1.0 \text{ and } 2.0 \text{ m/s}$), wind speed ($U_\infty = 1.5, 2, 4, 6, \text{ and } 8 \text{ m/s}$) and downstream locations (x) showed very good correlation with Equation 4.4. The least squares fit of these data to Equation 4.4 provides the correlation

$$d_p^* = 2.22 g^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3} \quad (\text{Eq. 8.1})$$

In total, data for 93 mean thermal maps were collected at the NRC facility for inner stack diameters of $d_i = 26.9, 52.6, \text{ and } 102.3 \text{ mm}$, exit velocities ranging from 0.5 to 2 m/s and wind speeds ranging from 2 to 8 m/s. (Note that smallest flare size tested at the NRC facility was chosen to overlap with data collected at the University of Alberta facility to provide a direct comparison.) Given the size range of the flares being tested, the thermal plume measurement plane ranged from 0.5 to 8.3 m downstream of the flare stack. These data were then compared quantitatively against the model presented in Equations 4.4 and 8.1.

Figure 8.4 shows the measured characteristic dimension for all the 93 plumes collected at the NRC facility. Marked on this figure is the maximum limit of the sub-scale data collected at

University of Alberta facility (i.e., $g^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3} < 0.17$). For these 93 data points ($d_i = 26.9, 52.6, \text{ and } 102.3 \text{ mm}$) the least squared fit to the data is given by:

$$d_p^* = 2.34 g^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3} \quad (\text{Eq. 8.2})$$

The correlation coefficient of these data was 0.98. If all the data were used to produce a best fit, the deviation between that fit and those from either set of data would be less than 3%, which is remarkable.

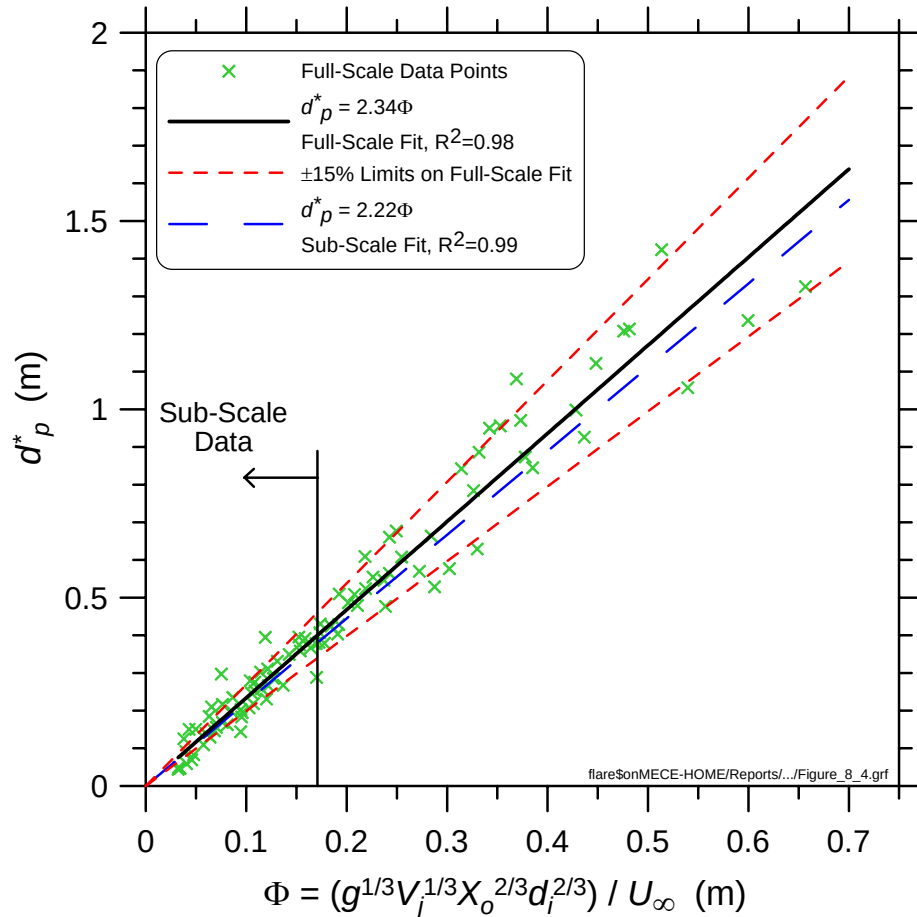


Figure 8.4: Characteristic Dimensions of Plumes

Conditions:

$$2.0 \text{ m/s} \leq U_\infty \leq 8.0 \text{ m/s}, 0.5 \text{ m/s} \leq V_j \leq 2.0 \text{ m/s}$$

$$26.9 \text{ mm} \leq d_i \leq 102.3 \text{ mm}, 0.5 \text{ m} \leq X_o \leq 8.3 \text{ m}$$

The main point to note is that both sets of data show a linear relationship between the parameter $g^{1/3} \frac{V_j^{1/3}}{U_\infty} x^{2/3} d_i^{2/3}$ and the characteristic dimension of the plume. This relationship implies that the fluid mechanics that establish the size and structure of the thermal plume are the same balance between the buoyancy of the combustion products and the momentum flux of the crosswind for all sizes of flares tested in this research. The importance of these observations can logically be extended to other aspects of the behavior and performance of flares operating in a crosswind. Since the mechanism that creates the combustion efficiency is a result of the fluid dynamics around the flare and the fluid dynamics are the same over all the scales of flares tested both at the UofA and the NRC, it would be expected that the relationships previously developed for the sub-scale flare should apply equally up to the full-scale flare. This hypothesis will be experimentally tested and confirmed in the next section.

8.2.2 Combustion Efficiency Data and Comparison

The research presented in this section concerns the mean compositional maps of 62 flare plumes and the overall combustion efficiencies calculated from that data. These maps contain cross-sectional data for carbon dioxide, hydrocarbons, oxygen, and carbon monoxide collected at the NRC facility. The experimental conditions were for natural gas flares that were bounded within the parameter ranges of $30.0 \leq d_o \leq 114.3$ mm, $0.5 \leq V_j \leq 2.0$ m/s and $4.0 \leq U_\infty \leq 14.0$ m/s. These compositional maps were created from data collected immediately downstream of the flame tip so that the effect of the flame was most predominant. The measured concentrations were converted into local and then overall combustion efficiencies by the techniques described previously (c.f., Chapter 5). The compositional mappings were very similar to those presented in Chapter 5 as viewed in Figure 8.5. The mean carbon dioxide concentration mapping coincided with the corresponding mean thermal mapping, while the hydrocarbon mappings again emphasized

that the spatial location of the inefficiencies occurs from beneath the flame as presented in Chapter 3.

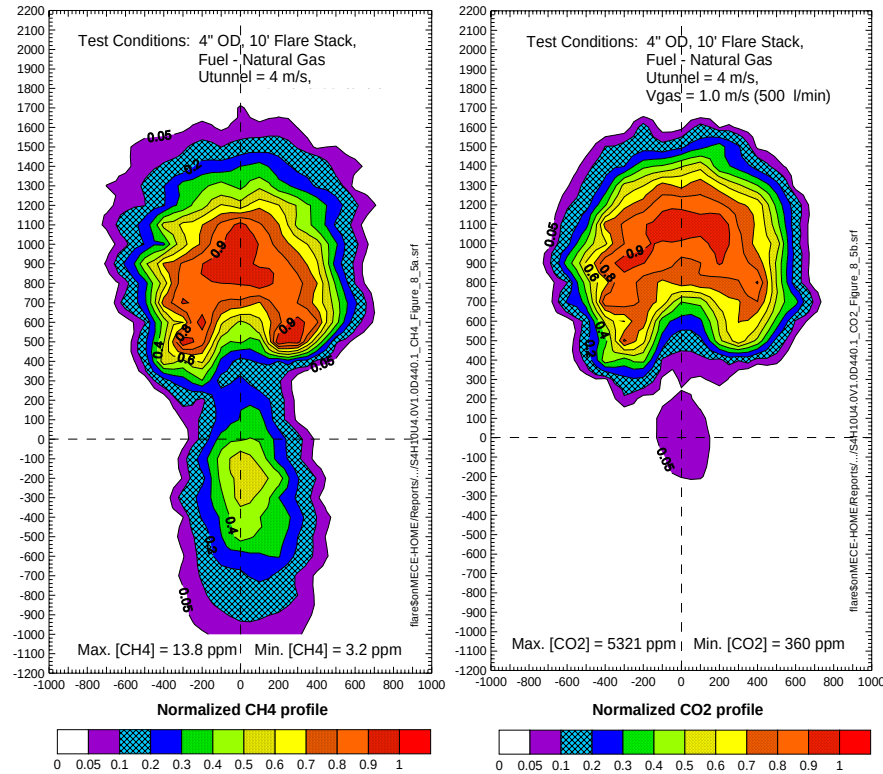


Figure 8.5: Compositional Maps for Full-Scale Flare Testing

Figure 8.6 shows the 62 overall efficiency data points collected at the NRC facility along side the approximately 200 natural gas flare efficiency measurements collected at the University of Alberta facility. The data have been plotted relative to the parameter $U_{\infty} / (gV_j d_o)^{1/3}$ which was developed in Chapter 3 and respects the idea that the major features of these flows result from the balance between the buoyancy of the combustion products and the momentum flux of the crosswind.

In general, there is good agreement between the two data sets. There is more data scatter associated with the efficiency measurement of the larger-scale flares. This larger scatter likely results from having unsteady conditions over the several hours needed to make an efficiency measurement and using a measurement technique that inherently had a greater

uncertainty when compared to the technique used at the UofA. A least squares fit to all these data provides the correlation

$$(1-\eta) \left(\frac{LHV_{mass}}{LHV_{mass,CH_4}} \right)^3 = 0.00166 \exp \left(0.317 \frac{U_\infty}{(gV_j)^{1/3} d_o^{1/3}} \right) \quad (\text{Eq. 8.3})$$

where LHV_{mass,CH_4} is the specific lower heating value of methane and is used to normalize this expression. The correlation in Equation 8.3 provides a reasonable fit to the data collected in this study and can be used in a predictive mode to estimate the combustion efficiency of natural gas-based flares for a set of operating conditions (i.e., LHV_{mass} , d_o , V_j , and U_∞). A similar expression for propane and ethane based flares can be found in Chapter 3.

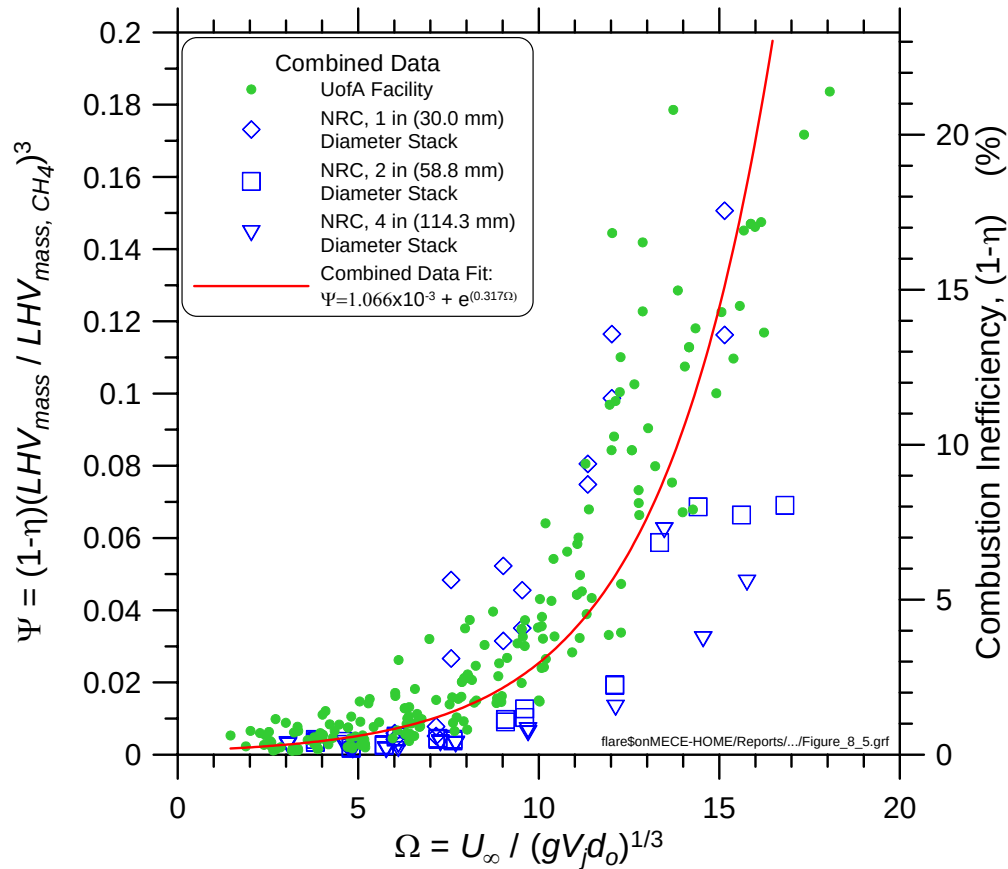


Figure 8.6: Efficiency Data Collected at the UofA and the NRC

It should be noted that there is some systematic variation in the data scatter in Figure 8.6 relative to the diameter of the flare stack. From a strictly empirical perspective, the data can be collapsed modestly better by increasing the dependency of the stack diameter relative to the efficiency to the power of one-half instead of one-third. (The numerical values of the fitting coefficients will of course change if this alternate functional form were adopted.) There is no physical justification for altering the power on d_o and this improvement in fit does not apply to the propane and ethane based flares.

8.3 EFFICIENCY OF HIGHER JET EXIT VELOCITY FLARES

The general characteristics of jet diffusion flames as the exit velocity is increased have long been of interest to combustion researchers in the case of no crosswind [52]. The classical perspective of these flames is that at low exit velocities the flames are laminar and their lengths increase with increasing exit velocity. At critical exit velocities, the upper parts of the flame become distinctly turbulent and the base of the flame lifts off from the rim of the stack. As the exit velocity is increased further, the lift-off height increases and a greater portion of the flame becomes turbulent with relatively little change in the overall height of the flame. The maximum heights of these flames have been reported to be between 80 and 200 stack diameters. It is these lifted highly turbulent jet flames that are briefly examined in this section because they relate to emergency and well-test flares.

These higher exit velocity flares were not studied at the University of Alberta facility since the usable core height of the wind tunnel test section (i.e., the physical height minus the thickness of the upper and lower boundary layers) was too small. This usable core height was approximately one meter and thereby relegating the diameter of higher speed flares to 5 mm or less. This scaled stack wall thickness would have been unacceptably thin for testing purposes.

The size and aspect ratio of the test section of the NRC facility provided the opportunity to examine flares with higher jet exit velocities at a reasonable physical scale. The usable

height of the NRC facility was approximately 5 m and, in practice, could accommodate the 1 m high flare stack with an outside diameter, d_o , of 30 mm. Natural gas flares were tested with exit velocities of 10, 20, and 40 m/s. These flow rates produced lifted jet flames that could be blown away from the stack and thereby extinguished at higher crosswind speeds. To avoid the possibility of blow-off and the dumping of large quantities of raw fuel into the tunnel, testing of these flares occurred at a wind speeds of 3, 3.5, and 4 m/s.

The overall combustion efficiencies of these higher exit velocity flares were calculated by the same process as described above, i.e., using compositional mappings of the flare plume. Table 8.1 shows the results of these experiments. In all cases, the overall combustion efficiencies of these higher exit velocity flares were very high, in excess of 98%.

Table 8.1: Test Results for High Velocity Jets

Outer Diameter	Cross Wind	Jet Exit	Efficiency
d_o , mm	U_∞ , m/s	V_j , m/s	η , %
30.0	3.0	10.0	99.23
30.0	3.5	20.0	98.85
30.0	4.0	40.0	99.11

8.4 CONCLUSIONS

The research results presented in previous chapters were derived from an experimental setup that had physical limitations that constrained testing to flares with sub-scale stack diameters (typically one-quarter scale or less). Though there were no specific expectations that the data derived from these sub-scale flares were not applicable nor scalable to larger diameter flares, it was important to validate the results up to full scale. Therefore, this chapter explored the characteristics and behavior of larger-scale flares for comparison with the results and models derived from the sub-scale flares. The basis of the comparison focused on the evolution of the thermal plume structure and the overall combustion efficiency for natural gas flare streams.

In order to perform these tests a new experimental facility at the National Research Council of Canada was commissioned. The test section of this facility was 6 m high and 3 m wide, which was approximately 5 times taller than the University of Alberta facility and thereby allowed testing of flares with a 114.3 mm outside diameter (full scale). Alternately, smaller diameter flares (i.e., 30 mm outside diameter, d_o) were tested with exit velocities up to 40 m/s to simulate well-test flares.

There was excellent agreement across all scales of flares in terms of the mean thermal plume structures. Comparisons were made qualitatively in terms of plume shape and quantitatively in terms of a characteristic plume dimension. Data across all scales ($18.6 \leq d_o \leq 114.3$ mm) were very consistent with a fluid-mechanics model dominated by the forces associated with the buoyancy of the plume and the momentum of the crosswind.

Comparisons based on combustion efficiency also showed a strong correlation over all the scales tested, though not as good as the mean thermal plume structure. The reasons for the poorer correlation was related to the techniques used to measure combustion efficiency in the National Research Council of Canada facility and the difficulties in maintaining stable conditions (i.e., crosswind) over the long duration of these tests. A semi-empirical model was presented that can be used to predict the overall combustion efficiency of a flare in crosswind. Data collected from the higher exit velocity jets had combustion efficiencies of approximately 99%. Even though these flares were highly efficient, the flames were fully lifted from the flare stack and could potentially be blown off by strong crosswinds.

9 CONCLUSIONS

Conflicting past research results concerning the emissions from flares have made the common practice of solution gas flaring an important environmental issue within Alberta. This previous research described flares as either very efficient or very inefficient and reported that the emissions included a multitude of toxic compounds. One of the goals of the research presented in this report was to reconcile these historically conflicting results through a better understanding of flaring. Rather than focus on specific local conditions, this study focused on the fundamental physical phenomena affecting flaring performance. The research utilized flare stacks modeled as simple vertical pipes that were tested within the confines of a wind tunnel. This experimental setup allowed for the scientific exploration of flaring performance as a set of physical parameters contained within a well-controlled environment. Consequently, the fluid mechanics and the combustion associated with flares were studied in near-uniform and steady crosswinds. These simplifications to the testing environment allowed the research to be generalized to cover a wide range of conditions rather than limited to site-to-site variations that exist in the field. While issues still surround the use of solution gas flaring, this study has expanded and enhanced the general understanding of this topic. The result of this research is a better appreciation of the complexities surrounding this common practice. It is hoped that this understanding will aid industry, regulators, and non-governmental organizations in their decisions regarding the use of flaring.

