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Review and Update of Methods Used for Air Emissions Leak Detection and Quantification

Prepared For:

**Petroleum Technology Alliance Canada
Technology for Emission Reduction and Eco-Efficiency
(TEREE) Steering Committee**

February 5, 2007

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ACKNOWLEDGMENTS

PTAC Petroleum Technology Alliance Canada (PTAC) would like to gratefully acknowledge the Alberta Energy Research Institute, Industry Canada and Western Economic Diversification for funding this project and for their continued efforts in supporting emission reduction and energy efficiency initiatives in the oil and gas sector. Also, PTAC wishes to acknowledge the significant contributions of the following individuals who provided their insights, practical experience and technical expertise to this project:

David Picard (Project Technical Advisor)	Clearstone Engineering
Allan Chambers	Alberta Research Council
Brian Ross	Nexen Canada
Terence Trefiak	ConocoPhillips Canada
Roxanne Pettipas	ConocoPhillips Canada
Hasan Imran	TransCanada PipeLines

Special thanks are also given to the individuals and companies who participated on the Technology for Emission Reduction and Eco-Efficiency (TEREE) TEREE Air Emissions Leak Detection and Quantification project working group, and who provided their insights and/or review comments.

We would also like to thank the many technology / product suppliers that were interviewed for this Project (listed in Appendix A) for giving their time and sharing their expertise.

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Executive Summary

There have been a number of technological advancements in recent years with regard to the detection and quantification of fugitive equipment leaks at upstream oil and gas facilities. In an effort to supplement previous technology evaluation work conducted by other agencies (e.g. Canadian Association of Petroleum Producers (“CAPP”) and the U.S. Natural Gas STAR Program), the Petroleum Technology Alliance Canada (“PTAC”), Technology for Emission Reduction and Eco-Efficiency (“TEREE”) Steering Committee initiated a project for the “Review and Update of Methods Used for Air Emissions Leak Detection and Quantification” (the “Project”). Pertinent information regarding these emerging technologies was to be combined with previous information already gathered for the more traditional methods of leak detection and quantification.

The overall goal of this Project was to provide industry and government with pertinent information regarding both traditional and emerging methods/technologies for air emissions leak detection and quantification. This work was also intended to support the general guidance for fugitive emissions management at oil and gas facilities provided by CAPP through the recent release of its Best Management Practice (“BMP”). This has been done in an objective and unbiased manner so that industry representatives and government could use the information provided to assist them in deciding which technologies/methods may be the most appropriate for their particular facility or circumstances.

The Project was comprised of the following tasks:

1. Identification of existing and emerging leak detection and quantification technologies and methods;
2. Evaluation of these technologies and methods based on costs, as well as their ability to identify, locate and quantify various substances; and
3. Summarization of the key benefits and limitations of the various technologies and methods for regulatory and industry decision-making purposes.

In addition to the above, a number of products that utilize these technologies/methods were investigated and are described more fully in the tables (Tables 1 to 3) of the Excel-based Information Tool accompanying this report. However, it should be noted that the focus of this Project was on a review of the technologies/methods for leak detection and quantification. The review of the many products on the market was not “exhaustive” and is provided only as examples of the technologies/methods investigated.

The criteria for the development of the Excel-based Information Tool (Tables 1 to 3) was that it must be easy to use, maintain, update and manage so that it can be updated periodically with new technology/method and product information. The functionality of Excel allows users to easily filter for those technologies/methods that meet their specific criteria.

The technologies/methods (traditional and emerging) that were reviewed as part of this Project were categorized into three (3) separate topic groups:

1. Point source leak detection and concentration measurement technologies/methods;
2. Point source leak quantification methods; and
3. Area source emissions leak detection and quantification technologies/methods.

Point source leak detection and concentration measurement technologies/methods are those that are used to detect and/or measure fugitive emissions from component equipment leaks and pipelines. Area source leak detection emissions quantification technologies/methods are those that are used to detect and/or measure emissions from area sources within a facility, including emissions from an entire facility.

Point Source Leak Detection and Concentration Measurement Technologies/Methods

Point source leak detection and concentration measurement methods were categorized as following (see Section 7.0):

- Close range detection and measurement methods;
- Remote sensing methods; and
- Airborne methods.

Close range detection and measurement methods and remote sensing methods under this category are used to detect and/or measure emissions from components contributing to fugitive equipment leaks; the airborne methods/technologies detect and/or measure fugitive emissions from pipelines.

The following close range detection and measurement methods technologies/methods were reviewed (see Section 7.1):

1. Flame Ionization (FI);
2. Photoionization (PI);
3. Catalytic Combustion (CC);
4. Solid-State (SS);
5. Infrared Absorption (IR);
6. Tunable Diode Laser Absorption Spectroscopy (TDLAS);
7. Bubble Test; and
8. Acoustic Leak Detection.

The following remote sensing technologies/methods were reviewed (see Section 7.2):

1. Passive IR Gas Imaging -Thermal Imaging;
2. Passive IR Gas Imaging -Image Multi-Spectral Sensing; and
3. Open Path - Tunable Diode Laser Absorption Spectroscopy (TDLAS)

The following airborne technologies/methods were reviewed (see Section 7.3):

1. Tunable Diode Laser Absorption Spectroscopy (TDLAS);
2. Differential Absorption LIDAR (Airborne DIAL); and
3. Passive Gas Filter Correlation Radiometry (PGFCR).