The approach taken in this research was to experimentally study sub-scale pipe flares in the well-controlled conditions that exist within wind tunnels. Within these wind tunnel environments, the defining parameters of a flaring operation (i.e., wind speed, wind direction, flare stream flow rate, stack size, flare stream composition, etc.) could be specified and varied independently to elucidate the important physical processes occurring around the flare that impact emissions. The two wind tunnels used during this research were located at the University of Alberta (U of A) in Edmonton and at the National Research Council of Canada (NRC) located on the Montreal Road campus in Ottawa.

The University of Alberta Flare Research Facility was developed to study the emissions, the efficiency, and the related fluid mechanics of flares in a crosswind. The centerpiece of the facility was a closed-loop wind tunnel that was capable of testing flares up to 49.8 mm in outside diameter (more typically 24.7 mm) at wind speeds up to 35 m/s. The flares could be supplied with mixtures of natural gas, propane, ethane, carbon dioxide, nitrogen, and liquid droplets. The liquid droplets could be supplied at various sizes and were composed of water, diesel, or octane. The diagnostic equipment used to make measurements of the emissions or to characterize the flow included a suite of on-line gas analyzers, a laser Doppler velocimeter, a hot-wire anemometer, a rake of thermocouples, a pair of fast flame ionization detectors, a laser-based flow visualization system, a particulate sampling system, and a particle size analyzer. Access to gas chromatographic analysis was available through third-party commercial laboratories.

The NRC wind tunnel was developed to conduct experiments on larger-scale flares similar in size to those found in the field. The focus of this research was to address the scalability of the data and models resulting from the U of A facility. The particular areas of interest of the NRC study were the size, shape, and downstream evolution of the thermal plume that were critical to any comparison to the results obtained at the U of A facility. Similarity in plume characteristics insured the consistency of the dominating fluid mechanics and the consistency of the overall combustion efficiency over all scales tested thus allowing conclusions to be made regarding the scalability of the results. The NRC wind tunnel was fitted with state-of-the-art gas analysis equipment and a rake of thermocouples. The tunnel test section was 6 m high, which was approximately 5 times that of the U of A wind tunnel, and was capable of wind speeds up to 39 m/s. This facility was also used to test higher exit velocity flares issuing from sub-scale stacks in order to simulate well-test flares.

As a part of conducting this research several different and novel experimental methodologies were developed. These methodologies included the ability to measure:

- the overall steady state efficiency of flares that do not produce significant amounts of soot of both sub-scale and full-scale flares;

- the overall steady state efficiency of flares that contain liquid droplets and may emit significant amounts of soot;
- the local average efficiency of flares that do not produce significant amounts of soot of both sub-scale and full-scale flares;
- the overall production rate of selected minor compounds (e.g., poly-nuclear aromatic hydrocarbons, aldehydes, etc.) in the vapor phase;
- the overall production rate of selected minor compounds (e.g., poly-nuclear aromatic hydrocarbons, aldehydes, etc.) as part of the particulate (soot) emissions.

Though there are many ways to characterize the overall performance of a flare, this research used the carbon conversion efficiency as the measure of combustion efficiency. This combustion efficiency was defined as the fraction of carbon mass in the fuel of the flare stream that becomes carbon dioxide.

Experiments were conducted on pipe flares in a crosswind over a range of operating conditions. The fuels used were undiluted sale-grade natural gas, technical-grade ethane, or commercial-grade propane, or these same fuels diluted with carbon dioxide or nitrogen by up to 80% by volume. Liquid droplets of either water (mass-mean diameter of 40 - 120 μ m), octane (mass-mean diameter of 4 - 90 μ m), or diesel (mass-mean diameter of 60 - 200 μ m) could be added to the flare stream in quantities up to 32% of the mass of the flare stream. The flares tested included stacks with outside diameters from 12.1 to 114.3 mm, and flare gas exit velocities varied from 0.5 to 4 m/s, though some tests were conducted at exit velocities up to 40 m/s. The wind speed was varied from 1 to 16 m/s.

9.1 COMBUSTION EFFICIENCY OF GASEOUS FLARES

The conclusions drawn in this section relate to gaseous flare streams with the fuel component being composed of methane, ethane or propane, but may also contain inert gases such as nitrogen or carbon dioxide. Exploration of the factors that affect the combustion efficiency showed energy density, wind speed, gas exit velocity, and stack diameter to be the principal variables. Energy density and wind speed are the parameters to which the combustion

efficiency is most sensitive. These flares tend to emit very little or no soot, hence the products of flaring are dominated by the gas phase. The nature and implications of the small amounts of particulate emissions from propane flares are discussed later in this chapter. Attention is restricted here to gas-only systems not because they have significant differences from flare streams containing liquid droplets, but because it allows the specific effects of droplets and particulate emissions to be treated as an added issue.

The measured efficiencies of natural gas, ethane, and propane flares (i.e., flares with relatively high energy densities) at calm and low winds were very high ($< 99.5\%$). With increased wind speed, the efficiency fell slowly and then eventually at high wind speeds there was a dramatic decline in the efficiency. The wind speed where the efficiency rapidly drops depended on the exit velocity of the flare stream, the size of flare stack, and the composition of the flare gases. In all cases, the dependency of efficiency on wind speed was exponential. Reduced energy density flare streams produced very similar results, except that the efficiency in calm conditions did not tend to 100%.

In order to construct a model based on the combustion efficiency data collected, it was necessary to understand the nature and origins of the inefficiencies. The key to this modeling was to identify the dominant fluid-mechanic processes associated with flaring and the specific pathways (i.e., chemical reaction or fluid flow) that are part of the inefficiency mechanism. A multitude diagnostics were used to elucidate these processes and included the following: two-dimensional cross-stream mapping of mean temperature and major species concentration; gas chromatography of the emitted gases; fast flame ionization mapping of hydrocarbons around the flame; and sheet laser imagery along the flow direction to track the flow emitted gases from the flare. The conclusion of these examinations was that the dominant fluid-mechanic forces associated with solution gas flares are the momentum flux of the crosswind and the buoyancy of the combustion products. The inefficiencies result from the emissions of either carbon monoxide (i.e., the partial oxidation of the hydrocarbon fuel) or raw fuel. In the case of raw fuel, the fuel is stripped from the flare stream without any participation in the combustion. At low crosswinds these two sources were of the same order of magnitude, but as the wind speed increased the fraction of raw fuel being stripped rapidly

increased and was the dominant cause of the inefficiency. The pathway that allows the raw fuel to be stripped away from the flame was determined to be driven by a standing vortex on the leeward side of the flare stack. The interaction of this standing vortex with the ring vortices emerging from the stack affects the flame such that packets or bursts of raw fuel could be drawn beneath the flame. Once under the flame, these packets of raw fuel were dispersed into the atmosphere and then measured as the main source of inefficiencies.

One implication of this fuel-stripping mechanism for inefficiency is that the composition of the emitted hydrocarbon depends on the composition of the flare stream. For example, if the fuel in the flare stream is natural gas then methane is the dominant emitted hydrocarbon. This raises issues regarding greenhouse gas emissions since methane has a greater greenhouse effect than carbon dioxide. This fuel-stripping mechanism has implications for flare gases containing H₂S. There is no reason that this stripping mechanism will not apply to the H₂S, and therefore increased inefficiencies will result in shifting the emissions from SO₂ to H₂S.

By considering the ratio of buoyancy flux of the combustion products to the momentum flux of the wind as the important parameter defining the flow, a simple model was proposed to connect the effects of wind speed (U_∞), exit velocity (V_j) and outside stack diameter (d_o). This model resulted in the parameter $U_\infty / (V_j d_o)^{1/3}$, which was successful in collapsing data for each of the different flare stream compositions. This same ratio of forces was also capable of correlating the size of the mean thermal plume downwind of the flare. Unfortunately, this simple model did not capture all of the physics since it was unable to bring the data from different flare streams with different energy densities together. The collected efficiency data was used to produce a semi-empirical relationship that can be used to estimate the efficiency of a flare burning in a crosswind. This relationship is:

$$(1 - \eta) \cdot (\text{LHV}_{\text{mass}})^3 = A \cdot \exp\left(B \frac{U_\infty}{(g V_j d_o)^{1/3}}\right) \quad (\text{Eq. 9.1})$$

where LHV_{mass} is the lower heating value of the flare stream on a mass basis and g is the gravitational acceleration constant. The values of the coefficients, A and B , are as follows: $A = 133.3 \text{ (MJ/kg)}^3$ and $B = 0.317$ for methane-based flares; and $A = 32.06 \text{ (MJ/kg)}^3$ and $B = 0.272$ for propane- and ethane-based flares.

The lower heating value raised to the third power in Equation 9.1 recognizes the sensitivity of lowering the energy density of the flare stream by diluting it with inert compounds. Once the flare stream energy density is reduced below 15 MJ/m^3 , significant inefficiencies result at wind speeds as low as 1 m/s .

Another observation made about flares burning in crosswinds was that the spatial distributions of carbon dioxide, carbon monoxide, and hydrocarbons within the plume were not the same. As a result, the combustion efficiency was not uniform across the plume. Hence, caution must be taken in interpreting the combustion efficiency originating from any single-point measurement since it may not be representative of the overall efficiency of the flare. Results presented here suggest that analyzing the core of the plume around the point of minimum dilution with air has the potential of providing a good estimate of the overall combustion efficiency. The implications of these results for the field sampling of the plumes of flares remain a topic of active research.

9.2 MINOR SPECIES EMISSIONS FROM FLARES

The dominant compounds emitted from hydrocarbon flares are stripped fuel, carbon dioxide and carbon monoxide. While this is generally true, there are instances where some minor species can be emitted. Regarding this issue, selected minor carbon-based species emitted from flares were used to describe the potential toxicity of the products of combustion. The minor species considered included selected poly-nuclear aromatic hydrocarbons (PAHs), cyclic aromatics, and aldehydes. Measurements of these compounds were divided into vapor phase and solid phase (i.e., particulates). For the natural gas and propane flares considered, all of the compounds analyzed in their vapor phase fell below detectable limits of the testing method used. The detectable limits for PAH were estimated to be in the order of $30 \text{ }\mu\text{g/kg}$ of

gas flared, while the detectable limit for the other compound were of the order of 1 mg/kg of gas flared. Natural gas flares did not produce measurable amounts of soot; propane flares produced a measurable, though small, amount of soot. An analysis of the soot showed that these particulates were embedded with several PAHs at measurable levels.

The general conclusion regarding this component of the research was that smoking flares, a visible indication of soot being emitted, need to be avoided. Regulatory agencies and the petroleum industry need to develop appropriate limits for the emission of soot particulates from flares. As well, a reliable and quantitative method is needed to measure the soot emissions from flares in the field in order to verify compliance with these limits.

9.3 EFFICIENCY OF FLARE WITH ENTRAINED LIQUID DROPLETS

The efficiencies of flares containing droplets were consistent with gas-only flares. The efficiency of natural gas-based flares remained strongly dependent on the crosswind speed and the overall energy density of the flare gas. It was observed that the addition of droplets, in the quantities used in this research, had no effect on the flame structures or patterns relative to gas-phase-only flares. The addition of the heavier hydrocarbons, such as octane or diesel, to the flare stream did not result in any emitted soot.

The results showed that water droplets, added to the flare stream, increased the combustion inefficiency proportionate to the amount of water added. In contrast, the addition of fuel droplets resulted in decreased inefficiencies where iso-octane had a greater impact than diesel on a per mass basis. The explanation for these results was found in the energy balance and the dilution effects associated with the various droplet compositions. Water droplets extract energy from the flow in order for evaporation to take place. The addition of these non-reacting vapors to the flare stream results in a flame that is less robust than a gas-phase-only natural gas flare. Therefore, flare streams with water droplets were more susceptible to the mechanisms that create inefficiencies in a crosswind. For combustible droplets, energy is still required for evaporation but the vapors are a fuel that contribute to the total chemical energy being converted to sensible energy at the flame. The energy associated with the

combustion of a fuel far exceeds the energy associated with its evaporation. Therefore, fuel droplets in the flare stream enhance the robustness of combustion and result in reduced inefficiencies.

The effect of altering the size of droplets carried out the stack exit was examined in these experiments. These results showed that if most of the liquid phase was converted to the gas phase before the flame, through evaporation, then the original diameter of the droplets had no influence on the combustion efficiency. In experiments, all of the water and octane droplets fully evaporated prior to the flame and, therefore, there was no observed effect of droplet size on the combustion efficiency. For the larger size diesel droplets, however, a notable portion of these droplets reached the flame intact and resulted in a slight increase in the combustion inefficiency. The size of droplet that will be evaporated prior to reaching the flame is highly dependent on the following factors: the size and luminosity of the flame; the travel time of the droplet between the stack exit and the flame; and the composition of the droplet. Therefore, no recommendation is made regarding an expectable size of droplet that can be emitted from a flare stack without adversely affecting the combustion efficiency.

Though not specifically part of this study, it should be highlighted that any water entrained in the flare stream would likely contain dissolved salts. The products of combustion would therefore likely include vapor-phase acids and chlorinated hydrocarbons. Hence, the issue of liquid droplets being part of the flare stream should not be viewed as an efficiency problem, but in terms of minor species emissions.

9.4 OPERATING FLARES WITHIN LIMITS

The general conclusion of this research was that the combustion efficiency of unassisted solution gas flares could be very high and the emissions of potentially toxic compounds could be very low as long as a few important conditions are observed. These operating conditions are as follows:

- The flare stream being burned must have a relatively high energy density (approximately 20MJ/m³ or higher). Further research on setting an appropriate lower limit for energy

density is required and it is suggested that that limit be based on a yearly averaged efficiency because of the strong dependency that efficiency has on wind speed.

- The flare stack size needs to be designed appropriately for the flow rate of flare gas to maintain a reasonable minimum exit velocity in the order of 1 m/s.
- The composition of the flare stream must have a low propensity to form and emit soot.
- The flare stream must not contain materials that form other toxic compounds (e.g., chlorine in salt water).

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Beetaloo Basin - Groundwater Impact Risk Assessment

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1 Introduction

1.1 Background

Origin Energy is the operating partner for exploration permits EP76, EP98, EP99 and EP117 in the Beetaloo Basin. Combined these permits cover an area of approximately 18,500 km² that is subject to a joint venture agreement between Origin Energy Resources Ltd, Falcon Oil and Gas Ltd and Sasol Ltd. In 2015, as the initial stage of a five year exploration campaign, Origin plans to drill vertical wells on EP98 and EP117 at three sites: Kalala S-1, Amungee NW-1, Beetaloo W-1 (see Figure 1).

CloudGMS was engaged by Origin Energy to prepare a risk assessment to identify specific impacts to the groundwater system associated with the exploration drilling phase of Origin' s 2015 work program.

1.2 Scope

The groundwater risk assessment has the following scope:

- Undertake a qualitative groundwater impact assessment covering the drilling, operation, Diagnostic Fracture Injectivity Tests (DFIT), potential hydraulic fracturing and abandonment phases of Origin' s exploration drilling program.
- Assess potential groundwater level drawdown associated with extraction from water bores used to supply drilling and construction water requirements.
- Assess the likelihood and potential groundwater impact of leakage from mud pit and flare pits used during drilling works.

The groundwater risk assessment prepared by CloudGMS is independent of the broader drilling environmental plan prepared for Origin' s 2015 exploration program by AECOM, 2015.



Figure 1 Proposed locations of exploration wells and associated groundwater supply bores.

2 Groundwater Impact Assessment

2.1 Introduction

Risk is an event that, if it occurs, adversely affects the ability of a project to achieve its objectives. Risk management is the process of identifying risk, assessing risk, and taking steps to reduce risk to an acceptable level. The fundamental steps of risk management are outlined Figure 2 and include:

1. Risk identification
2. Risk impact assessment
3. Risk prioritisation
4. Risk mitigation planning, implementation and progress monitoring



Figure 2 Fundamental steps of risk management (www.mitre.org)

Step 1. Risk Identification

Risk identification is the critical first step of the risk management process. Its objective is the early and continuous identification of risks.

Step 2. Risk Impact or Consequence Assessment

In this step, an assessment is made of the impact each risk event could have on the project objectives. Typically this includes how the event could impact cost, schedule, or technical performance objectives as well as broader project drivers such as political, social and environmental consequences. The impact of a risk is generally assessed using a risk matrix considering the severity of the consequence if the impact occurs and the likelihood of the risk occurring an example of such a matrix is presented below in Figure 3.

Step 3. Risk Prioritization

At this step, the overall set of identified risk events are ordered to derive a most critical to least critical ranking. A major purpose for prioritizing risks is to form a basis for allocating critical resources.

Step 4. Risk Mitigation Planning

This step involves the development of mitigation plans designed to manage, eliminate, or reduce risk to an acceptable level. Risk mitigation plans should involve the continual monitoring of risks and revision to ensure control measures are effectively managing risks.

This report discusses the results of a study to examine the first two steps in the Risk Management process identified above by identifying risks associated with drilling and undertaking a risk impact or consequence assessment of the risks identified.

2.2 Methodology

The groundwater impact assessment aims to identify potential hazards to the local and regional groundwater system resulting from activities directly associated with Origin's 2015 exploration drilling program.

A literature review was completed to establish a list of groundwater impacts associated with shale gas exploration drilling. This review covered Northern Territory, national and international studies and inquiries into shale gas exploration drilling and hydraulic fracturing activities. Sources reviewed include the Hawke Inquiry (Hawke, 2014), RSRAE (2012), CCA (2014), Frogtech (2013), Ecological Australia (2012), API (2009), King (2010), King (2012), King (2013).

Potential groundwater impacts identified from the literature were reviewed in a face to face meeting with the Origin staff responsible for the implementation of the drilling program. The relevance of each risk was reviewed relative to specific geological and hydrogeological conditions expected in the Beetaloo Basin and proposed drilling controls, well construction and abandonment design.

Results from the literature review and face to face meeting informed a qualitative risk assessment of potential groundwater impacts stemming from the exploration drilling program. The risk assessment was completed using the Origin Energy Risk Assessment framework. The consequence and likelihood of each risk were assessed according to the following risk matrix (Figure 3), further detail on likelihood and consequence levels is provided in Appendix A.

		COLOUR RATING		Low	Medium	High	Severe	Extreme
		LIKELIHOOD						
CONSEQUENCE		REMOTE	HIGHLY UNLIKELY	UNLIKELY	POSSIBLE	LIKELY	ALMOST CERTAIN	
	CATASTROPHIC	H	H	S	S	E	E	
	CRITICAL	M	M	H	S	S	E	
	MAJOR	M	M	M	H	S	S	
	SERIOUS	L	M	M	M	H	S	
	MODERATE	L	L	M	M	M	H	
	MINOR	L	L	L	M	M	M	

Figure 3 Origin Risk Matrix

Consequences were considered for three categories: impact to the environment and natural system, social and cultural impacts, and legal impacts (i.e. breach of laws or regulations). The category with the most severe consequence rating was used for the final risk rating. The likelihood of the risk takes into consideration proposed control measures documented in the drilling plan (Origin Energy, 2015a) and Environmental Plan (AECOM, 2015). In some cases a risk will have a number of potential causes (e.g. the risk of groundwater contamination from surface spills of fuel/chemicals can be caused by a breach of storage, spillage during transport to site or leakage during transfer onsite). Where an impact has more than one cause, the risk level has been discussed and assessed for each specific cause.