Point Source Leak Quantification Methods

The following point source leak quantification methods were reviewed (see Section 8.0):

1. Bagging;
2. Hi-flow sampling;
3. Rotameters and other Flow Metering Devices; and
4. Tracer Gas Detection.

Area Source Leak Detection and Quantification Technologies/Methods

The following area source leak detection and quantification technologies/methods were reviewed (see Section 9.0):

1. Light Detection and Ranging/Differential Absorption (LIDAR/DIAL);
2. AIR Detection and Ranging (AIRDAR);
3. Open Path Tunable Diode Laser Absorption Spectroscopy (TDLAS); and
4. Open Path Fourier Transform Infrared (FTIR).

Each technology/method was evaluated based on its ability to identify, locate, detect and/or quantify different types of hydrocarbon pollutants, technology/method strengths and limitations as well as pertinent costing information.

The findings are summarized and presented in Tables 1 through 3 of the Excel-based Information Tool accompanying this report.

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LIST OF ACRONYMS

PTAC	-	Petroleum Technology Alliance Canada
TEREE	-	Technology for Emission Reduction and Eco-Efficiency
CASA	-	Clean Air Strategic Alliance
CAPP	-	Canadian Association of Petroleum Producers
SEPAC	-	Small Explorers and Producers Association of Canada
EUB	-	Alberta Energy and Utilities Board
EC	-	Environment Canada
CCME	-	Canadian Council of Ministers of the Environment
U.S. EPA	-	U.S. Environmental Protection Agency
Method 21	-	US EPA Method 21
BMP	-	Best Management Practice
UOG	-	Upstream Oil and Gas
DI&M	-	Directed Inspection and Maintenance
VOC	-	Volatile Organic Compound
NMVOC	-	Non-Methane Volatile Organic Compounds
THC	-	Total Hydrocarbons
TOC	-	Total Organic Compounds
GHG	-	Greenhouse Gases
OVA	-	Organic Vapour Analyzer
FI	-	Flame Ionization
PI	-	Photoionization
CC	-	Catalytic Combustion
SS	-	Solid-State
SSS	-	Solid-State Sensor
IR	-	Infrared Absorption
IMSS	-	Image Multi – Spectral Sensing
TDLAS	-	Tunable Diode Laser Absorption Spectroscopy
LIDAR	-	Light Detection and Ranging
DIAL	-	Differential Absorption LIDAR
AIRDAR	-	AIR Detection and Ranging
FTIR	-	Fourier Transform Infrared
PGFCR	-	Passive Gas Filter Correlation Radiometry
PI-ORS	-	Path-Integrated Optical Remote Sensing
PIC	-	Path-Integrated Concentration
RPM	-	Radial Plume Mapping
ORS	-	Optical Remote Sensing
ORS-RPM	-	Optical Remote Sensing-Radial Plume Mapping
HRPM	-	Horizontal Radial Plume Mapping
VRPM	-	Vertical Radial Plume Mapping
1D-RPM	-	One Dimensional Radial Plume Mapping

1.0 Introduction

The management of fugitive emissions and identification of emissions reduction opportunities from the upstream oil and gas industry are increasingly coming under greater scrutiny by regulators and the public. Methane losses from natural gas systems account for 15% of total worldwide methane emissions (ref. Methane to Markets). In Canada, a national emissions inventory prepared by the Canadian Association of Petroleum Producers (CAPP, 2004) estimates that fugitive equipment leaks account for approximately 25% of the methane and VOC emissions and approximately 12% of the overall carbon dioxide equivalent (CO₂E) emissions from the upstream oil and gas sector.

Fugitive emissions can either be intentional (i.e. venting from tanks, controllers, stacks, etc.) or unintentional due to normal wear and tear, improper or incomplete assembly of components, inadequate material specification, manufacturing defects, damage during installation or use, corrosion, fouling and environmental effects. Fugitive emissions potentially cost the oil and gas industry millions of dollars in lost product and can pose safety risks to workers and the public.

Opportunities to reduce fugitive emissions from oil and gas operations generally fall into one of the following categories:

1. Technology or equipment upgrades, that reduce or eliminate equipment venting or fugitive emissions;
2. Improvements in operational practices to reduce venting; and
3. Employment of best management practices, such as leak detection and repair programs that take advantage of improved leak detection and emission measurement technology.

The Clean Air Strategic Alliance (“CASA”) in Alberta has put forth recommendations regarding the control of fugitive emissions from the oil and gas industry. In response to these recommendations, the Canadian Association of Petroleum Producers (“CAPP”), the Small Explorers and Producers Association of Canada (“SEPA”), Environment Canada (“EC”) and the Alberta Energy and Utilities Board (“EUB”) have recently developed a Best Management Practices (“BMP”) document that will assist the Canadian upstream oil and gas sector in managing fugitive emissions from its operations. This is intended to be achieved through the development and implementation of Directed Inspection and Maintenance (“DI&M”) programs at existing UOG facilities.

There have been a number of technological advancements in recent years with regard to the detection and quantification of fugitive equipment leaks at upstream oil and gas facilities. In an effort to supplement previous technology evaluation work conducted by other agencies (e.g. CAPP and the U.S. Natural Gas STAR Program), the Petroleum Technology Alliance Canada (“PTAC”) Technology for Emission Reduction and Eco-Efficiency (“TEREE”) Steering Committee initiated a project for the “Review and Update of Methods Used for Air Emissions Leak Detection and Quantification” (the “Project”). Pertinent information regarding these emerging technologies was to be combined with previous information already gathered for the more traditional methods of leak detection and quantification. On August 25, 2006, the TERE Steering Committee awarded the contract to Envirotech Engineering. Clearstone Engineering was also retained to act as a technical advisor for the Project.

2.0 Scope of Work

The scope of work for this Project included the following tasks:

1. Identify existing and emerging leak detection and quantification technologies and methods;
2. Evaluate these technologies and methods based on costs, as well as their ability to identify, locate and quantify various substances; and
3. Summarize the key benefits and limitations of the various technologies and methods for regulatory and industry decision-making purposes.

In addition to the above, a number of products that utilize these technologies/methods were investigated and are described more fully in the Excel-based Information Tool (Tables 1 to 3) accompanying this report. However, it should be noted that the focus of this Project was on a review of the technologies/methods for leak detection and quantification. The review of the many products on the market was not “exhaustive” and is provided only as examples of the technologies/methods investigated.

3.0 Project Approach

The overall goal of this Project was to provide industry and government with pertinent information regarding both traditional and emerging methods/technologies for air emissions leak detection and quantification. This work was also intended to support the general guidance for fugitive emissions management at oil and gas facilities provided by CAPP through the recent release of its Best Management Practice (“BMP” – see section 5.3). This has been done in an objective and unbiased manner so that industry representatives and government could use the information provided to assist them in deciding which technologies/methods may be the most appropriate for their particular facility or circumstances.

The specific tasks relating to this Project included the following:

- Task 1:** On September 13, 2006, a Project Kickoff Meeting was held with the project sponsors and the TERE Air Emissions Leak Detection and Quantification project working group (“The Working Group”). The intent of the meeting was to obtain feedback on the Project from the Working Group and to refine the format of the Excel-based Information Tool Template that Envirotech developed to summarize the key benefits and limitations of the various technologies and methods.
- Task 2:** A thorough desktop review of the many different methods, technologies and products for fugitive emission detection and quantification was conducted. As mentioned previously, investigative work conducted by CAPP and the U.S. Natural Gas STAR Program was not duplicated, but was summarized as part of the review process.
- Task 3:** Interviews with technology and product suppliers were undertaken in order to gain first hand knowledge of the key benefits, applicability and costs of implementation of the various technologies. A list of the technology and product suppliers contacted is provided in Appendix A.

- Task 4:** A number of representatives from industry who are responsible for fugitive emission management programs for their respective companies and who have first-hand experience in the implementation of some of the technologies/products were interviewed to obtain their opinions regarding strengths and limitations of the technologies/products they implemented at their facilities.
- Task 5:** On November 22, 2006, an interim meeting with the Working Group was held to discuss the findings to date and to obtain feedback prior to report preparation.
- Task 6:** On December 22, 2006, three separate summary tables (the Excel-based Information Tool) were submitted to the Working Group for review and comment:
- Table 1 - Point Source Leak Detection and Measurement Methods categorized as either (a) close range, (b) remote sensing, or (c) airborne;
- Table 2 - Point Source Leak Quantification Methods; and
- Table 3 - Area Source Leak Detection and Quantification Methods.
- The tables included a technical description of the various methods/technologies evaluated, a review of the various products and suppliers, as well as information of the facility type and substance applicability, commercial viability, safety performance, strengths, limitations and cost of implementation for the various methods.
- Task 7:** A draft report documenting the findings of the Project was prepared. The report was submitted to the Working Group for review on January 22, 2007.
- Task 8:** After obtaining comments from the Working Group and project sponsors, the draft report and the Excel-based Information Tool were finalized.
- Task 9:** The report findings are to be presented at a PTAC-facilitated information session in 2007.

4.0 Project Deliverables

The deliverables for this Project included the following:

1. A final report summarizing the findings of the investigation. These findings included a detailed description of the leak detection and quantification technologies/methods that were reviewed, their applicability for different facility and substance types, their strengths and limitations as well as their costs for implementation.
2. An Excel-based Information Tool developed to summarize pertinent information regarding the technologies/methods and products investigated. The functionality of this Information Tool is further discussed in Section 4.1 below.
3. A presentation at a PTAC-facilitated information session.

4.1 Excel-based Information Tool

The criteria for the development of the Excel-based Information Tool (Tables 1 to 3 accompanying this report) were that it must be easy to use, maintain, update and manage so that it could be updated periodically with new technology/method and product information. The functionality of Excel allows the user to easily filter for those technologies/methods that meet their specific criteria. For further detail regarding the use of the Excel's AutoFilter capabilities, please refer to Appendix B.

Please note that the information contained in the Excel-based Information Tool (Tables 1 to 3) is best viewed with a zoom rate of 75%. These tables were prepared in order to provide as much information as possible on the various technologies/methods and products that were reviewed. As a result, the width of the tables exceeds the typical printer's ability to provide a readable printout. The tables have been formatted for on-line viewing only. However, condensed versions of Tables 1 and 3 are also included for printing on 11 X 17.

Please also note that when reviewing the Excel tables, the length of text displayed in a cell is limited to 1,024 characters. In order to read the full text for cells that exceed this number of characters, click directly onto the cell. The full text for that cell will be able to be reviewed in the formula bar.

5.0 Regulatory Framework

The following sections provide a brief description of the regulatory references for the identification, control and management of fugitive emissions.

5.1 US EPA Method 21

The current work practice, described as US EPA Method 21 ("Method 21"), is used primarily for the measurement and control of fugitive volatile organic compound (VOC) emissions from equipment leaks at petroleum refineries and organic chemical plants.

According to Method 21 (US EPA Method 21), leak definition concentration means the concentration at the surface of a leak source that indicates that a hydrocarbon emission (leak) is present. The leak definition is an instrument meter reading based on a reference compound. The reference compound is the hydrocarbon species selected as the instrument basis for specification of the leak definition concentration (for example, if a leak definition concentration is 10,000 ppm as methane, then any source emission that results in a local concentration on an instrument meter calibrated with methane would be classified as a leak. In this example, the leak definition concentration is 10,000 ppm and the reference compound is methane).