The groundwater impacts assessed relate to exploration drilling activities planned for the 2015 program (see Section 2.3) with two exceptions. The first exception relates to hydraulic fracturing. There is no hydraulic fracturing program proposed in the 2015 exploration program, however, Origin requested that CloudGMS consider the groundwater risks associated with possible future hydraulic fracture treatments. This assessment is based on conditions at the three drilling sites targeted in the 2015 exploration program. Origin also requested the impact assessment to consider the cumulative risk to groundwater that may occur if a gas resource is identified and developed, specifically the impact of groundwater extraction required for development.

Origin required a more rigorous characterisation of pit leakage and groundwater drawdown risks. The impact assessment for each of these risks is informed by separate modelling investigations which are discussed briefly in section 3 and in more detail in Appendix C and Appendix D.

2.3 Assumptions and Limitations

- The groundwater impact assessment only considers hydrogeological risks, a broader risk assessment that covers all risks associated with the 2015 exploration drilling program can be found in the Drilling Environmental Plan (AECOM, 2015).

- The 2015 exploration activities covered by the risk assessment are the drilling and construction of the three proposed exploration wells, in addition to DFITs and wireline logging. DFITs provide data for fracture stimulation design and reservoir modelling. They involve the injection of fluid - in this program drilling fluid already in the well - into the target formation through a small (approximately 5 cm) perforation in the casing. The fluid is injected under pressure for a short time (minutes) to create a fracture, the injection is then ceased and the pressure in the well is allowed to fall-off naturally. Full detail on the proposed DFIT design and control measures is provided in the Origin Energy internal document "Beetaloo DFIT Campaign - Project Overview".
- The risk assessment is based on and limited to the three proposed drilling sites for the 2015 program (Kalala S-1, Amungee NW-1, Beetaloo W-1). The risk assessment does not cover additional unspecified drilling locations in other areas of the basin where different geological conditions may affect the risk profile.
- For the purpose of this risk assessment groundwater impacts are only considered where they will affect a utilised aquifers or an aquifer containing groundwater with a beneficial use. Beneficial use is defined for this assessment as a groundwater quality less than 10,000 mg/l (the upper limit of water tolerance of cattle (ANZECC, 2000), which represents the main groundwater use in the region). For a list of described aquifers and recorded water quality attributes refer to the Beetaloo Basin Hydrogeological Baseline Study (Fulton and Knapton, 2015).
- The risk assessment directly relies on operational inputs specifically the drilling program plan (Origin Energy, 2015a) and detail provided at the face to face meeting (Origin Energy, 2015). Any risks arising from subsequent variations to these inputs are outside the scope of the assessment.
- The risk assessments relating to DFITs, hydraulic fracturing and the development of the gas resource are general in nature.

2.4 Identified Risks

The literature review identified the following nine potential groundwater impacts relating to Origin's 2015 exploration drilling activities and possible future hydraulic fracture treatments.

- 1) A surface spill of drilling fluids/diesel/stimulation additives/flow back water leads to the contamination of groundwater resources.
- 2) Leakage of drilling fluids/formation water from mud pits/flare pits leads to the contamination of groundwater resources.
- 3) Groundwater extraction required to supply water for the project results in drawdown of water levels which impacts existing groundwater users and/or the environment.
- 4) The loss of drilling fluids into a utilised aquifer leads to localised groundwater contamination and impaired capacity in adjacent groundwater bores.

- 5) Cross flow of groundwater from a utilised aquifer to another formation causes declining groundwater levels leading to impacts on existing groundwater users and/or the environment.
- 6) Exploration drilling enables cross formational flow between shallow aquifers in contravention of Water Act (NT) Regulations.
- 7) Cross flow of water/hydrocarbons/gas from deeper formations to a utilised aquifer results in groundwater contamination.
- 8) Hydraulic fracturing induces seismicity which increases connectivity between formations and enhances the potential for cross flow of water/hydrocarbons/gas.
- 9) The loss of a radioactive source during geophysical logging results in groundwater contamination of a utilised aquifer.

2.5 Risk Impact Assessment

The risk assessment including the likelihood, consequences, assumptions and controls for each of the nine identified impacts is detailed in Appendix B. The following sections provide a summary of the risks and brief discussion of the impact assessment results.

1) SPILL OF FUEL/ADDITIVES/PRODUCED WATER CAUSES GROUNDWATER CONTAMINATION

Assessed Risk Level: LOW

Consequence: Moderate

Likelihood: Remote to Highly Unlikely

There is a risk that surface spillage of mud products/diesel/stimulation additives/flow back water during transport, storage or transfer onsite will lead to the contamination of groundwater resources. This has the potential to impact groundwater users close to the spill site and environmental receptors. Risk causes for surface spills include:

- Vehicle accident during transport leading to an uncontrolled discharge of diesel.
- Leakage from onsite storage due to a tank/storage integrity breach.
- Loss of containment during transfer onsite (e.g. leakage from pipes, hoses, fitting).
- Uncontrolled surface discharge of formation water/hydrocarbons due to well integrity failure.

The risk level of surface spills leading to groundwater contamination for all causes is assessed as low, primarily because of a deep watertable (>60 mBGL) and the presence of thick clay layers between the surface and the watertable aquifer which will impede the downward movement of the spilled fluid. Leakage modelling (see Appendix D) suggests the volumes that can reasonably be expected from a spill/leakage event are insufficient to mobilise fluid and any potential contaminant to the watertable under expected site conditions.

2) LEAKAGE FROM MUD/FLARE PITS CAUSES GROUNDWATER CONTAMINATION

Assessed Risk Level: LOW

Consequence: Moderate

Likelihood: Remote

The leakage of drilling fluids/formation water/hydrocarbons from mud/flare pits during drilling has the potential to contaminate groundwater resources and impact groundwater users and environmental receptors. Identified causes which may result in mud/flare pit leakage include:

- Inadequate storage capacity.
- Storm water ingress.
- Failure of pit liner or pit design.

The risk level of groundwater contamination resulting from mud/flare pit leakage is assessed as low. Leakage modelling (see Appendix D) indicates that with expected site conditions, proposed pond dimensions and drilling timeframes leakage from an unlined mud/flare pit is not predicted to infiltrate further than 30 mBGL and is therefore unlikely to impact the watertable which is in excess of 60 mBGL at the three investigation sites.

This impact assessment is also relevant for leakage from retention ponds storing flow-back water from hydraulic fracturing. However, Origin has advised that flow-back water from hydraulic fracturing will be contained in sealed storage tanks mitigating the risk of retention pond leakage (Origin Energy, 2015).

3) GROUNDWATER EXTRACTION CAUSES DECLINING WATER LEVELS IN UTILISED AQUIFERS

Assessed Risk Level: LOW (Exploration/Development)

Consequence: Serious

Likelihood: Remote (Exploration/Development)

There is potential that groundwater extraction required for road construction/drilling/hydraulic fracturing may lead to a decline in water levels in a utilised aquifer. This may result in impaired capacity (i.e. reduced bore yields) in existing groundwater bores and a reduction in environmental flows in connected springs/rivers.

Groundwater supply bores will most likely be constructed in the Cambrian Limestone Aquifer (CLA). This is a regional aquifer with significant storage capacity. Water level drawdown modelling based on exploration water demand (see Appendix C) suggests that the water level drawdown will be limited to 0.3 m at a distance of 500 m from the project supply bores. The nearest pastoral bore (i.e. bore that is regularly used) is located 4000 m from the proposed supply bore locations. The nearest recorded groundwater dependencies are located over 100 km north of the drilling sites at Mataranka (Fulton and Knapton, 2015). The risk of projected groundwater extraction impacting existing groundwater users or the environment is assessed as low for the exploration program.

Projected water demand under a development scenario is estimated to be in the order of 1000 ML/year during development. While significantly greater than exploration requirements this

volume represents around 1% of estimated annual water availability from the Georgina Basin (NALWTF, 2009). Under a development case Origin intends to implement additional controls such as the use of non-potable water from brackish aquifers (if available), treating and recycling recovered water, and entering into "make good" agreements with existing users (K Horton 2015, pers comm., 28 Aug). Assuming water supply bores are located with a reasonable offset from existing groundwater bores the risk of groundwater extraction impacting on existing users or the environment under a development scenario is also assessed as low.

4) LOSS OF DRILLING FLUIDS INTO AN AQUIFER IMPAIRS CAPACITY IN EXISTING BORES.

Assessed Risk Level: LOW

Consequence: Moderate

Likelihood: Remote

There is a risk that the significant loss of drilling fluid into a utilised aquifer will lead to the local contamination of the aquifer. This may result in impaired capacity in existing groundwater bores near the drilling site. The level of this risk is assessed as low. Significant mud loss is expected in the CLA (Gum Ridge Formation and Anthony Lagoon Beds) due to the presence of cavernous limestone. Drilling of these formations is proposed to be undertaken using air methods (Origin Energy, 2015), mitigating the risk of fluid loss into the CLA. These formations will be isolated with a casing barrier before the drilling method is changed to a mud system for the drilling of deeper formations. In the instance that fluid loss does occur in the CLA the available mud volume is a limiting factor on the dispersion of the drilling fluid into the aquifer. Fluid loss is likely to only occur in the immediate vicinity of the drilling site and is highly unlikely to approach existing bores, the closest of which is a roads bore located 1000 m from the proposed drilling locations.

5) CROSS FLOW OF WATER FROM A UTILISED AQUIFER TO ANOTHER FORMATION CAUSES DECLINING WATER LEVELS

Assessed Risk Level: LOW

Consequence: Serious

Likelihood: Remote

There is a risk that uncontrolled cross flow of groundwater from a utilised aquifer to another formation/s could lead to declining groundwater levels. This may result in impaired capacity (i.e. reduced bore yields) in existing groundwater bores and a reduction in environmental flows in connected springs/rivers. Likely causes of groundwater cross flow include:

- Wellbore failure due to incomplete cement placement or casing failure during operation or post abandonment.
- The breach of aquitard layers by hydraulic fracture propagation.

The magnitude of any potential cross flow is dependent on the relative permeability of the aquifer and the formation receiving the flow and also the pressure gradient between the two formations. The potential for migration of groundwater from the main regional aquifer (CLA) to deeper formations is limited by:

- The low permeability of the deeper formations.
- An upward pressure gradient between deep formations and the CLA (Fulton and Knapton, 2015)

These factors suggest that any drawdown response resulting from cross flow will be localised and is unlikely to result in a water level decline that will affect existing users/environmental dependencies. The level of this risk is assessed as low.

6) EXPLORATION DRILLING ENABLES CROSS FORMATIONAL FLOW BETWEEN SHALLOW AQUIFERS IN CONTRAVENTION OF WATER ACT REGULATIONS.

Assessed Risk Level: HIGH

Consequence: Serious

Likelihood: Likely

There is potential that incomplete casing/cementing of shallow utilised aquifers will allow cross formational flow. This will contravene Water Act (NT) regulations, which require effective isolation of multiple aquifers to prevent cross formational flow. Assuming there is a contrast in water quality between the aquifers and a driving pressure gradient, potential also exists for the deterioration in groundwater quality, which in turn could impact existing groundwater users and/or environmental dependencies.

The risk that incomplete casing/cementing of shallow aquifers will allow cross formational flow in contravention of Water Act (NT) regulations is assessed as High for drilling site Beetaloo-W1 where multiple aquifers (basal Cretaceous Sandstone, Anthony Lagoon Beds, Gum Ridge Formation) are expected. The risk is lower at the northern well sites (Amungee-NW1, Kalala-S1) where the Gum Ridge Formation is the only expected aquifer above the proposed surface casing shoe. The High risk level specifically relates to legal/regulatory implications, the consequence level for environmental and community impact is assessed as medium – see Appendix B for further detail.

7) CROSS FORMATIONAL FLOW FROM DEEPER FORMATIONS TO A UTILISED AQUIFER RESULTS IN GROUNDWATER CONTAMINATION.

Assessed Risk Level: LOW to MEDIUM

Consequence: Serious

Likelihood: Remote to Unlikely

There is potential that the cross formational flow of water/hydrocarbons/gas from deeper formations to a utilised aquifer will result in groundwater contamination and impact existing users and environmental dependencies. Possible causes leading to cross-formational flow include:

- Well failure due to incomplete cement placement or casing failure during operation or post abandonment
- Blow out during drilling causes annular leakage
- Breach of aquitard by hydraulic fracture propagation
- Hydraulic fracturing opens pathway through an abandoned exploration well
- Leakage along faults intersected by drilling or induced fracturing

The level of risk associated with cross formational flow leading to groundwater contamination is assessed as Low to Medium for the range of risk causes (see Appendix B for further detail).

The risk of well failure is mitigated by the exploration well design. Utilised aquifers will be isolated from producing formations by a triple barrier of cemented casing (surface casing, intermediate casing and production casing). Aquitards separating utilised aquifers from fracture targets are of significant thickness (100s metres) in the Beetaloo basin (Fulton and Knapton, 2015). The combined aquitard thickness at the well sites is significantly greater than the potential fracture growth resulting from hydraulic fracturing. The 2015 well sites are also located away from major structural zones where most significant faulting occurs limiting the risk of leakage along existing faults.

8) HYDRAULIC FRACTURING INDUCES SEISMICITY INCREASING CONNECTION BETWEEN FORMATIONS AND ENHANCING THE POTENTIAL FOR CROSS FORMATIONAL FLOW

Assessed Risk Level: LOW

Consequence: Serious

Likelihood: Remote

There is a risk that hydraulic fracturing induces local seismicity leading to greater connection between deeper formations and utilised aquifers. This may enhance the potential for cross formational flow of saline groundwater/hydrocarbons/gas causing groundwater contamination in utilised aquifers and impacting existing groundwater users and environmental dependencies.

The pressure exerted in hydraulic fracture stimulations is not sufficient to induce seismicity of a magnitude capable of deforming the volume of rock (> 1500 m, Origin Energy, 2015a) separating the target formation and utilised aquifers. Most induced seismicity associated with fracture stimulation is microseismicity. Larger events are very uncommon and are generally associated with pre-stressed faults (RSRAE, 2012). The proposed well locations for the 2015 program are located in relatively undeformed regions of the Beetaloo Basin, reducing the likelihood that drilling and potential hydraulic fracturing will intersect pre-stressed faults.

9) THE LOSS OF A RADIOACTIVE SOURCE DURING GEOPHYSICAL LOGGING RESULTS IN GROUNDWATER CONTAMINATION.

Assessed Risk Level: LOW

Consequence: Moderate

Likelihood: Remote

There is a risk that during wireline logging a radioactive source could be lost leading to groundwater contamination of a utilised aquifer with potential impacts on existing groundwater users and the environment. The loss of a radioactive source is likely to be associated with the tool becoming stuck and the wireline cable breaking during logging.

Wireline logging in the exploration wells is only proposed for the lower formations. This will occur after shallow utilised aquifers are sealed with a cemented casing string. Wireline tools are less likely to become stuck in a cased section of the well. The cemented casing will also isolate water supply aquifers from any contamination in the event a tool is lost while logging the deeper formations.

3 Detailed risk assessment studies

3.1 Groundwater drawdown impact assessment

3.1.1 Introduction

To investigate the likely impacts of groundwater extraction from the Cambrian Limestone Aquifer (CLA) during the construction phase of the exploration wells, drawdown studies were conducted to examine the probable magnitude and extent using a Monte Carlo approach and analytical methods.

A full description of the drawdown assessment is provided in Appendix C and is summarised below.

3.1.2 Methodology

The likely range of hydraulic parameters (transmissivity and storage) for the CLA were determined from available information. The range of hydraulic parameters were then used to define probability distributions function (PDF) for both transmissivity and storage parameters. The drawdown at increasing distance from the pumping well was then calculated after a period of 60 days using a random combination of transmissivity and storage generated from the PDF for 10000 different realisations.

3.1.3 Results

The results from the drawdown analysis suggest that for the scheduled drilling duration of 60 days that there was a 50% probability of a drawdown of less than 0.3m at distances greater the 500 metres from the pumping bore and there was a 95% probability of a drawdown of less than 0.6m at distances greater the 500 metres from the pumping bore.

3.2 Drilling fluid leakage risk assessment

3.2.1 Introduction

This section discusses the results of a study to examine the leakage that could be expected from the unlined mud pit and flare pits used during the drilling phase of the exploration well construction. A full description of the drilling fluid leakage assessment is provided in Appendix D.

3.2.2 Methodology

Unsaturated parameters were derived from soil and water bore lithological logs in the vicinity of the proposed exploration wells. Based on the bore information two base cases were identified as representative and leakage from basins investigated.

3.2.3 Results

Generally it was found that due to the retention properties and capacity of the soils to store moisture, the infiltrated water did not migrate further than approximately 30 metres below surface.

4 Conclusions

The principal groundwater aquifer (CLA) underlying the exploration sites is an extensive, regional aquifer. Generally, groundwater impacts resulting from the exploration activities are expected to be reasonably isolated and localised due to the deep watertable (> 60m), overlying unsaturated clay layers, underlying regional aquitards and large storage capacity of the CLA.

The groundwater risk assessment identified nine potential impacts to groundwater system in the Beetaloo basin associated with Origin's 2015 exploration drilling program. These impacts are ranked below according to the assessed risk level.

HIGH

- Exploration drilling enables cross formational flow between shallow aquifers in contravention of Water Act regulations.

MEDIUM

- Cross formational flow of formation water/hydrocarbons from deeper formations to a utilised aquifer causes groundwater contamination and impacts existing groundwater users.

LOW

- Spill of fuel/additives/produced water causes groundwater contamination.
- Leakage from mud/flare pits causes groundwater contamination.
- Groundwater extraction causes declining water levels in utilised aquifers which impacts on existing groundwater users/environmental values.
- Loss of drilling fluids into an aquifer impairs capacity in existing bores.
- Cross flow of water from a utilised aquifer to another formation causes declining water levels.
- The loss of a radioactive source during geophysical logging results in groundwater contamination.
- Hydraulic fracturing induces seismicity increasing connection between formations and enhancing the potential for cross formational flow.

More extensive investigations utilising groundwater modelling techniques were undertaken to assess the likelihood of water level drawdown impacting existing groundwater users and leakage of drilling fluids from drilling pits contaminating the watertable aquifer.

The drawdown assessment found that it is unlikely that significant drawdown will result due to groundwater abstraction from the CLA system for exploration well construction. This extraction poses a low risk to other users with respect to reducing yields of adjacent pastoral bores.