Method 21 involves a portable monitor used to detect leaks of hydrocarbons and hazardous air pollutants directly at the surface of the component. This method is intended to locate and classify leaks only, and is not to be used as a direct measure of mass emission rate from individual sources. The instrument detector type is not specified, but it must respond to the compounds to detect and also meet the specifications and performance criteria contained in Section 6.0 of the

Method 21 document. According to the document, detector types include, but are not limited to catalytic oxidation, flame ionization, infrared absorption, and photoionization.

The specifications for the monitoring instrument require that:

1. The instrument must be able to respond to the compounds being processed;
2. Both the linear response range and measurable range of the instrument must encompass the leak definition;
3. The scale of the instrument meter must be readable to $\pm 2.5\%$;
4. An electrically driven pump must be used to ensure that a sample is provided to the detector at a constant flow rate and that the nominal flow rate at the tip of the probe be 0.10 to 3.0 liters per minute;
5. The instrument must be intrinsically safe; and
6. The probe or probe extension must not exceed $\frac{1}{4}$ in. in outside diameter;

The performance criteria for the monitoring instrument require that:

1. The response factor for each VOC to be measured must be <10 ;
2. The response time must be ≤ 30 seconds; and
3. The calibration precision must be $\leq 10\%$ of the calibration gas value.

A procedure for monitoring is described in the following paragraph (US EPA Method 21):

“Place the probe inlet at the surface of the component interface where leakage could occur. Move the probe along the interface periphery while observing the instrument readout. If an increased meter reading is observed, slowly sample the interface where leakage is indicated until the maximum meter reading is obtained. Leave the probe inlet at this maximum observed meter reading location for approximately two (2) times the instrument response time. If the maximum observed meter reading is greater than the leak definition in the applicable regulation, record and report the results as specified in the regulation”.

The current regulatory standards for equipment leaks at petroleum refineries and organic chemical plants assume that Method 21 is the sole means of leak detection. However, this method is based on a 25-year-old technology, and therefore it holds a number of significant limitations. The following are some of the Method 21 limitations (Encompas, 2006):

1. Method 21 has a very limited distance of effectiveness. As gas exits the equipment, its concentration will be 100% (1×10^6 ppm), but as the gas diffuses into the atmosphere, the concentration in the plume will decrease. Because the gas from an equipment leak is pulled into the probe under slight negative pressure, the probe dilutes the concentration by pulling in ambient air from around the leaking component. The instrument's effectiveness at capturing the leaking gas decreases very rapidly with distance from the leak interface and the inlet to the probe (thus the limit on maximum outside diameter of the probe). Several probe diameters away from the probe inlet (maybe even less than a half inch), there can be almost negligible capture. The poor capture capability of the analyzers makes them especially sensitive to changes in gas flow rates through the analyzer. As the flow rate decreases, the ability to draw in the emission plume decreases. This increases

the importance of keeping the probe in close proximity to the component and trying various orientations.

2. Factors such as temperature at which measurements are being taken, physical variables associated with the leak measurement, such as pressure behind the leak, size of hole or porosity of the leaking component, wind, incorrect positioning of the sampling probe, interference from other nearby leakers affecting background levels, accessibility to components for sampling, interference from insulation coverings, slow response time, not taking long enough time to find a leak, leaking probes, handles, plugged probes and others will impact on the results to a lesser or greater degree.
3. There are a number of potential sources of error in determining whether or not a component is "leaking". Using equipment that meets the specifications required under Method 21, these sources of error include:
 - a) calibration gas error of $\pm 2\%$;
 - b) error between the analyzer reading and the calibration gas (precision $\pm 10\%$);
 - c) error between the analyzer and sampled gas (affects response factor which must be <10);
 - d) error in reading the analyzer meter of $\pm 2.5\%$.
4. Method 21 is limited, because it cannot be used on inaccessible components and it will also miss "leaking" components if they were not surveyed.
5. It is costly, as it requires intensive labor to monitor every component individually. Only up to approximately forty (40) components per hour can be surveyed using this method. This method is generally perceived to be overly burdensome due to the fact that 100% of components must be surveyed to meet the compliance requirements when the majority (up to 98 %) of the surveyed components do not leak.
6. After the leak detection and repair program has been used for a few periods, the number of leaks detected decreases because pre-existing leaks have been repaired and may not leak for extended periods of time. Although repair costs decrease as the number of leaks are reduced, the costs of conducting the Method 21 monitoring remains relatively constant, resulting in a decrease in cost-effectiveness.

For the purposes of developing an overall emissions inventory, fugitive emissions from a facility can be estimated using Method 21 screening data by applying emission factors or correlation methods such as the following:

- Leak/no leak emission factors;
- Three-stratum emission factors;
- Published leak-rate correlations, and
- Unit specific leak-rate correlations.

It should be noted, however, that fugitive emissions from a single component should not be quantified using these estimation methods as the emission rate from a single component may easily be in error by 2 to 3 orders of magnitude.

5.2 EUB Directive 060

On November 16, 2006, the EUB released a bulletin 2006-41 that announced the November 2006 transition from Guide 60 “Upstream Petroleum Industry Flaring Guide and Guide 60 Updates and Clarifications” to Directive 060 “Upstream Petroleum Industry Flaring, Incineration, and Venting”. Directive 060 replaced all previous editions of Guide 60.

One of key revisions in the 2006 edition of Directive 060 is a new requirement for operators to develop and implement programs to address fugitive emissions at upstream oil and gas facilities. These programs must meet or exceed the CAPP Best Management Practice for Fugitive Emissions Management (Section 8.7 of Directive 060).

The requirements in the November 2006 edition of Directive 060 are effective January 31, 2007.

5.3 CAPP Best Management Practice for Fugitive Emissions Management (BMP)

The purpose of the recently released BMP (CAPP, 2007) is to help the UOG industry to cost effectively manage the most likely sources of significant fugitive emissions. Efficient management of fugitive emissions will minimize the potential for leaks and provide early detection and repair. The emissions of primary concern are methane (CH₄) and non-methane volatile organic hydrocarbons (NMVOC). The BMP is specific to the monitoring and control of fugitive equipment leaks.

The BMP:

1. Identifies the typical key sources of fugitive emissions at UOG facilities;
2. Presents strategies for achieving cost-effective reductions in these emissions through improved designs, DI&M practices, improved operating practices, and the application of new and retrofit technologies; and
3. Summarizes key considerations and constraints.

The BMP also considers the use of emerging technologies that have the potential to improve the efficiency and effectiveness of leak detection.

With respect to fugitive equipment leaks, the BMP defines a leak as a screening gas concentration of 10,000 ppm or more. This leak definition is derived from the 1993 Canadian Council of Ministers of the Environment (“CCME”) document entitled “Code of Practice for the Measurement and Control of Fugitive VOC Emissions from Equipment Leaks” and is based on the criteria outlined in Method 21. Below 10,000 ppm the emissions are generally too small to quantify.

According to the BMP, leak screening must be done on accessible equipment components using a portable organic vapor analyzer in accordance with Method 21, **or using such alternative methods that provide a reasonable measure or estimate of a leak (10,000 ppm or more)**. Alternative methods may involve the use of traditional monitoring devices that may not meet all of the performance specifications of Method 21, or new emerging methods/technologies that are capable of detecting a leak. This approach minimizes the potential for missed leaks and also

provides flexibility and practicability for facility operators to determine which method would be the most applicable for their particular facilities or circumstances.

The BMP identifies two (2) types of fugitive equipment leaks detection and concentration measurement methods: qualitative and quantitative. A leak detection method is deemed to be “quantitative” where it provides a leak detection capability consistent with, or better than, the leak definition (10,000 ppm or more) and provides a quantitative output that can be related to the leak definition. A leak detection method is deemed to be “qualitative” where it provides a leak detection capability consistent with, or better than, the leak definition (10,000 ppm or more) but is not able to provide a quantitative output that can be related to the leak definition. If a qualitative method can be enhanced to consistently provide quantitative output that can be related to the leak definition then it may be reclassified as a quantitative. In any gas detection application, the method used must be appropriate for the use and capable of detecting a leak.

6.0 Categorization of Technologies/Methods Reviewed

The technologies/methods (traditional and emerging) that were reviewed as part of this Project have been categorized into three (3) separate topic groups:

1. Point source leak detection and concentration measurement technologies/methods;
2. Point source leak quantification methods; and
3. Area source emissions leak detection and quantification technologies/methods.

Point source leak detection and concentration measurement technologies/methods are those that are used to detect and/or measure fugitive emissions from equipment component leaks and pipelines. Area source leak detection emissions quantification technologies/methods are those that are used to detect and/or measure emissions from area sources within a facility, including emissions from an entire facility.

Point source leak detection and concentration measurement methods are further categorized into the following (see Section 7.0):

- Close range detection and measurement methods;
- Remote sensing methods; and
- Airborne methods.

Close range detection and measurement methods and remote sensing methods are used to detect and/or measure emissions from components contributing to fugitive equipment leaks; the airborne methods/technologies detect and/or measure fugitive gas emissions from pipelines.

The following close range detection and measurement methods technologies/methods were reviewed (see Section 7.1):

1. Flame Ionization (FI);
2. Photoionization (PI);
3. Catalytic Combustion (CC);
4. Solid-State (SS);

5. Infrared Absorption (IR);
6. Tunable Diode Laser Absorption Spectroscopy (TDLAS);
7. Bubble Test; and
8. Acoustic Leak Detection.

The following remote sensing technologies/methods were reviewed (see Section 7.2):

1. Passive IR Gas Imaging -Thermal Imaging;
2. Passive IR Gas Imaging -Image Multi-Spectral Sensing; and
3. Open Path - Tunable Diode Laser Absorption Spectroscopy (TDLAS)

The following airborne technologies/methods were reviewed (see Section 7.3):

1. Tunable Diode Laser Absorption Spectroscopy (TDLAS);
2. Differential Absorption LIDAR (Airborne DIAL); and
3. Passive Gas Filter Correlation Radiometry (PGFCR).

The following point source quantification methods were reviewed (see Section 8.0):

1. Bagging;
2. Hi-flow sampling;
3. Rotameters and other Flow Metering Devices; and
4. Tracer Gas Detection.

The following area source leak detection and quantification technologies/methods were reviewed (see Section 9.0):

1. Light Detection and Ranging/Differential Absorption Lidar (LIDAR/DIAL);
2. AIR Detection and Ranging (AIRDAR);
3. Open Path Tunable Diode Laser Absorption Spectroscopy (TDLAS); and
4. Open Path Fourier Transform Infrared (FTIR).

Each technology was reviewed based on its ability to identify, locate, detect and/or quantify different types of hydrocarbon pollutants, technology strengths and limitations as well as technology implementation costs (capital and operating). Various products and suppliers of the products were also identified and the information was collected.

The findings are summarized and presented in Tables 1 through 3 of the Excel-based Information Tool accompanying this report.

Please refer to **Appendix C - North American and European Hazardous Area Standards and Approvals** and **Appendix D – Laser Safety** for further information regarding safety performance specifications of the various technologies/methods and products reviewed.