The drilling fluid leakage modelling found that the likelihood of groundwater contamination resulting from surface spillage is low when taking into consideration the water table depth (>60 m),

the retention properties of subsurface clay layers, spill volumes, timeframe for spill containment / remediation and existing controls.

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Appendix A Origin Risk Matrix

Table A—1 Risk matrix risk likelihood description

		COLOUR RATING					
		Low	Medium	High	Severe	Extreme	
		LIKELIHOOD					
CONSEQUENCE		REMOTE	HIGHLY UNLIKELY	UNLIKELY	POSSIBLE	LIKELY	ALMOST CERTAIN
	CATASTROPHIC	H	H	S	S	E	E
	CRITICAL	M	M	H	S	S	E
	MAJOR	M	M	M	H	S	S
	SERIOUS	L	M	M	M	H	S
	MODERATE	L	L	M	M	M	H
	MINOR	L	L	L	M	M	M
		1 REMOTE <1% chance of occurring within the next year. Occurance requires exceptional circumstances. Exceptionally unlikely event in the long term future. Only occur as a 100 year event	2 HIGHLY UNLIKELY >1% chance of occurring within the next year. May occur but not anticipated. Could occur years to decades	3 UNLIKELY >5% chance of occurring within the next year. May occur but not for awhile. Could occur within a few years	4 POSSIBLE >10% chance of occurring within the next year. May occur shortly but a distinct probability it won't. Could occur within months to years.	5 LIKELY >50% chance of occurring within the next year. Balance of probability will occur. Could occur within weeks to months.	6 ALMOST CERTAIN 99% chance of occurring within the next year. Impact is occurring now. Could occur within days to weeks.

Table A—2 Risk matrix consequence categories

	Natural environment	Community damage/impact/social/cultural heritage	Breach of law or criminal prosecution or civil action (eg. OHS, environment, industrial relations, trade practices, industry acts)
Catastrophic - 6	Long term destruction of highly significant ecosystem or very significant effects on endangered species or habitats.	Multiple community fatalities, complete breakdown of social order, irreparable damage of highly valued items or structures of great cultural significance.	Potential jail terms for executives and or very high fines for the Company. Prolonged multiple litigations.
Critical - 5	Major offsite release or spill, significant impact on highly valued species or habitats to the point of eradication or impairment of the ecosystem. Widespread long-term impact.	Community fatality. Significant breakdown of social order. Ongoing serious social issue. Major irreparable damage to highly valuable structures/ items of cultural significance.	Very significant fines and prosecutions. Multiple prosecution and fines.
Major - 4	Offsite release contained or immediately reportable event with very serious environmental effects, such as displacement of species and partial impairment of ecosystem. Widespread medium and some longterm impact.	Serious injury to member of the community, Widespread social impacts. Significant damage to items of cultural significance.	Major breach of regulation and significant prosecution including class actions.
Serious - 3	Moderate effects on biological or physical environment and serious short term effect to ecosystem functions.	Media attention and heightened concerns by local community and criticism by NGOs. Ongoing social issues. Permanent damage to items of cultural significance.	Serious breach of law/regulation with investigation or report to authority with possible prosecution. Performance Infringement Notice (PIN)
Moderate - 2	Event contained within site. Minor short term damage to area of limited significance. Short term effects but not affecting ecosystem functions.	Medical treatment injury to a member of the community, Minor adverse local public or media attention and complaints. Minor medium term social impact on local population, mostly repairable.	Breach of law/regulation or non-compliance. Minor legal issues, minor litigation possible.
Minor - 1	Minor consequence, local response. No lasting effects. Low level impacts on biological and physical environment to an area of low significance.	Public concern restricted to local complaints, low level repairable damage to common place structures.	Local investigation, minor breach of regulation, on the spot fine or technical noncompliance. Prosecution unlikely.

Appendix B Groundwater Impact Risk Assessment

RISK IDENTIFICATION													COMMENT	
RISK IDENTIFICATION				CONSEQUENCES	POTENTIAL EXPOSURE	CONSEQUENCE CATEGORY			EXISTING CONTROLS		RA			
Risk ID	Risk Title <i>There is a chance that...</i>	Phase of Works	Risk Causes <i>Because...</i>	Consequences <i>(This will mean ...)</i>	Assumptions	Community	Environment	Legal	Control Title	Control Type	Consequence	Likelihood		Assessed Level of Risk
1	Spillage of mud products/diesel/stimulation additives/flow back water during transport, storage or transfer onsite leads to the contamination of shallow groundwater resources	Exploration DFIT Hydraulic Fracturing Development/Production	1) Vehicle accident during transport leads to uncontrolled discharge of diesel	Contamination of shallow aquifers by flowback/formation water impacts existing groundwater users and environmental dependencies	- Relatively shallow groundwater occurrence - Unsaturated zone sediments are permeable and provide pathway to watertable aquifer	2 - Moderate	2 - Moderate		Oil Pollution Emergency Plan NT-2050-15-MP-004	Corrective	2 - Moderate	1 - Remote	LOW	Refer to leakage modelling results for assessment of likelihood of impact from spill Likelihood of groundwater contamination resulting from surface spillage is low when taking into consideration watertable depth, spill volumes and existing controls
			2) Leakage due to tank/storage integrity breach			2 - Moderate	2 - Moderate		Oil Pollution Emergency Plan NT-2050-15-MP-004	Corrective	2 - Moderate	2 - Highly Unlikely	LOW	
			3) Loss of containment during transfer onsite (leakage from pipes, hoses, fittings etc)			2 - Moderate	2 - Moderate		Oil Pollution Emergency Plan NT-2050-15-MP-004	Corrective	2 - Moderate	2 - Highly Unlikely	LOW	
			4) Uncontrolled surface discharge of formation water/hydrocarbons due to well integrity failure			2 - Moderate	2 - Moderate		Blow-out protection/flare pit Oil Pollution Emergency Plan NT-2050-15-MP-004	Preventative Corrective	2 - Moderate	2 - Highly Unlikely	LOW	
2	Leakage of drilling fluids/flow back/formation water from mud pits/flare pits/retention ponds	Exploration DFIT Hydraulic fracturing Development/Production	1) Inadequate storage capacity in mud/flare pits 2) Storm water ingress 3) Failure of pit liner/design	Contamination of shallow aquifers by flowback/formation water impacts existing groundwater users and environmental dependencies	- Drilling program uses open mud pit system.	2 - Moderate	2 - Moderate		Oil Pollution Emergency Plan NT-2050-15-MP-004	Detective Corrective	2 - Moderate	1 - Remote	LOW	Refer to leakage modelling results for assessment of likelihood of impact from spill. Risk only relates to mud pits and flare pits as flowback fluids will be stored in sealed tanks Classed as unlikely given possibility that in future works Orign workplan might approach the wet season and possibility of storm water ingress increases substantially
3	Groundwater extraction for the project impacts on existing users and/or environmental values	Exploration	Groundwater extraction for project activities causes the decline of groundwater levels in the Cambrian Limestone Aquifer (CLA)	1) Pastoral groundwater bores suffer impaired capacity (i.e. reduced bore yields) 2) Reduced environmental flows in connected springs/rivers	- Groundwater from the CLA is used to supply the project	2 - Moderate	3 - Serious		Groundwater level and use monitoring (NT-2050-15-MP-0011) Response to observed change in accordance with follow-up framework	Detective	3 - Serious	1 - Remote	LOW	Consequence of impacting ecosystems in Roper River is significant, however, likelihood of this occurring is remote considering the expected production volumes, the large storage in the regional aquifer, distance from the discharge points and risk controls (water re-use, targeting brackish groundwater from alternative aquifers)
		Development/Production				2 - Moderate	3 - Serious		Groundwater level and use monitoring (NT-2050-15-MP-0011) Response to observed change in accordance with follow-up framework	Detective	3 - Serious	1 - Remote	LOW	
4	Significant loss of drilling fluids into utilised aquifer	Exploration Development	Intersection of cavernous rocks during drilling with mud system	Local contamination of utilised aquifer may lead to impaired water quality or capacity in pastoral bores	- Cambrian Limestone Aquifer is drilled with mud system	1 - Minor	2 - Moderate		Drilling through CLA completed using air system	Preventative	2 - Moderate	1 - Remote	LOW	Drilling through CLA is proposed to be undertaken with mud balanced air methods rather than mud system. This mitigates the risk of mud/fluid loss into cavernous sections of the CLA

RISK IDENTIFICATION														
RISK IDENTIFICATION				CONSEQUENCES	POTENTIAL EXPOSURE	CONSEQUENCE CATEGORY			EXISTING CONTROLS		RA			COMMENT
Risk ID	Risk Title <i>There is a chance that...</i>	Phase of Works	Risk Causes <i>Because...</i>	Consequences <i>(This will mean ...)</i>	Assumptions	Community	Environment	Legal	Control Title	Control Type	Consequence	Likelihood	Assessed Level of Risk	
5	Cross flow of groundwater from a utilised aquifer to another formation results in drawdown of water levels	Exploration DFIT Hydraulic Fracturing Development Abandonment	1) Wellbore failure due to incomplete cement placement or casing failure during operation or post abandonment 2) Breach of aquitard by hydraulic fracture propagation	1) Pastoral groundwater bores suffer impaired capacity (i.e. reduced bore yields) 2) Reduced environmental flows in connected springs/rivers	- Lack of zonal isolation extends continuously between zones - Differential pressure between zones	1 - Minor	1 - Minor		1) Drilling Program Design (NT-2050-35-TR-0001) 2) Beetaloo DFIT Campaign Project Overview 3) Stimulation Design	Preventative	3 - Serious	1 - Remote	LOW	Highly dependant on relative permeability of formations and pressure difference between formations. Any drawdown response is likely to be very localised and not affect existing users/environmental dependencies
6	Cross flow of groundwater between shallow aquifers results in deterioration of water quality in utilised aquifer	Exploration Development/production Abandonment	Incomplete cementing and casing of shallow aquifers provides pathway for cross-formational flow	Deterioration in water quality in aquifer may impact existing groundwater users and environmental dependencies	- Multiple shallow aquifers at drill site - Aquifers have contrasting water quality - Differential pressure between aquifers enables migration of groundwater from poorer quality to better quality aquifer	2 - Moderate	2 - Moderate	3 - Serious	Drilling Program Design (NT-2050-35-TR-0001)		3 - Serious	5 - Likely	HIGH	Failure to isolate separate aquifers will breach water act regulations. This is considered highly likely in the centre and south of basin where there are multiple shallow aquifers (Cretaceous/Anthony Lagoon Beds/Gum Ridge) which are proposed in well design to be sealed by a single run of cemented surface casing.
7	Cross-formational flow of water/hydrocarbons/gas from deeper formations to utilised aquifer results in contamination of utilised aquifer	Exploration DFIT Hydraulic Fracturing Development/production Abandonment	1) Wellbore failure due to incomplete cement placement or casing failure during operation or post abandonment	Deterioration in water quality in utilised aquifer impacts existing groundwater users and affects environmental dependencies (springs, ecosystems).	- Lack of zonal isolation extends continuously between formations - Differential pressure between formations - Abandoned exploration bore has compromised construction - Intersected faults extend through aquitard	3 - Serious	2 - Moderate		Drilling Program Design (NT-2050-35-TR-0001)	Preventative	3 - Serious	3 - Unlikely	MEDIUM	Risk mitigated by well design, utilised aquifers isolated from producing formations by triple barrier of cemented casing (surface casing, intermediate casing and production casing)
			2) Blow out during drilling causes annular leakage			3 - Serious	2 - Moderate		1) Drilling Program Design (NT-2050-35-TR-0001) 2) Blow out protectors/flare pits	Preventative	3 - Serious	1 - Remote	LOW	Uncontrolled flow into shallow aquifer considered highly unlikely as utilised aquifers will be isolated by surface casing before gas bearing formations are drilled
			3) Breach of aquitard by hydraulic fracture propagation			3 - Serious	2 - Moderate		1) Beetaloo DFIT Campaign Project Overview 2) Stimulation design	Preventative	3 - Serious	1 - Remote	LOW	Aquitards separating utilised aquifers from fracture targets are of significant thickness (100s metres) in Beetaloo basin. Thickness of aquitards significantly exceeds extent of recorded fracture propagation
			4) Hydraulic fracturing opens pathway through abandoned exploration well			3 - Serious	2 - Moderate		1) Beetaloo DFIT Campaign Project Overview 2) Stimulation design	Preventative	3 - Serious	1 - Remote	LOW	Very few abandoned wells in the Beetaloo Basin and none in the immediate vicinity of Origins planned works
			5) Leakage along faults intersected by drilling or induced fracturing			3 - Serious	2 - Moderate		1) Drilling Program Design (NT-2050-35-TR-0001) 2) Beetaloo DFIT Campaign Project Overview 3) Stimulation design	Preventative	3 - Serious	3 - Unlikely	MEDIUM	Planned holes located away from major structural zones where most significant faulting occurs. Fault intersections are identified during fracture stimulation by leak-off and stage of fracturing will be abandoned ceasing fracture propagation
8	Induced seismicity leads to greater connection between deeper formations and utilised aquifers	DFIT Hydraulic Fracturing	Hydraulic fracturing induces local seismicity	Change in flowpaths and aquifer interconnection leads to flow of groundwater between formations and results in contamination of utilised aquifer and impacts on existing pastoral use and environmental dependencies	- Lack of zonal isolation extends continuously between zones - Differential pressure between zones - High permeability in deeper zone - Poorer water quality in deeper zones	3 - Serious	3 - Serious		1) Beetaloo DFIT Campaign Project Overview 2) Stimulation Design	Preventative	3 - Serious	1 - Remote	LOW	Seismic event of magnitude sufficient to deform existing geology structures/pathways and induced by hydraulic fracturing is unprecedented and likelihood is considered extremely remote
9	Loss of radioactive source in utilised aquifer during logging results in contamination of aquifer	Exploration Development	Logging tool becomes stuck in hole Logging cable breaks	Localised contamination of utilised aquifer with radioactive source impacts ability of existing groundwater users to exploit the resource	- Radioactive source on the logging string when the tool becomes stuck	2 - Moderate	2 - Moderate		1) Well Design (NT-2050-35-TR-0001) 2) Logging procedure	Preventative	2 - Moderate	1 - Remote	LOW	Utilised aquifers will be isolated with casing before wire-line logging is undertaken, in the event of cable breakage any radioactive source will most likely be lost in deeper, non-potable formations which are the target for logging operations.

Appendix C Construction water supply drawdown risk assessment

C.1 Background

C.1.1 Objective

The objectives of the drawdown assessment were to:

- Assess the likely magnitude and extent of groundwater level drawdown in the water table aquifer resulting from extraction at construction supply bores located near each of Origin's proposed exploration well sites; and
- Identify bores that may be impacted by the groundwater abstraction.

C.1.2 Scope

The scope of the drawdown modelling exercise was confined to the following tasks:

- Determine the likely range of hydraulic parameters in the vicinity of the three proposed exploration wells;
- Determine the volume and duration of pumping based on the supplied information for three bores;
- Estimate the drawdown versus distance from the pumping well at selected times for the range of hydraulic parameters; and
- Identify any landholder bores that fall within the zone of influence of the construction supply bores.

To demonstrate the effects of the groundwater abstraction outputs from the modelling will include:

- Distance drawdown graphs displaying the minimum and maximum expected drawdown scenario and radial distance from the production bore.
- Local scale water level drawdown maps showing the modelled cone of depression (minimum and maximum) around each supply well at the end of development year 1 (2015) and year 2 (2016).
- The water level drawdown maps will also identify any landholder bores that fall within the zone of influence of the construction supply bores.

C.1.3 Assumptions and limitations

- The assessment assumes a continuous pumping rate based on the average water demand;

- The drawdown analysis will not consider the cumulative drawdown resulting from the operation of landholder bores or interference resulting from the simultaneous pumping of multiple construction supply bores.

C.1.4 Model confidence level classification

The groundwater model presented is deemed to be Class 1 using the classification presented by Barnett et al (2012). A Class 1 model is suitable for understanding groundwater flow processes under various hypothetical conditions, and developing coarse relationships between groundwater extraction locations and rates and associated impacts.

Based on the objectives of the modelling study a Class 1 confidence level is considered appropriate.

C.2 Methodology

The drawdown modelling was undertaken using analytical methods based on conventional pumping test solutions (i.e. Theis solution). The drawdown from three separate extraction bores was modelled, this assumes that a maximum of one supply bore is required for each exploration well and an exploration scenario with three wells drilled in 2015.

The permeability and storage parameters were sourced from the baseline hydrogeological assessment (Fulton and Knapton, 2015). There is a reasonable level of uncertainty in the range of hydraulic parameters due to the limited number of studies on the aquifers in the Gum Ridge and Anthony Lagoon Beds. The hydraulic parameters of these formations are poorly constrained and a probabilistic approach using Monte Carlo simulation methods has been applied to characterise the likely range of drawdowns.

C.2.1 Monte Carlo simulations

Monte Carlo simulation is a versatile method for analysing the behavior of an activity, plan or process that involves uncertainty. Its core idea is to use random samples of parameters or inputs to explore the behavior of a complex system or process.

In groundwater modelling, Monte Carlo simulation is typically used to describe a method for propagating (translating) uncertainties in model inputs into uncertainties in model outputs (results). Hence, it is a type of simulation that explicitly and quantitatively represents uncertainties. Monte Carlo simulation relies on the process of explicitly representing uncertainties by specifying inputs as probability distributions. If the inputs describing a system are uncertain, the prediction of future performance is necessarily uncertain. That is, the result of any analysis based on inputs represented by probability distributions is itself a probability distribution.

In Monte Carlo simulation, the entire system is simulated a large number of times (e.g., 10000). Each simulation is equally likely, referred to as a realization of the system. For each realization, all of the uncertain parameters are sampled (i.e. a single random value is selected from the specified distribution describing each parameter). The system is then simulated through time (given the particular set of input parameters) such that the performance of the system can be computed. This

results in a large number of separate and independent results, each representing a possible “future” for the system (i.e. one possible path the system may follow through time). The results of the independent system realizations are assembled into probability distributions of possible outcomes. As a result, the outputs are not single values, but probability distributions.

C.2.2 Analytical model

The Monte Carlo analysis was conducted using the Theis equation (Theis, 1935). The solution is for a confined aquifer enabling the drawdown to be estimated using the pumping rate Q , transmissivity T and the storage coefficient S of the aquifer.

$$s = \frac{Q}{4\pi KD} \int_u^{\infty} \frac{e^{-y} dy}{y} = \frac{Q}{4\pi KD} W(u)$$

$$u = \frac{r^2 S}{4KDt}$$

where

s = the drawdown in m measured in a piezometer

r = the distance of a piezometer from the well in metres

Q = the constant well discharge in m³/d

KD = the transmissivity (T) of the aquifer in m²/d

S = the dimensionless storage coefficient of the aquifer

t = the time in days since pumping started

$W(u)$ = is the Theis well function and is approximated by:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \dots$$

The Theis equation was coded into an executable that generated multiple realisations using the probability distributions detailed above in . The results were output in the form of a text file suitable for analysis in Excel and displayed using Grapher 11 (Golden Software, 2015).

C.3 Site characteristics

C.3.1 Bore locations

The locations of three bores to be used construction bores associated with the drilling of the exploration wells are based on the information from Origin Energy (Origin, 2015) identifying the co-ordinates of the proposed exploration wells. The locations of the exploration wells are tabulated below in Table C—1 and presented above in Figure 1. The construction water supply bores are assumed to be within close proximity to each of the exploration wells.

Table C—1 Proposed locations of the exploration wells.

Well ID	Easting	Northing	Nearest bore	Distance (metres)
Amungee NW-1	380808	8192693	RN005844	4000
Beetaloo W-1	368312	8106695	RN004882	6600
Kalala S-1	351740	8198029	RN005942	1000

Datum = GDA94, Projection = MGA Zone 53

C.3.2 Pumping schedule and water demand

It is expected that groundwater extraction bores will be constructed at each site to produce sufficient quantities of water for drilling of the exploration well, camp operations and civil construction: (AECOM, 2015). The anticipated volumes of water for each component are:

- 0.5 ML per exploration well for drilling (AECOM, 2015);
- 0.6 ML per site for camp operations based on 200L/person/day @ 60 days (AECOM, 2015);
- 10 ML max per site is expected for civil works (A Moser 2014, pers comm., 3 Dec);

This equates to approximately 11.1 ML per site. Assuming a 60 day timeframe for each well, this is equivalent to a continuous rate of 2 l/s.

If hydraulic fracturing is undertaken then:

- A maximum of 4.8 ML per site is required for fracture stimulation (A Moser 2014, pers comm., 3 Dec).

This gives a total demand of approximately 15.9 ML per site. Assuming a 60 day timeframe for the drilling and construction of each well, this is equivalent to a continuous rate of 3 l/s.

C.3.3 Hydraulic parameters

The location of the water bores proposed covers a large area and the hydraulic properties of the aquifer are expected to vary between sites.

C.3.3.1 Transmissivity

Transmissivity values determined from available pumping tests are relatively sparse throughout the Beetaloo Basin. Pumping tests are available for seven bores along the Carpentaria Highway, four of these tests were conducted on bores in the vicinity of the northern sites (Amungee NW-1 and Kalala S-1). The estimated transmissivities range from 300 to 3400 m²/d.

A pumping test was conducted near the southern site (Beetaloo W-1) at Jingaloo Outstation (Karp, 1985) and three pumping tests have been conducted approximately 50 km to the south of the proposed site. The estimated transmissivities are greater than 300 m²/d and generally greater than 1000 m²/d.

This would suggest transmissivity is relatively high with minimum likely value of around 300 m²/d, maximum greater than 3000 m²/d and a median value of around 1000 m²/d.

C.3.3.2 Storage coefficient

Previous water balance methods and groundwater modelling of the Cambrian Limestone Aquifer (CLA) system indicate the system behaves regionally as an unconfined system with specific yields of approximately 0.01 to 0.04 (Jolly, 2002; Jolly et al., 2004; Knapton, 2006). However, available pumping test data for the CLA within the study area suggests that, over the shorter timeframe of the pumping tests, the local system behaves as a confined to semi-confined system. Assuming confined to semi-confined conditions exist will result in an over estimate of the final drawdown calculated at each site.

The range, mean and expected standard deviation for the log transformed transmissivity and storage coefficients are presented below in Table C—2.

Table C—2 Hydraulic parameter probability distribution properties.

SITE	Log T			S		
	Range	Mean	Std Dev.	Range	Mean	Std Dev.
1	2 - 4	2.8	0.25	1e-03 – 1e-05	2e-04	5e-04
2	2 - 4	2.8	0.25	1e-03 – 1e-05	2e-04	5e-04
3	2 - 4	2.8	0.25	1e-03 – 1e-05	2e-04	5e-04

C.3.4 Hydraulic parameter uncertainty

The hydraulic parameters that are to be changed during the analysis (i.e. transmissivity and storage coefficient) are assumed to be either normally or log-normally distributed.

Material properties that are directly related to hydraulic conductivity appear to have a log-normal distribution (Neuman, 1982) and this is true of transmissivities. On the other hand, the distribution of porosities is usually regarded to exhibit a normal distribution. Assuming that hydraulic conductivity is an exponential function of porosity as suggested by some empirical formulas, then a normal distribution of porosities implies that the distribution of hydraulic conductivities must be log-normal (Neuman, 1982).

C.3.4.1 Transmissivity

The average transmissivity has been assigned a value of 600 m²/d, which is lower than the likely T of around 1000 m²/d as suggested from available pumping test data and is therefore considered a conservative estimate. The probabilistic approach to the modelling does investigate the higher transmissivity values.

C.3.4.2 Storage coefficient

Based on the discussion above the storage coefficient has been assumed to be normally distributed with a mean of 0.0002 and a standard deviation of 0.0005 this provides a distribution that spans the observed values where p5 is approximately 0.00005 and p95 is approximately 0.001, which is considered to be representative of the confined / semi-confined CLA.

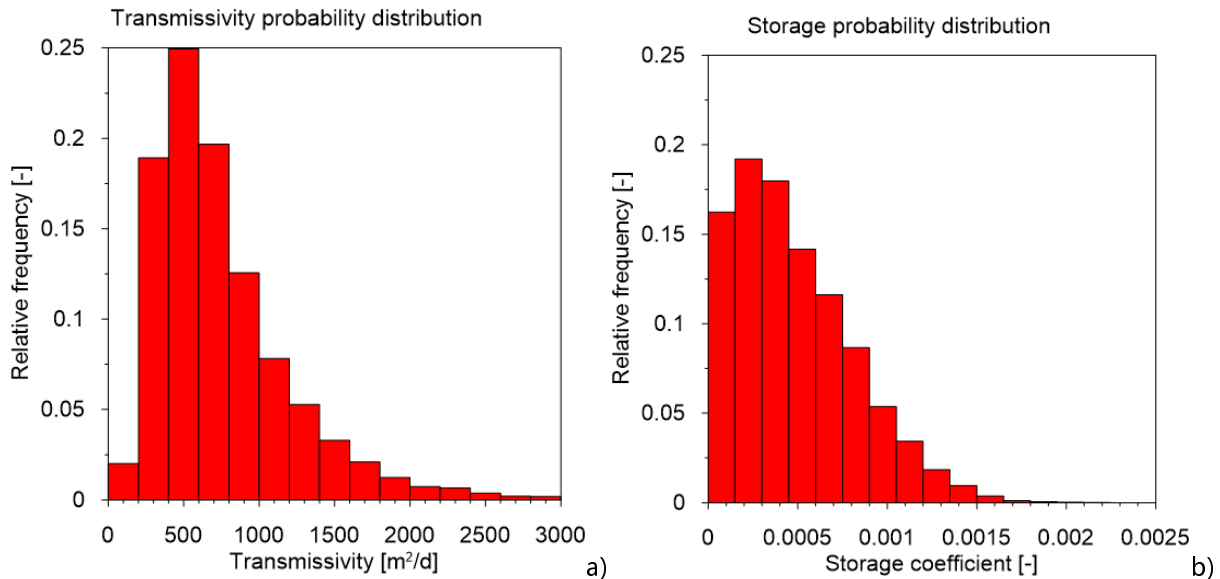


Figure 4 Probability distribution for a) transmissivity and b) storage coefficient.

C.4 Predicted drawdowns

C.4.1 Drawdown from the proposed drilling schedule timeframe and water demand

Using the information from the construction timetable and expected water demands the predicted drawdowns were calculated for 10000 realisations and are presented as percentiles at increasing distances from the pumping bore.

The pale grey bands indicate the extreme values (5th / 95th percentile of the drawdown data), the dark grey bands are defined the lower and upper quartiles, and the dashed centre-line is the median.

The most likely response represented by the median suggests that the impact away at a distance greater than 500 metres from the pumping bore is less than 0.3 metres and that for 95% of the realisations an impact of less than 0.5 metres can be expected.

This suggests that the impacts due to interference at any bores within the vicinity of the water supply well would be 2 – 3 times less than the expected drawdown in the bore being pumped.

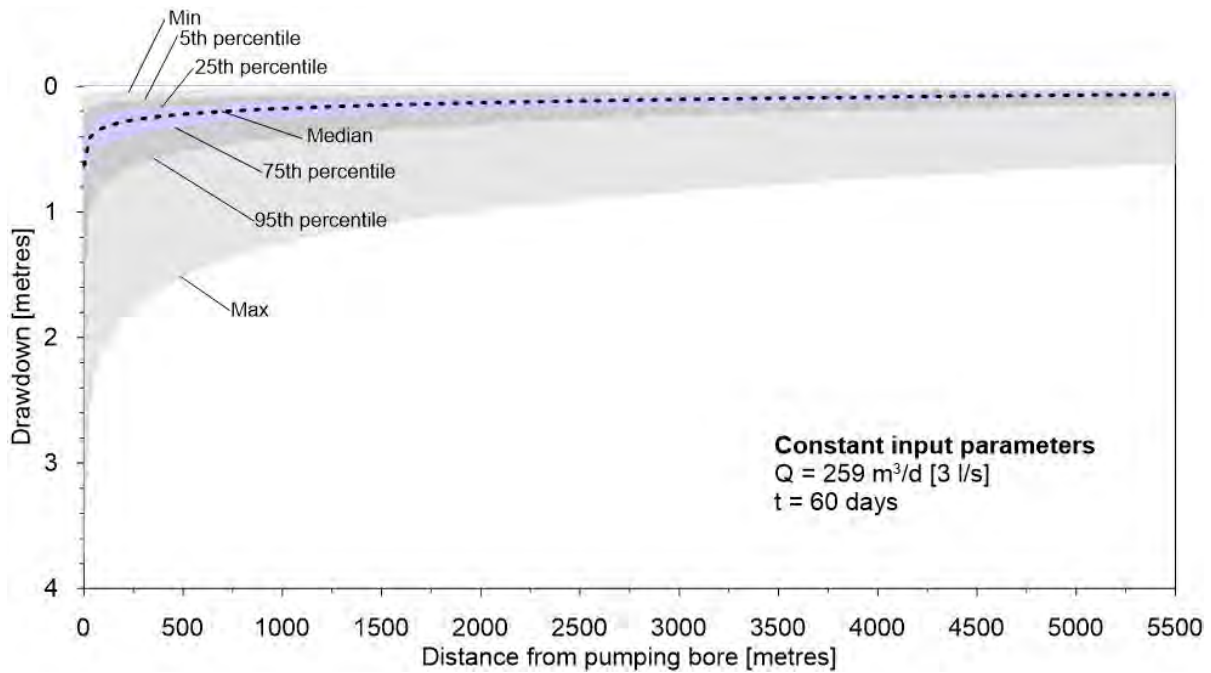


Figure 5 Percentiles of drawdown vs distance from the pumping bore based on 10000 realisations using the input hydraulic parameters from Table 1 and discharge $Q = 259 \text{ m}^3/\text{d}$ (3 l/s) and time $t = 60$ days. Note the vertical scale is 0 – 4 metres.

The 95th percentile 0.5 metre drawdown contours at each site are presented in plan view to provide an appreciation of the lateral extent of the drawdown cone. A drawdown of 0.5 metres is considered the extent that a response would be measurable using manual methods such as a dipper and allowing for errors such as variations in atmospheric pressure.

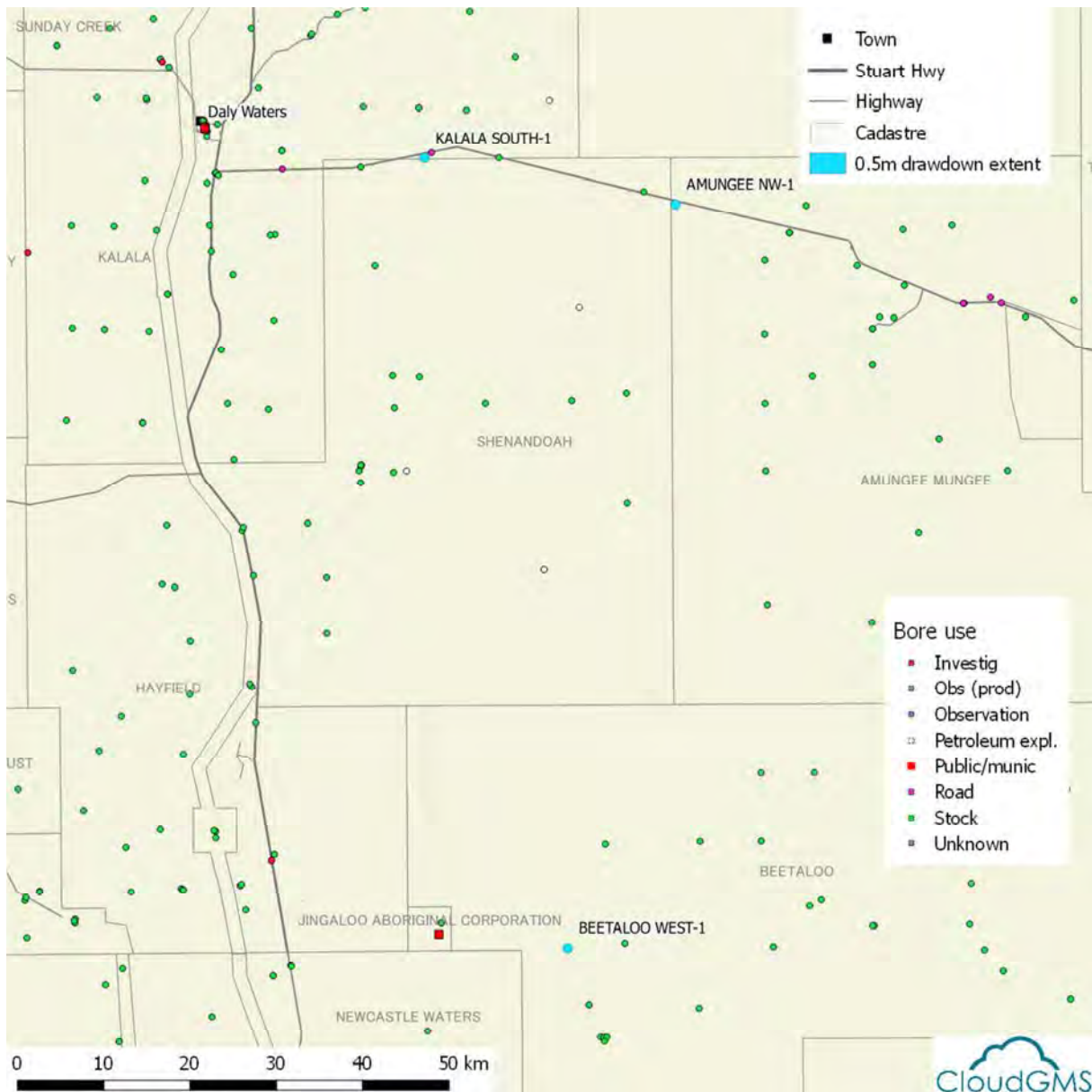


Figure 6 Predicted 95% probability 0.5 metre drawdown extent (radius ~500-600 m) at the 3 exploration well sites using discharge $Q = 259 \text{ m}^3/\text{d}$ (3 l/s) and time $t = 60$ days.

C.4.2 Drawdown assuming a fivefold increase in drilling schedule timeframe and water demand

An additional analysis was conducted to investigate the impacts if the discharge and timeframe were increased by a factor of five taking the pumping time to 300 days and the discharge to 15 l/s (1296 m^3/d), which is the maximum rate before requiring an extraction licence. The results of using these parameters are presented in Figure 7 (Note that the vertical scale is 0 – 25 m cf 0 – 4 m in Figure 3).

Table C—1 indicates that the closest bore is 1000 m from the pumped bore at Kalala NW-1. The 95th percentile drawdown at a distance of 1000 m for any of the bores considered is expected to be between 2 – 3 m. The drawdown for the sites at 4000 m can be expected to be between 1 – 2 m and at 6600 m with a drawdown of less than 1 m expected at approximately 7550 m.

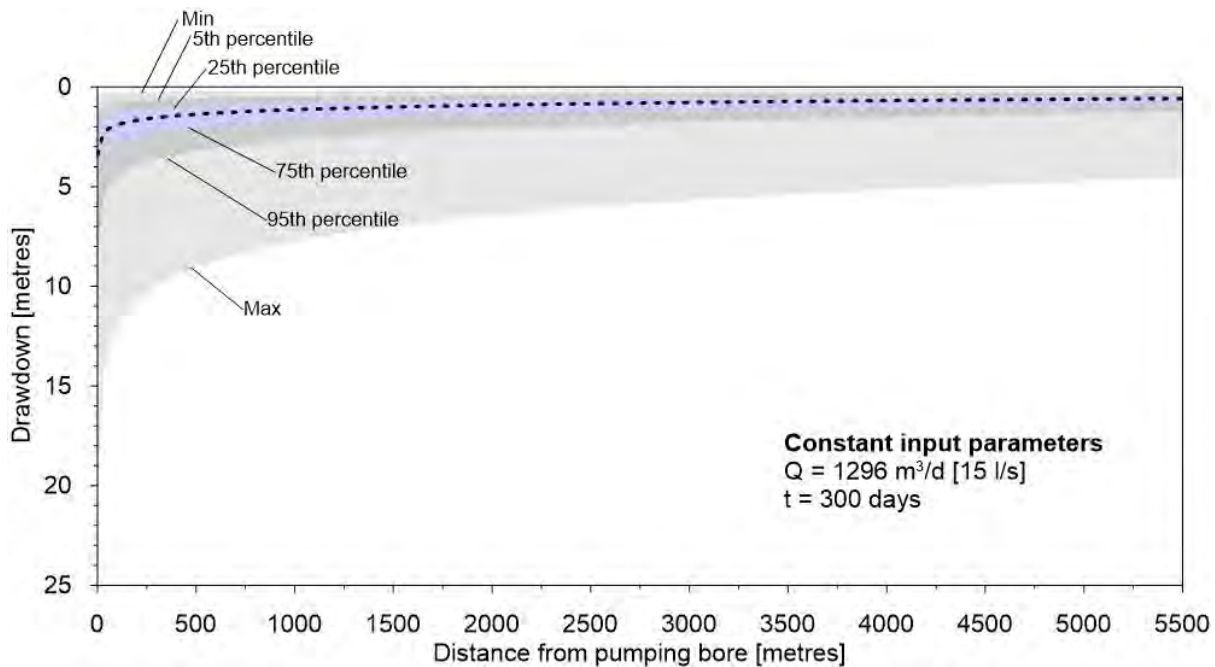


Figure 7 Percentile drawdowns vs distance from the pumping bore based on 10000 realisations and using the input hydraulic parameters from Table 1 and discharge $Q = 1296 \text{ m}^3/\text{d}$ (3 l/s) and time $t = 300 \text{ days}$. Dashed line is the median drawdown response. Note the vertical scale is from 0 – 25 metres.