7.0 Point Source Leak Detection and Concentration Measurement Methods

There are many different technologies (traditional and innovative) currently available for the detection of fugitive equipment leaks. They all utilize different physical and/or chemical properties of the gas, which can be used as a method of detecting its presence.

A summary of the findings for this category is provided in Table 1 of the accompanying Excel-based Information Tool.

7.1 Close Range Detection and Measurement Methods

7.1.1 Flame Ionization Detection (FID)

Description of the Method

The Flame Ionization (FI) detection method is based on measuring organic compounds by utilizing a flame produced by the combustion of hydrogen and oxygen (air). When hydrocarbons in the sample are introduced to the detection zone, ions are produced. A collector electrode with a polarizing voltage is also located within the detection chamber, and the ions produced by this reaction are attracted to it. As the ions migrate toward the collector, a current is produced which is directly proportional to the concentration of hydrocarbons introduced to the flame. The current is then amplified and sent to a microprocessor or analog readout device.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Flame ionization detection is a quantitative method. Units of quantification are ppmv.

Method Strengths

1. High sensitivity to most hydrocarbons;
2. Ability to measure methane;
3. Wide dynamic and linear range;
4. Fast, stable and repeatable response; and
5. Virtually unaffected by CO, CO₂, and water vapor.

Method Limitations

1. The method is less sensitive to aromatic and chlorinated compounds than the Photoionization (PI) detection method;

2. Cannot measure inorganic compounds, including hydrogen sulfide;
3. Low oxygen can affect the characteristics of the hydrogen flame, causing readings to be artificially elevated and possibly extinguishing the flame (greater than 14% oxygen is required to support the flame);
4. Concentrations greater than about 50000 ppm (5%) will flame-out an FID which will result in increased screening time due to needing restart the flame.
5. If high concentrations of hydrocarbons or inert gas samples with low oxygen concentrations are to be measured by the FID method, a dilutor kit needs to be used to combat the problem,
6. Requires 20-30 minutes to warm up prior to use;
7. Requires a constant supply of hydrogen carrier gas. Hydrogen must be stored in a high pressure gas cylinder to operate the instrument; and
8. An FID detector can be easily damaged if it draws in any water and therefore should not be used if it is wet outside.

Costs

Costs associated with the purchase of the FID detectors that were reviewed in this study are approximately \$12,000.

7.1.2 Photoionization Detection (PID)

Description of the Method

The Photoionization (PI) detection method is based on measuring organic compounds by utilizing an ultra violet (UV) emitting lamp to ionize a wide range of VOCs. A PI detector (PID) consists of an UV lamp of a specific energy and an ionization chamber. Compounds passing through the chamber are excited by photons of UV energy from the lamp and are ionized. These ions are attracted to a collecting electrode, producing a current proportional to the concentration of the compound. Whether or not a compound can be detected by a PID depends upon the lamp energy and the energy required to remove an electron from the compound (its ionization potential). If the lamp energy is greater than the compound's ionization potential, the PID will detect it. The standard lamp in the commercial PID is 10.6eV, however most of the PIDs can utilize 9.6, 10.0, and 11.8eV lamps. The 11.8 eV lamp permits detection of many compounds not ionized by the standard lamp, while the lower energy lamps allow more sensitivity by not responding to undesired compounds with a higher ionization potential.

Pollutants the Method is able to Detect

Methane: No
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: Yes

Type of Detection Qualitative/Quantitative the Method can provide

Photoionization detection is a quantitative method. Units of quantification are ppmv.

Method Strengths

1. The PID does not require hydrogen or oxygen; therefore, it would be a method of choice when fuel is limited or unavailable, or when ambient oxygen concentrations are low;
2. The PID is more sensitive to aromatic (benzene for example) and chlorinated compounds, and can measure some inorganic compounds that the FID does not detect at all (hydrogen sulfide for example);
3. It is very simple in operation; and
4. Non-destructive detector allows sample to be recovered.

Method Limitations

1. The PID does not respond to methane at all;
2. Because of its smaller dynamic range (0-2000 ppm in majority PID analyzers), the PID would not be the detector of choice for measuring high concentrations of vapors (unless a dilutor kit is used);
3. The PID is more susceptible to interference from water vapor than the FID;
4. Ethane can be detected with use of the 11.7 eV lamp only; and
5. 11.7 eV lamps have a very short life and are adversely affected by humidity.

Costs

Costs associated with the purchase of the PID detectors that were reviewed in this study are approximately in a range from \$4,500 to \$5,700.

7.1.3 Catalytic Combustion (CC)

Description of the Method

Catalytic combustion (CC) detection is the original method on which modern gas detection was based. Catalytic bead sensors/or catalytic pellistor sensors are used to detect combustible gases. Combustible gas mixtures will not burn until they reach an ignition temperature. However, in the presence of certain chemical media, the gas will start to burn or ignite at lower temperatures. This phenomenon is known as a catalytic combustion. Platinum, palladium, and thoria compounds are excellent catalysts for combustion. A gas molecule oxidizes on the catalyzed surface of the sensor at a much lower temperature than its normal ignition temperature. All electrically conductive materials change their conductivity as temperature changes. This is called the coefficient of temperature resistance. Platinum has a large coefficient of temperature resistance in comparison to other metals. In addition, its coefficient of temperature resistance is linear between 500°C to 1000°C, which is the temperature range at which the sensor needs to operate. Because the signal from the sensor is linear, this means that the concentration of gas readings is in direct proportion to the electrical signal. The electrical circuit used to measure the output of catalytic sensors is called a Wheatstone bridge. Pellistor detectors consist of two coils of fine platinum wire each embedded in a bead of alumina, connected electrically in a bridge circuit. One of the beads is impregnated with a special catalyst which promotes oxidation whilst the other is

treated to inhibit oxidation. Current is passed through the coils so that they reach a temperature at which oxidation of a gas readily occurs at the catalyzed bead (about 500°C). This raises the temperature further which increases the resistance of the platinum coil in the catalyzed bead, leading to an imbalance of the bridge. This output change is linear, for most gases, up to and beyond 100% Lower Explosive Limit (LEL) and response time is only a few seconds.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Catalytic combustion detection is a quantitative method. Units of quantification are ppmv. However, it can be also used as qualitative method in "sniffing" devices.