C.5 Conclusions

Based on the available aquifer material properties and the pumping information supplied it is unlikely that significant drawdown will result due to groundwater abstraction from the CLA system for exploration well construction and poses a low risk to other users with respect to reducing yields of adjacent pastoral bores.

Appendix D Drilling fluid leakage risk assessment

D.1 Background

D.1.1 Objective

The objectives of this task are to:

- Model the leakage from the retention basins during their operational life;
- To provide guidance on the suitability of the pit construction to limit leakage with consideration to local soil and hydrogeological conditions; and
- Using the results of the mud / flare pit leakage assessment to constrain the likelihood of short term spills at the surface migrating to the groundwater.

D.1.2 Scope

The modelling process is guided by the Groundwater Modelling Guidelines (Barnett et al, 2012) and involves the following steps:

- A literature review to establish local hydrogeological conditions (informed by the baseline assessment, Fulton and Knapton, 2015) and the likely unsaturated hydraulic parameters;
- The unsaturated zone parameters and average water level depth will be based on the typical soils / bore logs in the area;
- Development of a conceptual model based on the flare / mud pits geometry and expected material properties based on the local hydrogeological conditions;
- Design, configure and construct a single base case transient numerical model based on the conceptual model. No calibration will be undertaken as there are no site specific observations available;
- Construct variant models using unsaturated material properties specific to each of the areas to be considered;
- Assess the leakage risk from the flare / mud pits for each variant of the base model;
- Undertake uncertainty modelling to examine seepage quantities and migration of the infiltrated fluid using different soil parameters.

The outputs from the leakage assessment modelling will include:

- A time series of the 2-dimensional cross-section through the pit and the underlying unsaturated zone showing leakage rates and pressure distribution over the operational life of the retention ponds.
- The calculated cumulative seepage flux over the operational life of the basins for each case considered.

- Based on the predictive results provide an assessment on the suitability of the construction of the pits to limit the depth of migration of the infiltrated fluid to the unsaturated zone over their operational life.

D.1.3 Assumptions and limitations

The leakage assessment modelling has been undertaken using the following assumptions and limitations:

- It is assumed that the flare / mud pits will be unlined;
- The model assumes a constant head level in the flare / mud pits during operation;
- No further water infiltrates into the unsaturated zone due to rainfall or overland flow following cessation of operations;
- The modelling will not consider the impact and/or fate of the leakage water if it reaches the saturated zone (water table);
- The modelling will not consider risks and impacts associated with overtopping in the mud/flare pits; and
- Solute transport modelling has not been considered.

D.1.4 Model confidence level classification

Based on the objectives and limitations of the modelling study, the model presented herein is deemed to be Class 1 using the classifications presented by Barnett et al (2012). A Class 1 model is suitable for understanding groundwater flow processes under various hypothetical conditions; and developing coarse relationships between groundwater extraction locations and rates and associated impacts. A Class 1 confidence level is considered appropriate.

D.2 Methodology

A seepage modelling analysis was performed to evaluate the leakage through the floor of the mud/flare pits and interaction (if any) with the groundwater. This analysis was based on likely unsaturated zone material parameters based on available lithological information and basin geometry and schedule provided by Origin.

The model development and seepage analysis was conducted using FEFLOW. FEFLOW is a commercially available computer modelling software package that is designed to analyse steady-state and transient flow under saturated and partially saturated conditions.

The analysis involved developing a single axisymmetric 2D transient numerical model based on the conceptualisation of the site. The model will be used to examine the leakage from several scenarios looking at different combinations of soil permeability and retention properties consistent with the available information.

The outcomes of the modelling will be to make quantitative predictions about seepage fluxes, compare the alternative construction techniques and identify the main governing parameters (such as presence of a liner or unsaturated zone permeability).

D.3 Site characteristics

D.3.1 Basin locations

The locations of the drilling mud / flare pits are adjacent to the exploration well sites. The proposed locations are listed in Table C—1 presented above in Figure 1.

D.3.2 Basin geometry

The geometry of the modelled pits is based on the supplied dimensions of the mud pit and flare pit which are approximately 50 x 50 metres 25 x 25 metres respectively (R. Morris pers comm., May 4, 2015). This is a combined area of 3125 m² and is equivalent to a circular area with a radius of 32 metres. The pit is assumed to be 2.5 m deep.

D.3.3 Description of natural soils

Local soil textures have been derived from the 1991 Digital Atlas of Australian Soils after Northcote et al (1960-1968). The distribution of soil types in the study area is presented below in Figure 8.

The unsaturated properties considered for the leakage assessment, were initially based on the dominant Principal Profile Form (PPF) interpretations after McKenzie et al (2000). PPFs for each mapped soil type and the 50% percentile (median) properties of the dominant PPF. However, the saturated hydraulic conductivity designated by McKenzie et al., (2000) do not appear to be related to the texture of the soil and are expected to be overestimates. The estimates of unsaturated hydraulic parameters for the soils in this study have, therefore, been assigned based on the texture designated by McKenzie et al., (2000) and using the pedotransfer functions between soil texture and soil water characteristics in Table D—7 developed by Carsel and Parrish, (1988). These pedotransfer functions were also utilised to assign unsaturated hydraulic parameters to the unsaturated profile between the upper soil horizons and the watertable based on the lithologies specified in the available bore logs.

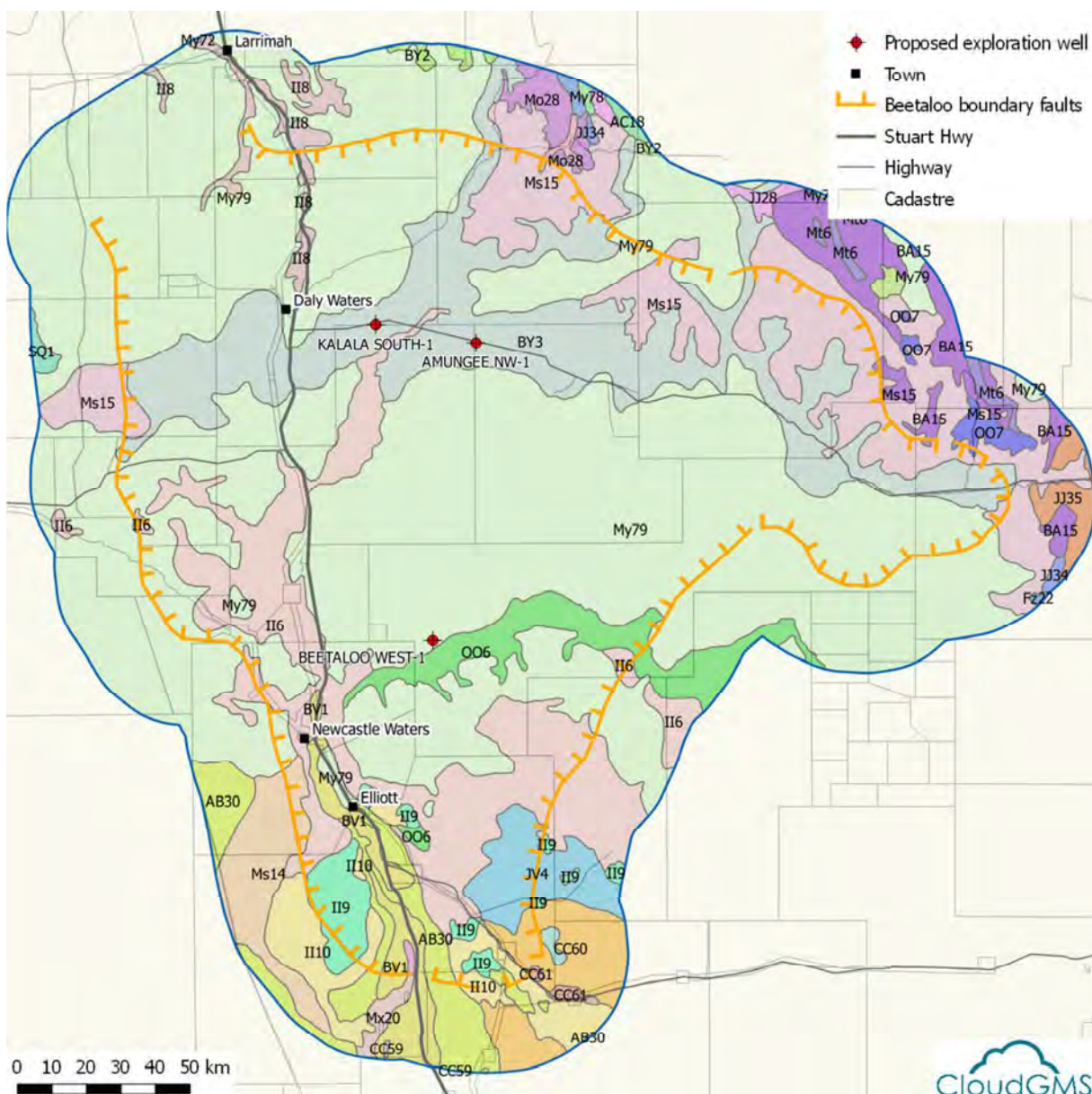


Figure 8 Soil distribution in the study area showing the locations of the proposed exploration wells.

The PPF soil data are estimated using a simple two-layer model of soil consisting of an A and B horizon. The horizon thickness, texture and saturated hydraulic conductivity properties of the two main soil types, which represent approximately 80% of the study area are listed below in Table D—1. Generally the soils are described as red earth sandy loams and loams.

Table D—1 Soil types underlying the leakage assessments in the study area.

Map Unit	Area	PPF1	PPF2	PPF3	PPF4	PPF5
BY3	6150	K-Uc1.4	K-Uc4.1	KS-Uc1.4	KS-Uc4.1	
My79	31000	Gn2.12	Gn2.21	Gn2.22	Gn2.24	Gn2.61

Table D—2 Two-layer soil model parameters (after McKenzie et al, 2000).

Soil Type	PPF	A _{text}	A _{thick}	B _{text}	B _{thick}	AK _{sat} m/d	BK _{sat} m/d
My79	Gn2.12	Loam	0.20	Clay Loam	0.70	7.59	0.76
	Gn2.21	Loam	0.20	Clay Loam	0.70	2.40	0.76
	Gn2.22	Sandy Loams	0.20	Loam	0.60	2.40	0.76
	Gn2.24	Loam	0.30	Clay Loam	0.80	2.40	2.40
	Gn2.61	Loam	0.20	Light Clay	0.80	2.40	0.76
BY3	K-Uc1.4	Sands	0.40		0.00	7.59	
	K-Uc4.1	Sands	0.40	Sands	0.50	2.40	2.40
	KS-Uc1.4	Sandy Loams	0.40		0.00	7.59	
	KS-Uc4.1	Sands	0.40	Sands	0.50	2.40	2.40

PPF = Principal Profile Form identified in Table D—1.

D.3.4 Description of underlying geology

The underlying geology and average groundwater level depth have been determined from mandatory drilling completion reports, referred to as the statement of bore (SOB). The lithological logs suggest that the northern sites have an unsaturated zone profile that is quite different to the southern site. The differences in the strata and the depth to water table between the two areas are discussed in the following sections. As a result of the distinct site conditions separate base models were developed for the northern sites and southern site.

D.3.4.1 Northern sites

The Amungee NW-1 and Kalala S-1 exploration wells are located along the Carpentaria Highway. The SOBs for the three closest bores reveals a relatively consistent lithological profile and depth to groundwater (see Table D—3).

The bore logs for RN005761 and RN005764 show lateritised clay to approximately 23 metres and 6 metres respectively and unweathered clay to approximately 70 metres and 55 metres respectively. The clayey strata are interpreted to be the upper layers of the undifferentiated Cretaceous sequence and overlie a basal sandstone; the overlying lateritic clays are interpreted to be weathered undifferentiated Cretaceous or Quaternary aged sediments.

The depth to the watertable ranges between 76 and 110 mBGL across the three sites, the variation in watertable depth is controlled by differences in topography across the area.

Table D—3 Lithological summary and depth to watertable for bores adjacent to the northern well sites.

Bore ID	Thickness of Cretaceous	SWL (mBGL)	Date
RN005761	Lateritised clay to 23 m; Clay to 70 m; dolomite to 96.6 m (TD)	87	12/04/1967
RN005764	Lateritised clay to 6 m; Clay to 55 m; sandstone to 70 m; dolomite to 84.4 m (TD)	76	26/05/1967
RN005844	Clay to 73 m; sandstone to 124 m (TD)	109	16/09/1967

TD = total depth

The layering for the leakage model representing the northern sites is based on the available lithological information summarised in Table D—3.

The layers intervals as referenced from the top of the model domain are:

- Loam sand 0-6
- Clay / claystone 6-70
- Sandstone / limestone 70-100

The watertable represented by a saturation of 1 and pressure of 0 kPa was assigned at a depth of 80 m below the top of the model

D.3.4.2 Southern site

Three bores in the vicinity of Beetaloo W-1 provide lithological and depth to the watertable controls for the southern well site.

The bore log for RN004882 shows sand and or clay to approximately 6 metres and clay or claystone to approximately 15 – 35 metres and sandy clay to approximately 90 metres. The clayey strata encountered are interpreted to be the upper layers of the undifferentiated Cretaceous sequence with a basal sandstone unit. The laterite is interpreted to be weathered Cretaceous or Quaternary alluvium.

The watertable depth ranges from around 64 mBGL (RN004882) to 70 mBGL (RN023794). The variation in watertable depth is considered to relate to changes in topography between the bore sites rather than a temporal water level trend.

Table D—4 Lithological summary and depth to watertable for bores adjacent to the southern well site.

Bore ID	Thickness of Cretaceous	SWL (mBGL)	Date
RN004882	Sand to 6 m; Claystone to 35 m; sandstone with bands of clay to 87 m;	64	03/05/1965
RN023794	Sand to 7.5 m; Clay to 25 m; Clay and sandstone to 88 m; sandstone to 103 m;	71	22/05/1985

	limestone to 110 m (TD)		

TD = total depth

The layering for the leakage model representing the southern site is based on the available lithological information summarised in Table D—4 with particular reference to the closest bore RN023794.

- Sand 0-6
- Clay / claystone 6-25
- Sandstone / clay bands 25-88
- Sandstone 88 - 100

The water table represented by a saturation of 1 and pressure of 0 kPa was assigned at a depth of 60 m below the top of the model.

D.3.5 Profile conceptualisations

Based on the lithological descriptions provided above a conceptualisation of the unsaturated zone profiles for the two sites has been determined. The generalised profiles are presented below in Figure 9.

Unsaturated parameters for limestone, which was encounter in the northern bores, are not available and will be modelled using the parameters derived for sand.

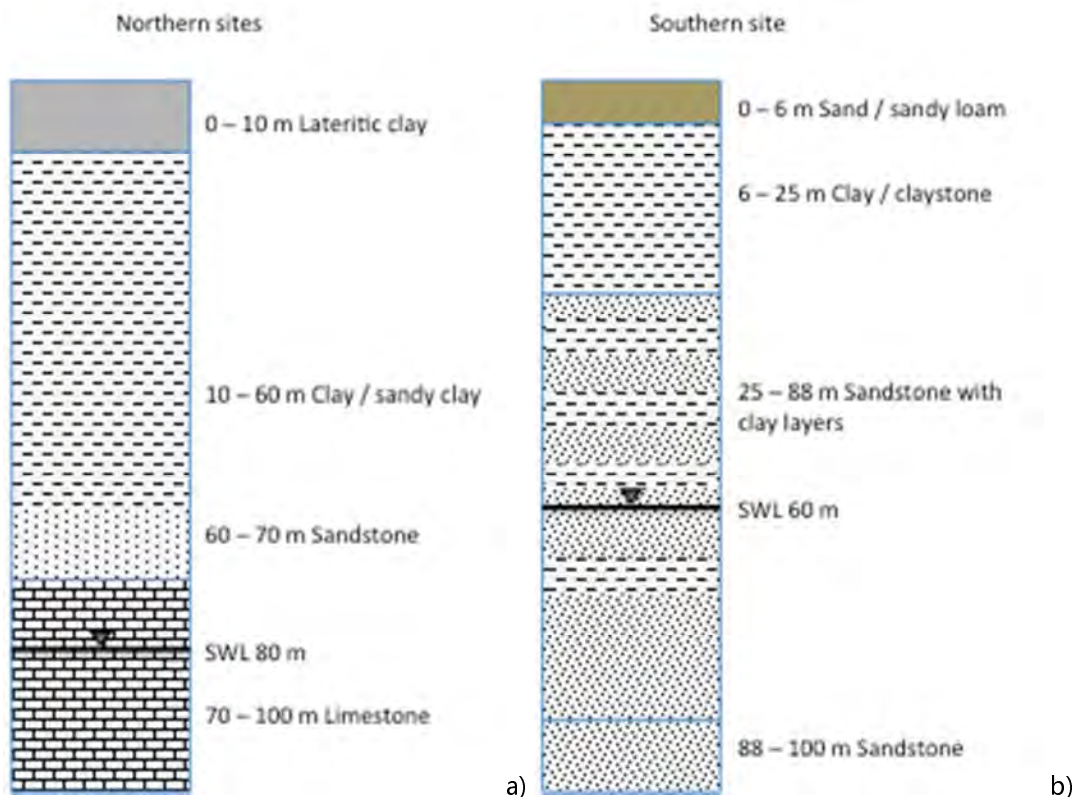


Figure 9 Conceptualisation of the unsaturated profiles for the two base case models based on available lithological data a) northern sites and b) southern site.

D.3.6 Unsaturated zone hydraulic parameters

Unsaturated flow parameters are difficult to obtain from sub-surface samples, therefore, the soil texture has been used as a proxy to determine unsaturated flow parameters. Several catalogues of soil texture to water retention parameters are available in the literature (Rawls et al., 1982; Carsel and Parrish, 1988; Schaap, 2000; Schaap et al., 2001). The unsaturated model HYDRUS 1D utilises the soil texture classes and the corresponding average van Genuchten parameters determined by Carsel and Parrish, (1988). The averaged parameters (refer Table D—7) are employed in this study as estimates for the soils / lithologies identified in the bore logs.

Twelve soil texture classifications are defined by the USDA. Soil textures are classified by the fractions of each soil separate (i.e. sand, silt, and clay) present in a soil. Classifications are typically named for the primary constituent particle size or a combination of the most abundant particles sizes, e.g. "sandy clay" or "silty clay." A fourth term, loam, is used to describe a roughly equal concentration of sand, silt, and clay, and lends to the naming of even more classifications, e.g. "clay loam" or "silt loam".

D.4 Numerical model description

D.4.1 Problem summary

The leakage assessment has been conducted using the finite element method, with the model(s) being constructed and analysed using the FEFLOW code. The problem class, settings and mesh details for the base model are presented below in Table D—5.