Method Strengths

1. Catalytic sensors are sensitive to most flammable gases and vapors. Therefore, it is possible to use one detector to monitor a wide range of flammable gases and vapors;
2. Catalytic sensors respond in direct proportion to the degree of explosivity (LEL) of the sample; and
3. Catalytic sensors are easy to manufacture; therefore, they are relatively cheaper than all other gas measuring devices. However, the quality of the sensor varies quite drastically from one manufacturer to another.

Method Limitations

1. Catalytic bead type sensors are intended for use below the LEL, and usually scaled from 0-100 % LEL;
2. Catalytic bead type sensors must "burn" the gas on the surface of the bead. Therefore, high concentrations of hydrocarbons above LEL or inert gas samples with low oxygen concentrations will cause limited combustion or no combustion at all. This will result in dangerously low false readings or no readings at all;
3. If a catalytic sensor is exposed to gas above the UEL for more than a few minutes, it may suffer reduction in sensitivity caused by "sooting". The degree of sensitivity reduction and whether the effect is permanent will depend on the gas. Aromatic compounds, having a high carbon content cause the worst problems;
4. Catalytic sensors can be "poisoned" temporarily (e.g. by compounds containing halogens, sulphur or chlorine) or permanently (e.g. by substances containing lead or silicones such as common oil and lubricants with silicon compounds used as additives in machinery). This has the effect of reducing sensor's sensitivity and a sensor eventually becoming totally nonresponsive to gases;
5. Because catalytic sensors "burn" the gas being detected, sensor material is consumed and changed in the process and the sensor eventually burns out (life time is usually two (2) years);

6. In a Wheatstone bridge, there is no self compensation for component aging and in particular the changing performance characteristics of the measuring and reference elements. That will cause a sensor drift;
7. The measuring circuitry and the catalytic reaction itself requires the use of a "sintered filter" to cool heated gases and prevent ignition of the combustible atmosphere, which significantly increases this technology's response speed.
8. A catalytic detector can be easily damaged if it draws in any water and therefore should not be used if it is wet outside; and
9. Oily mist from seal vents and crank case vents can easily deactivate catalytic detectors.

Costs

Costs associated with the purchase of the catalytic pellistor detectors that were reviewed in this study are approximately \$4,000.

7.1.4 Thermal Conductivity (TC)

Description of the Method

Thermal conductivity (TC) detection is based on the principle that gases differ in their ability to conduct heat. A TC detector consists of two elements, typically a pair of wires (filament) or thermistors that are heated above ambient temperature. One of the elements (active) is exposed to the gas sample to be measured, and the second element (reference) is exposed to a reference gas (usually air). If the sample gas has a different thermal conductivity as compared to the reference gas, the temperature of the active filament will change as compared to the reference element. As with the catalytic bead type sensor, the resultant temperature change results in a resistance change that is measured with a Wheatstone bridge circuit to produce a digital reading proportional to the gas concentration. The greater the thermal conductivity of the sample, the cooler the exposed filament will become. This will cause a reduction of resistance which will be proportional to the concentration of the gas in the sample.

Pollutants the Method is able to Detect

Methane: Yes

NMVOC: Yes

Benzene: Yes

Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Thermal conductivity detection is a quantitative method. Units of quantification are ppmv. However, it can be used as qualitative method in "sniffing" devices.

Method Strengths

1. The TC type detector has the ability to detect concentrations of flammable gases and vapors up to 100% by volume, well above LEL and UEL ranges;
2. The TC sensor can be used for a variety of gases, and does not require oxygen to operate; and

3. The thermal conductivity method is a physical method. It does not involve any chemical or electrochemical reactions. It depends only on the relative cooling capability of one gas over another, as they are exposed to heated filaments in a bridge circuit. Therefore, the TC sensor has a long life.

Method Limitations

1. The TC detector has low sensitivity in the LEL range and it is intended for detection of combustible gases above % LEL and up to 100% by volume. Therefore, thermal conductivity sensors are always used in conjunction with catalytic combustible bead sensors providing dual range combustible capability;
2. Gases with thermal conductivities of less than one (1) are more difficult to measure, partly because they cause an interference problem;
3. Gases with thermal conductivities close to one (1) cannot be measured by this technique; and
4. Because the thermal conductivity of different gases as compared to air can vary widely, and be either positive or negative in direction, the thermal conductivity detector must be tuned or calibrated for a specific gas or vapor.

7.1.5 Solid State (SS)

Description of the Method

The solid-state (SS) or semi-conductor technology is an alternative to the catalytic combustion technology. A solid-state sensor (SSS) consists of one or more metal oxides from the transition metals, such as tin oxide, aluminum oxide, etc. In the presence of gas, the metal oxide causes the gas to dissociate into charged ions or complexes which results in the transfer of electrons. A pair of biased electrodes is imbedded into the metal oxide to measure its conductivity change. The changes in the conductivity of the sensor resulting from the interaction with the gas molecules are measured as a signal. A heating element is used to regulate the sensor temperature, since the finished sensors exhibit different gas response characteristics at different temperature ranges. The built-in heater, which heats the metal oxide material to an operational temperature range that is optimal for the gas to be detected, is regulated and controlled by a specific circuit.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Solid-state detection is a quantitative method. Units of quantification are ppmv. However, it can be also used as qualitative method in “sniffing” devices.