Table D—5 FEFLOW problem summary details

Problem class	
Property	Setting
Description	Separate flow process
Type	Unsaturated
Projection	Vertical axisymmetric
Time Class	Transient flow
Time Stepping	Forward Euler/Backward Euler (FE/BE) predictor-corrector
Upwinding	No upwinding
Mesh	
Domain dimensions	100 x 100 m
Number of dimensions	2
Element type	Triangle
Mesh elements	35881
Mesh nodes	18260

D.4.2 Vertical 2D axisymmetric model domain

Vertical 2D axisymmetric (or radially symmetric) models (refer Figure 10), where the axis of rotation corresponds to the y-axis (i.e. the x-coordinate is zero) offer an efficient alternative to full 3D models with considerable computational gains. This is provided the assumption of axial symmetry can be justified. In this case the system is assumed to be centred in the middle of a retention pond and parameters are radially homogeneous.

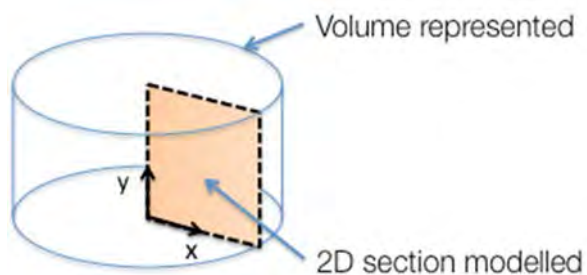


Figure 10 Conceptualisation of the axisymmetric model domain.

D.4.3 FEFLOW settings

The various settings for unsaturated flow modelling used in this study are presented in Table D—6.

Table D—6 Unsaturated flow solution settings

Property	Setting	Comment
Richards' equation formulation	Head based (standard form)	This is the default solution and is based on hydraulic head and represents the standard form and is applicable for larger and moderate capillary pressure heads (e.g., Psi > -10 m or -1000 kPa).
Error checking	Predicted pressure-head and saturation values	Error checks for pressure head and saturation values can be performed in addition to checking hydraulic-head values. The computed error is used to determine the time-step length in simulations with an automatic time-stepping scheme.
Spatial integration of hydraulic conductivity	Upstream weighting correction	By default, the average of the relative conductivity at the centroids of elements is used (central-weighting method). Alternatively, an upstream-weighting can be applied where the relative conductivity in an element is then moved upstream. In case of spurious local minima and maxima at coarse mesh sizes upstream-weighting may smoothen the results.
Numeric solver	SAMG multigrid solver	SAMG internally switching between multigrid and CG method depending on the matrix properties it can also be a very good option for many transient models with more homogeneous element sizes.
Error tolerance	Euclidian L2 integral (RMS) norm (default)	The Error tolerance (unit: 10^{-3}) is defined as the averaged absolute error (change in the primary variable) divided by the maximum value occurring in initial or boundary conditions.
Error criterion	10^{-3} (default)	The dimensionless error criterion is used for the automatic time-stepping process.

D.4.4 Model development

D.4.4.1 Model domain

The model domain used to investigate the leakage from the mud and flare pits at the exploration well sites consists of a 100 x 100 m domain with a 2.5 m deep basin centred on $x = 0$ m and extending to $x = 32$ m (physically representing a circular pond of radius 32 metres). The 2D section showing the finite element mesh is presented below in Figure 11.

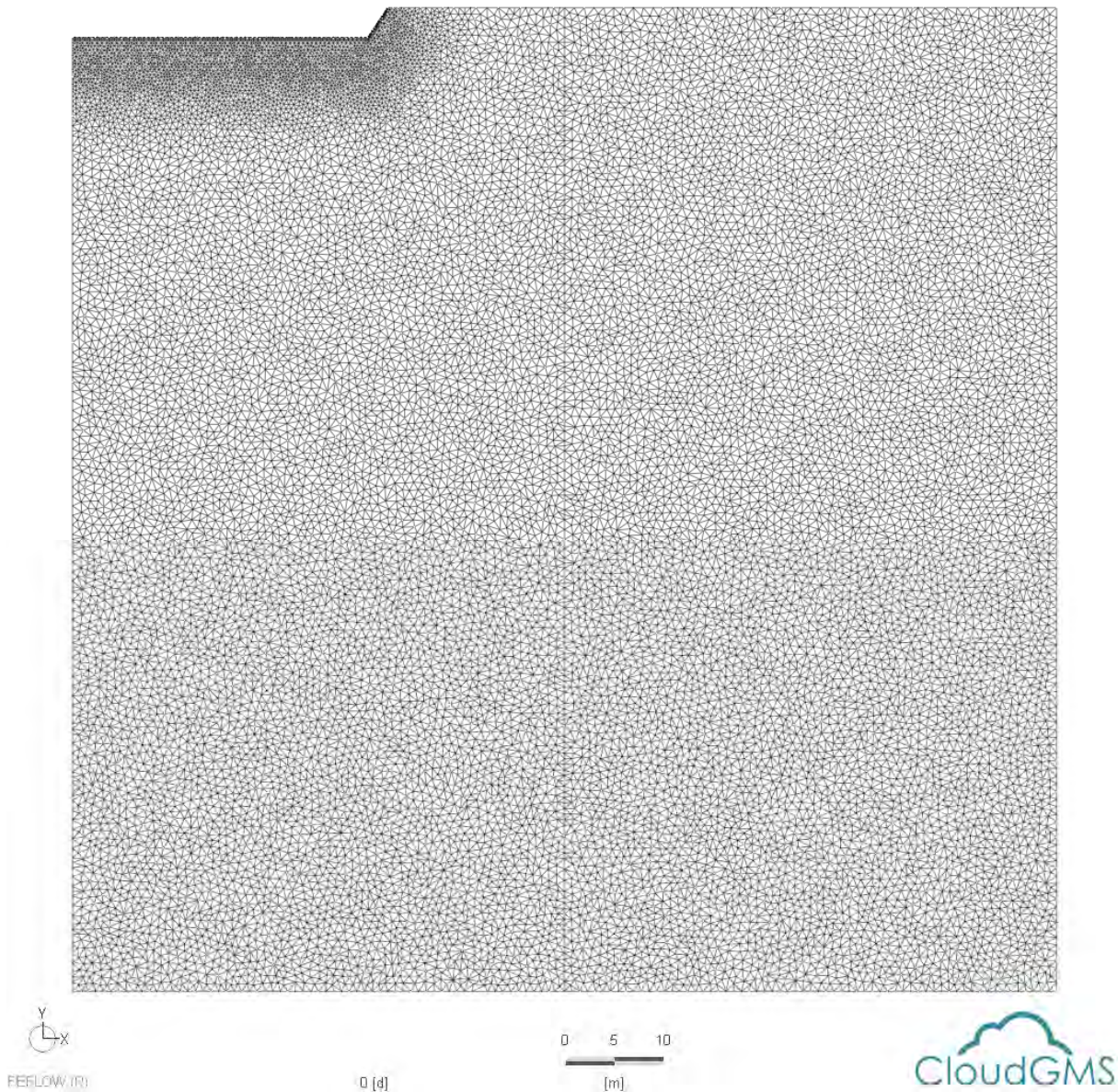


Figure 11 Leakage assessment model domain and finite element mesh.

D.4.4.2 Model layering

The layering of material properties within the model was based on the lithological information presented in sections D.3.4 and the profile conceptualisations presented in section D.3.5. The layering within the model and the differences between the two sites is demonstrated using the hydraulic conductivity distributions, which are presented below in Figure 12.

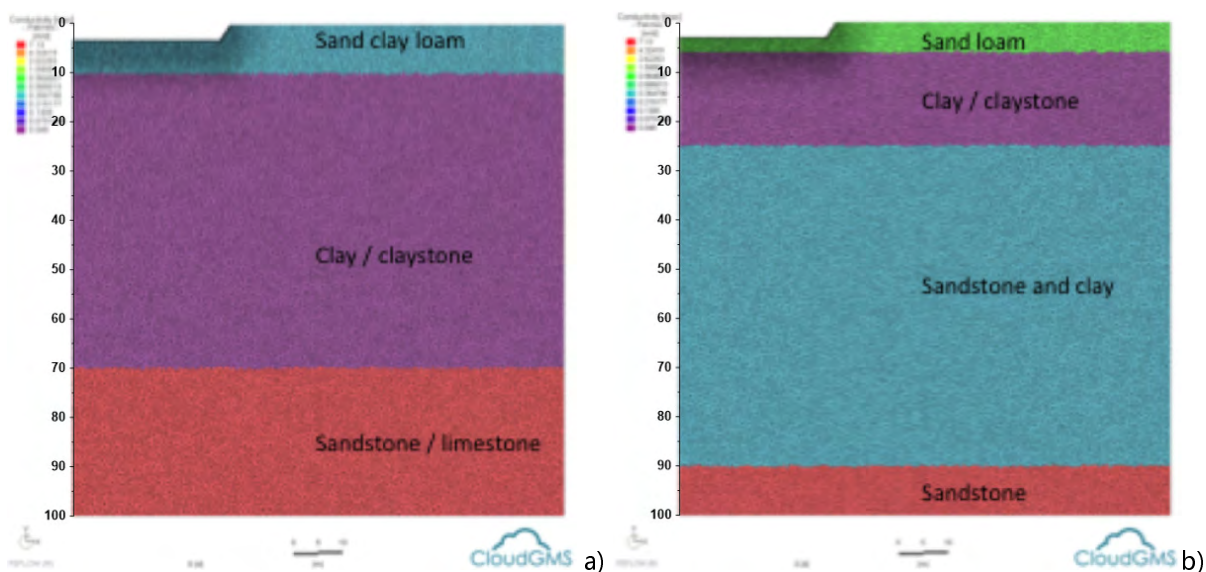


Figure 12 Saturated hydraulic conductivity (Ksat) distribution showing the layering for the a) northern unsaturated profile and b) southern unsaturated profile.

D.4.4.3 Material parameters

The same parameters have been used for the lithologies identified in the conceptualised unsaturated profiles, that is sand, loam sand, sandy clay loam and clay.

Table D—7 van Genuchten unsaturated soil parameters converted to FEFLOW units (after Carsel and Parish, 1988). Highlighted records are used in the current modelling study.

Soil texture	Porosity	Sr	Ss	A	n	Ksat
Units	(m ³ /m ³)	(-)	(-)	(1/m)	(-)	(m/d)
Silty Clay	0.36	0.194	1	0.500	1.090	0.005
Silty Clay Loam	0.43	0.207	1	1.000	1.230	0.017
Sandy Clay	0.38	0.263	1	2.700	1.230	0.029
Clay	0.38	0.179	1	0.800	1.090	0.048
Silt	0.46	0.074	1	1.600	1.370	0.060
Clay Loam	0.41	0.195	1	1.900	1.310	0.062
Silt Loam	0.45	0.149	1	2.000	1.410	0.108
Loam	0.43	0.181	1	3.600	1.560	0.250
Sandy Clay Loam	0.39	0.256	1	5.900	1.480	0.314
Sandy Loam	0.41	0.159	1	7.500	1.890	1.061
Loamy Sand	0.41	0.139	1	12.400	2.280	3.502
Sand	0.43	0.105	1	14.500	2.680	7.128

Sr = residual saturation

Ss = maximum saturation

A = van Genuchten fitting coefficient

n = van Genuchten fitting parameter

D.4.4.4 Anisotropy

It is expected that the hydraulic parameters associated with the claystone and sandstone strata will exhibit some degree of anisotropy, resulting in differing vertical and horizontal hydraulic conductivity values. A typical ratio of anisotropy between horizontal hydraulic conductivity and vertical hydraulic conductivity is 10:1. In the absence of any other information this anisotropy ratio will be employed for this study.

D.4.5 Boundary conditions

No boundary conditions have been assigned to the nodes along the bottom of the model domain, along the left edge at $x = 0$, along the right edge at $x = 100$ and along the top of the model domain outside of the retention basin. This results in no-flow across these boundaries.

The nodes located within the basin are designated a constant head equivalent to 2 metres above the floor of the basin (i.e. hydraulic head = 99 m).

D.4.6 Initial conditions

The moisture content distribution within the unsaturated profile was determined by assigning a constant pressure of -100 kPa (approximately -10 m head) to the profile above the water table. This is not an unreasonable assumption given that other studies in semi-arid areas show matric potentials considerably lower than this (Allison et al., 1990; Cossens et al., 2007). This resulted in initial moisture content of 0.08 in the sandy loam strata in the top 6-10 m and initial moisture content of 0.32 in the clayey strata above the water table.

The clay and sandstone layers in the southern unsaturated profile have been assigned the parameters for sandy clay loam and the initial moisture content of this layer is 0.08. The different initial water contents for each layer is due to the different moisture retention characteristics of each of the soils used to represent the profile.

D.5 Leakage assessment

The results of the leakage assessment are presented as cross-sectional views of pressure for the northern and southern sites presented below in Figure 13 and Figure 14 respectively. The depth that the wetting front reaches after 60 days (taken as the 0 kPa value) is 20 m below ground level for the northern sites and 16 m below ground level for the southern site.

The migration of the water infiltrated into the unsaturated zone becomes relatively static once the basin is emptied and no more fluid infiltrates into the ground. This is primarily due to the retention characteristics of the clay / claystone layer.

The results are consistent with the amount of recharge expected in areas where the upper sequence of the Cretaceous sediments is present.

The major constraining factor determining the depth of flow beneath each of the basins is the hydraulic conductivity and retention characteristics of the clay / claystone layer.

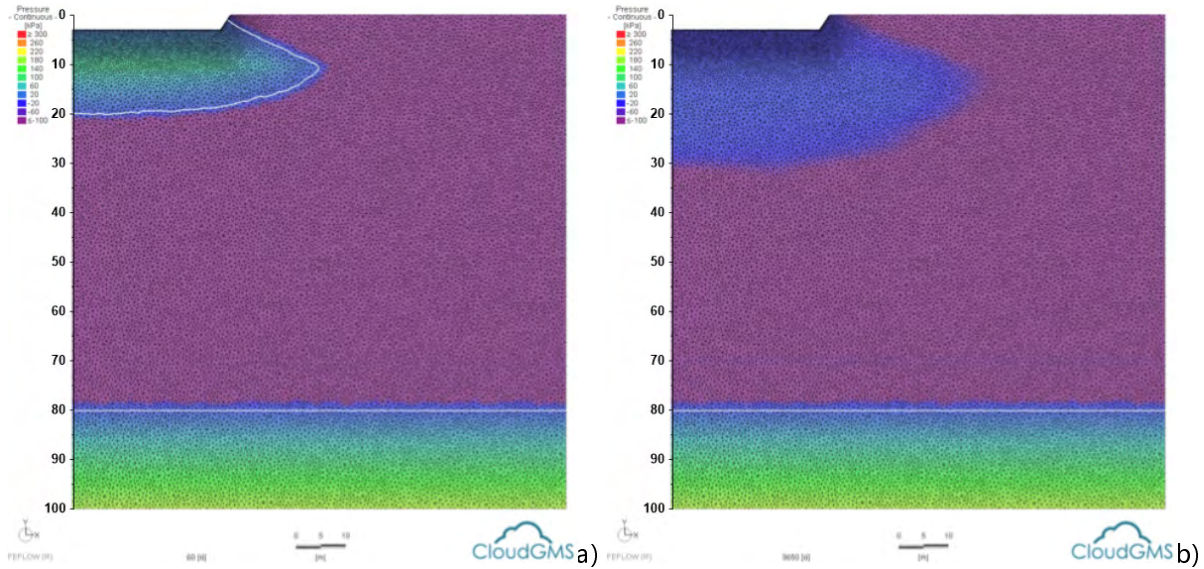


Figure 13 Unsaturated profile pressure distribution for the northern site after a) 60 days and b) 3650 days or 10 years. The white line represents 0 kPa or fully saturated media.

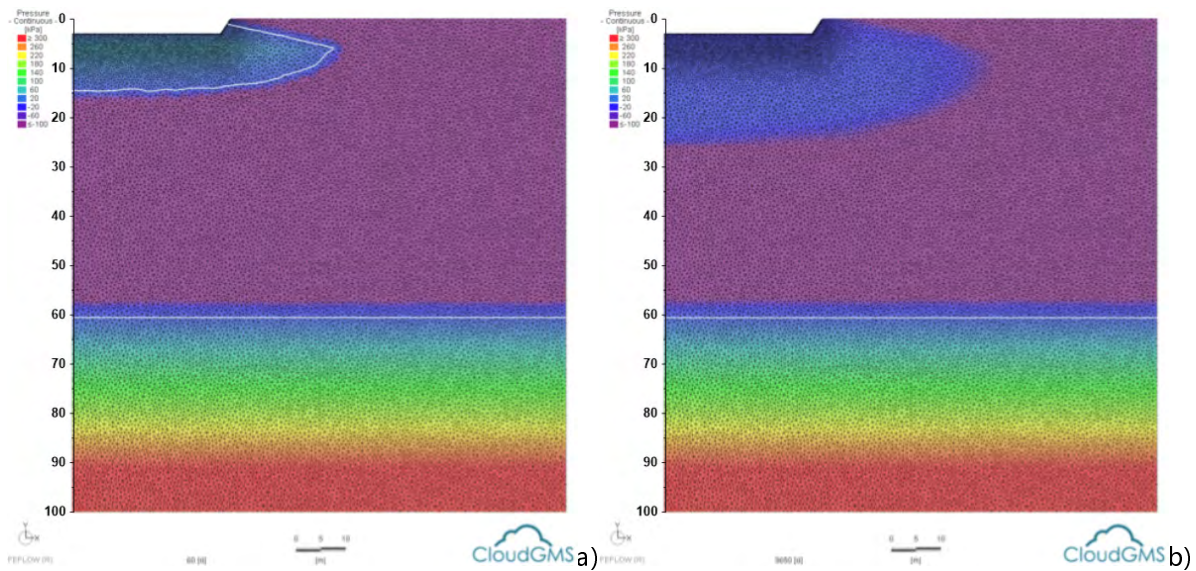


Figure 14 Unsaturated profile pressure distribution for the southern site after a) 60 days and b) 3650 days or 10 years. The white line represents 0 kPa or fully saturated media.

D.5.1 Leakage rates

The expected leakage through the floor of each modelled retention basin has been determined and the time series rates are presented below in Figure 15.

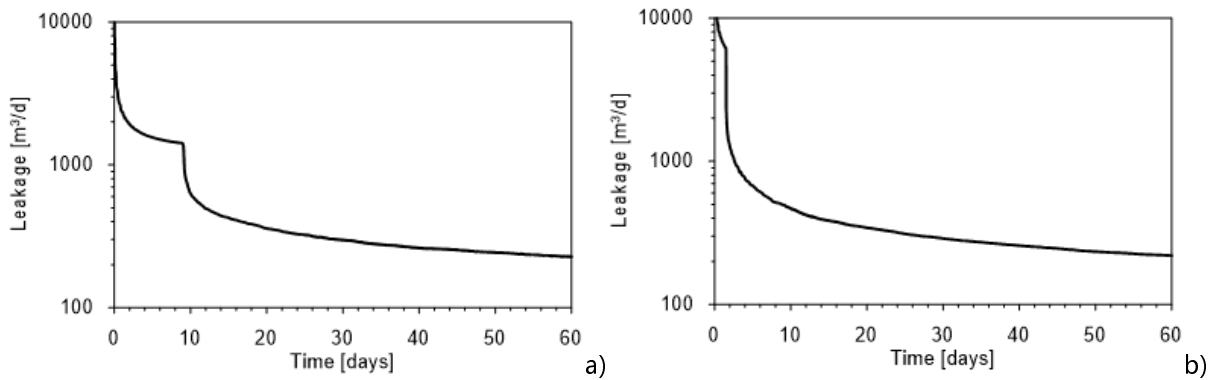


Figure 15 Expected leakage rates for the retention basins for the northern sites a) and southern site b).

It can be seen that for the first 10 days the leakage rates are quite different, however, after this point the rates are similar and coincide with the wetting front intercepting the clay layer which occurs at approximately 10 metres at the northern sites and 6 metres at the southern site. The final leakage rate at both sites is approximately 200 m³/d, which equates to 2.3 l/s.

The total volume required to meet the leakage through the basin floor was approximately 30-35 ML.

D.5.2 Uncertainty analysis

There is uncertainty regarding the exact hydraulic parameters to assign to the various lithologies expected at the sites. However, this does not mean that the range of values are completely unknown, based on the lithological description and the associated pedo-transfer functions there could be expected an order of magnitude change to the assigned parameters such as hydraulic conductivity, due to an incorrect assignment of texture to any particular lithology. For example if the clay / claystone is actually more of a sandy clay loam the hydraulic conductivity would increase from 0.048 m/d to 0.314 m/d.

The preceding scenarios indicate that the constraining factor on the leakage beneath the basins is the unsaturated hydraulic properties of the clay / claystone layer. To investigate the likely impact on the depth that the saturated wetting front that an incorrect lithology has been identified in the bore logs or that the parameters used were not appropriate, the unsaturated parameters used to describe the clay / claystone were adjusted to reflect a more sandy strata (sandy clay loam and sandy loam) using the southern site to compare the outcomes.

D.5.2.1 Case 1 Sand clay loam

The unsaturated parameters for a sand clay loam soil were used to replace the parameters describing the clay / claystone layer resulting in a continuous profile to the water table. The lighter textured sand loam clay has a higher hydraulic conductivity, however, the available moisture content (assuming an initial pressure of -100 kPa) is 0.24 compared with 0.06 for the clay / claystone.

Therefore the available storage volume is approximately four times that of the clay / claystone resulting in a reduced migration of fluid beneath the basin to 14 m below ground level despite the

increased leakage rate and total volume infiltrated of 50 ML. The results of this scenario are present below in Figure 16.

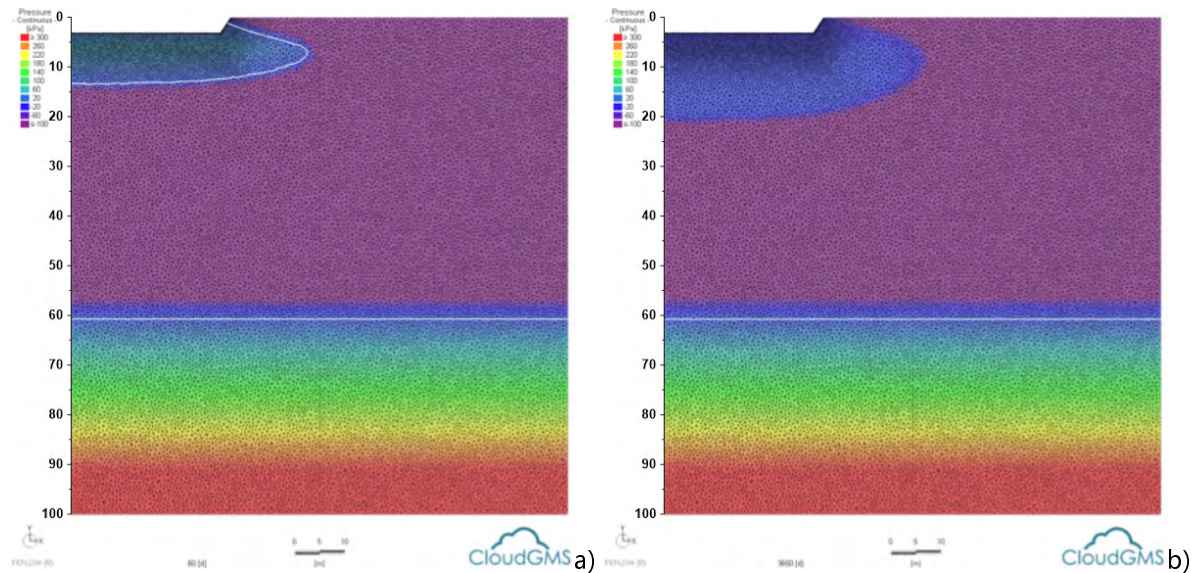


Figure 16 Unsaturated profile pressure distribution for the southern site after a) 60 days of infiltration and b) 3650 days or 10 years.

D.5.2.2 Case 2 Sandy loam

The lighter textured sandy loam has a higher hydraulic conductivity, however, the available moisture content (assuming an initial pressure of -100 kPa) is 0.33 compared with 0.24 for the sandy clay loam and 0.06 for the clay / claystone. Therefore the available storage volume is approximately five times that of the clay / claystone resulting in migration of the fluid to only 16 m below ground level, despite the increased leakage rate and total volume infiltrated of 86 ML. The results of this scenario are present below in Figure 17.

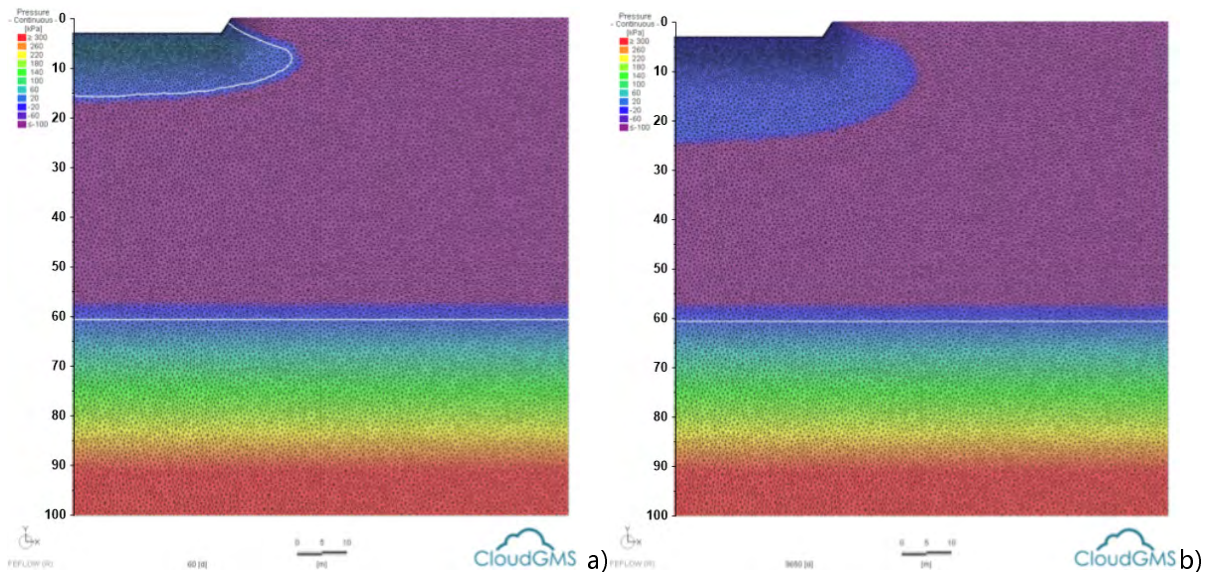


Figure 17 Unsaturated profile pressure distribution for the southern site after a) 60 days of infiltration and b) 3650 days or 10 years.

D.5.2.3 Filter cake

The modelling undertaken above has assumed that the basins are constructed without a liner and that the drilling fluids do not have any effect on the leakage through the basin floor as a result of a filter cake forming.

One of the main functions of drilling fluids during the drilling process is to isolate formations from drilling fluids, thus preventing fluid loss to the formation. Drilling fluid is designed to deposit a thin, low permeability filter cake to limit the invasion of drilling fluid (and suspended solids) into permeable formations and it can be expected that the same mechanism will prevent fluid loss due to leakage through the floor of the retention basin. To investigate the effects due to the formation of a filter cake a thin low hydraulic conductivity layer was applied to the floor of the basin for the southern site base case to simulate the effects of the filter-cake forming.

Testing on sand / bentonite slurries (Castelbaum and Shackelford, 2009) suggest that the expected reduction in hydraulic conductivity of sand due to a sand / bentonite filter cake, is typically four orders of magnitude and it is expected that similar reduction in hydraulic conductivity would result from the use of bio-polymers. To be conservative it was assumed that the reduction in the hydraulic conductivity due to the formation of a filter cake on the floor of the basin was approximately two orders of magnitude. The hydraulic conductivity of the soil for the southern sites is 1 m/d a reduction of two orders of magnitude results in a hydraulic conductivity of 0.01 m/d. The filter cake layer was 0.2 m thick.

The depth of migration of the wetting front after 60 days and 3650 days for the northern and southern sites are presented in Figure 18 and Figure 19 respectively.

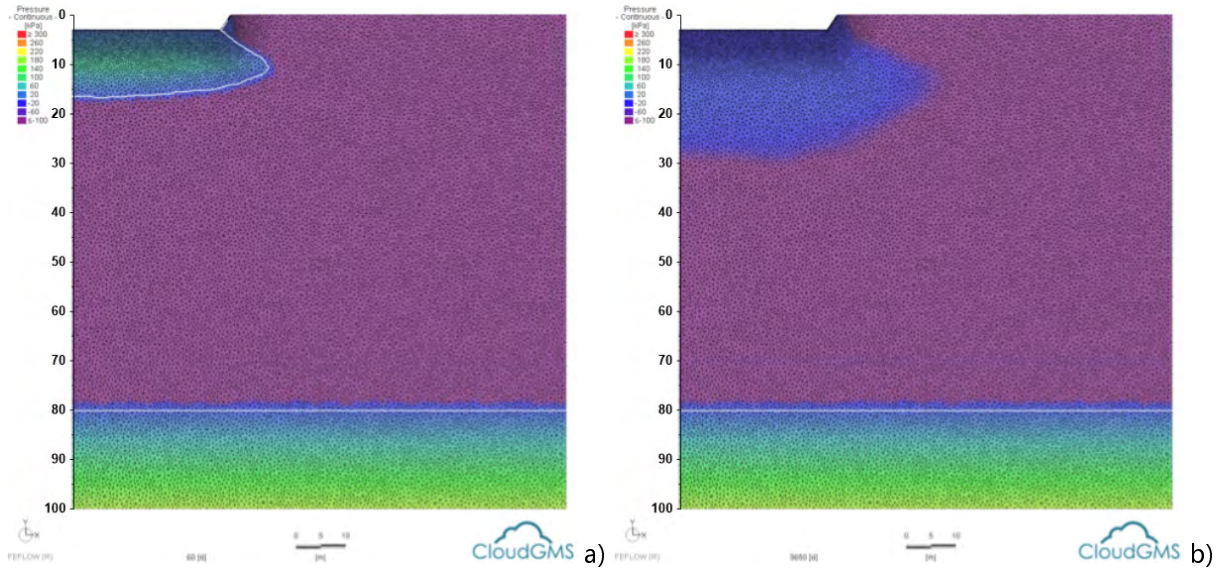


Figure 18 Unsaturation profile pressure distribution for the northern site after a) 60 days of infiltration and b) 3650 days or 10 years.

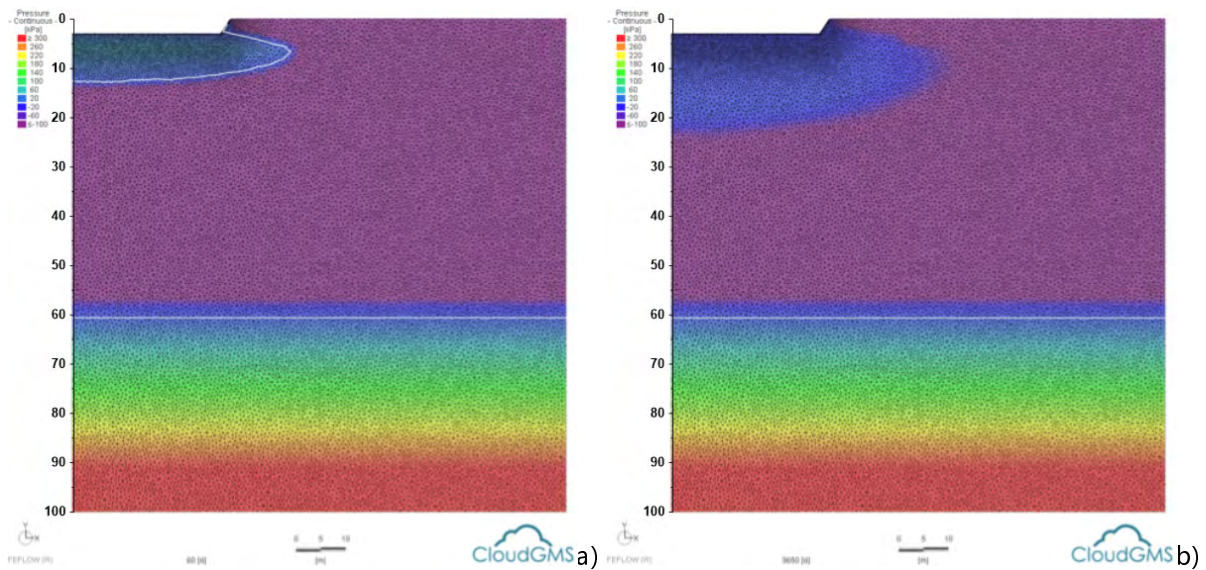


Figure 19 Unsaturation profile pressure distribution for the southern site after a) 60 days of infiltration and b) 3650 days or 10 years.

The final depth of the wetting front for the southern site is approximately 13 m below ground level and the total infiltrated volume is approximately 15 ML. The final depth of the wetting front for the northern site is approximately 17 m below ground level and 19 ML. Although the depth of the wetting front is about 15-20% less than the case with no filter cake formation, the infiltrated volume is approximately 50% of the volume infiltrated with no filter cake formation.

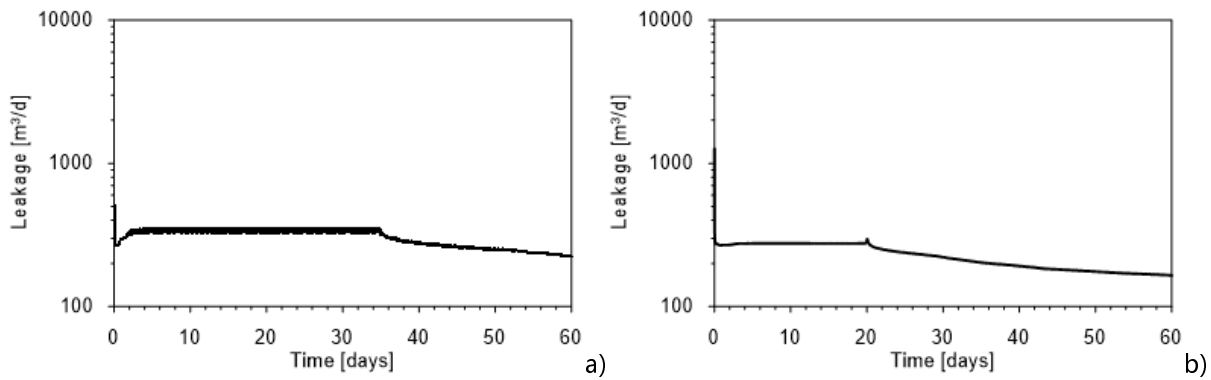


Figure 20 Expected leakage rate for the retention basin for a) the northern site and b) the southern site.

D.5.3 Discussion

D.5.3.1 Leakage assessment

The leakage assessment results are summarised below in Table D—8. Generally the depth of migration of the infiltrated water during the operational phase is less than 20 metres and less than 30 metres after 10 years after the end of operation, assuming no further water infiltrates into the unsaturated zone due to rainfall or overland flow events.

Table D—8 Summary of leakage assessment results.

Scenario	Infiltrated Vol.	Wetted depth 60d	Wetted depth 3650d
	ML	mBGL	mBGL
Base south	30-35	16	25
Base north	30-35	20	30
Case 1	50	14	21
Case 2	86	16	25
Filter cake south	15	13	22
Filter cake north	19	17	28

mBGL = metres below ground level

D.5.3.2 Likelihood of spillage migrating to groundwater

There is a risk that surface spillage of mud products/diesel/stimulation additives/flow back water during transport, storage or transfer onsite will lead to the contamination of groundwater resources. This has the potential to impact groundwater users close to the spill site and environmental receptors.

The leakage assessment presented suggests that based on the volumes that can reasonably be expected from a spill/leakage event would be insufficient to mobilise fluid and any potential contaminant to the watertable under the expected site conditions. Based on the following assumptions:

- the maximum volume of any spill would be less than 0.001 - 0.002 times considered in the leakage assessment (based on 50000 litres maximum load of a B Double trailer); and
- the spill would be removed in less than the 60 days of the mud/flare pit operation timeframe considered in the leakage assessment.

D.6 Conclusions

The following conclusions have been determined from the leakage assessment modelling:

- The major constraining factor determining the depth of flow beneath each of the basins is the hydraulic conductivity and retention characteristics of the clay / claystone layer which comprises the majority of the unsaturated zone above the watertable.
- Despite the relative uncertainty of the properties of the unsaturated profile beneath the basins, it is felt that the possible range of depths that the infiltrating water will migrate is relatively well constrained.
- The inclusion of a filter cake (or a clay liner) would result in a reduction in the depth of migration of the wetting front beneath the pits and a considerable reduction in the leakage rate through the floor of the pit. A reduction in the hydraulic conductivity of two orders of magnitude resulted in a reduction in the leakage by a similar magnitude.
- Although reduction in leakage through the pit floor, by utilising a liner (or drilling muds), will reduce the migration of fluid beneath the pits by between 10-20%, it is expected that a major benefit will be a reduction in the operational volumes by between 40-50% from the base case.
- Based on the scenarios considered the likelihood of surface spillage migrating to the watertable is low when taking into consideration the water table depth (>60 m), spill volumes, timeframe for spill containment / remediation and existing controls.