Method Strengths

1. Solid-state sensors (SSSs) are among the most versatile of all sensors, as they detect a wide variety of gases, and can be used in many different applications;
2. SSSs respond to the widest possible range of toxic and combustible gases, including chlorinated solvent vapors and other contaminants difficult to detect by other means. Different response characteristics are achieved by varying the semiconductor materials, processing techniques, and sensor operating temperature;
3. The SSS is a good choice to use to detect gases that can "poison" the catalytic sensors and make them impossible to use;
4. The SSS is able to detect both low ppm levels of gases, as well high combustible levels. This greatly simplifies the system design and maintenance required because it eliminates or minimizes the use of multiple sensor technologies which must be designed and maintained differently;
5. The SSS provides better sensitivity and faster response in a low range of combustible gases than the catalytic combustible gas sensor;
6. The main strength of the SSS is its long life expectancy up to ten (10) years or more; and
7. As catalytic sensors "burn" the gas being detected which eventually will cause a sensor to burn out, SSSs simply "absorb" gas into the sensor surface. When the gas disappears, the sensor returns to its original condition. No sensor material is consumed in the process and therefore, the solid-state sensors offer a long life expectancy.

Method Limitations

1. SSSs are more susceptible to interference gases than the other types of sensors. These devices are generally unsuitable for use in industrial gas detectors, because they react to almost any gas, sometimes unpredictably. Thus, in applications where other background gases are present, SSSs may trigger false positive readings; and
2. Humidity affects the sensor's output. As humidity increases, sensor output increases as well. As humidity drops to very low levels, sensor output may fall to zero even in the presence of gas.

Costs

Costs associated with the purchase of the solid-state detectors that were reviewed in this study are in a range from \$300 to \$1,500.

7.1.6 Infrared Absorption (IR)

Description of the Method

Infrared (IR) detection is based on the fact that most combustible gases absorb infrared radiation at defined wavelengths at the mid-wave IR spectrum (3.3-3.5 μ m range) in a unique manner; therefore, they can be detected using infrared techniques. The principle of an infrared detector is based upon the absorption of the infrared light at the specific wavelength as it passes through the gas. The more of the absorbing gas that is present, the more light is absorbed. The detector measures the energy from an infrared light beam at a wavelength that is absorbed by the gas and compares it to the energy emitted by the source. The difference in energy received by the

detector indicates the level of the gas concentration. The IR energy absorption is directly proportional to the molecular structure of the hydrocarbon and, therefore, to the concentration of the hydrocarbon present.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Infrared detection is a quantitative method. Units of quantification are ppmv. However, it can be also used as qualitative method in "sniffing" devices.

Method Strengths

1. Infrared sensors are highly selective and offer a wide range of sensitivities, from ppm to 100% concentrations;
2. Infrared sensors measure many absorption lines over a wide wavelength range providing measurement of THC;
3. Periodic calibration must be done on all sensor types. However, on IR units, as long as the zero is maintained, the IR unit is assured a good response and good span accuracy. Because of this characteristic, abnormal functioning of an IR unit can be easily determined;
4. Gases to be detected are often corrosive and reactive. With most sensor types, the sensor itself is directly exposed to the gas, often causing the sensor to drift or die prematurely. The main advantage of instruments that utilize IR technology is that the detector does not directly interact with the gases to be detected. The major functional components of the analyzer are protected with optical parts. In other words, gas molecules interact only with a light beam;
5. Infrared technology is not oxygen dependant; therefore, it can operate in atmospheres which are oxygen deficient;
6. Modern infrared devices pass the infrared light through the measuring cell and back again via a reflector. As such, "sintered filters" to cool heated gases and prevent ignition of the combustible atmosphere are not required as they are in the case of catalytic combustion sensors. This significantly increases their response times, which is approximately three times faster than catalytic combustion sensors,
7. Although an IR detector is a temperature sensor and, therefore, is potentially very sensitive to changes in the ambient temperature (which can affect response times), a properly designed detector can be operated between -40°C and + 60°C without being susceptible to ambient temperature fluctuations. For outdoor applications, this usually is not a serious problem, because the ambient temperature changes slowly; and
8. For toxic and combustible gas monitoring applications, IR instruments are among the most user friendly and require the least amount of maintenance. Their robust design guarantees up to five (5) years of the IR sensor life.

Method Limitations

1. The IR detector is least sensitive to methane with its single bond. With propane and butane the sensitivity increases dramatically. Therefore, if the instrument is calibrated for 100% pure methane, only a few percent by volume of propane or butane will saturate the system. As a result, an IR sensor will greatly overstate the concentration of other hydrocarbons that may also be present resulting in false alarms;
2. H₂O and CO₂ cause interference in IR detectors as they both have absorption features in the same IR region;
3. The detectors in general, can be very slow to respond especially to high concentrations;
4. An IR detector is essentially a temperature sensor and, therefore, is potentially very sensitive to changes in the ambient temperature, which can affect response times;
5. For high concentrations the response time can be long;
6. The instrument requires 10-20 minutes to achieve temperature equilibrium, which is longer than the warm-up time required for other alternative technology instruments;
7. Water vapor condensation at the optics and/or the detector can seriously affect the performance of the analyzer;
8. Monitoring gas samples from dusty areas can also seriously affect the performance of the analyzer; and
9. Even though the infrared sensor is long-lived (3-5 years), it is the most expensive sensor in comparison to all other alternative combustible gas sensors.

Costs

Costs associated with the purchase of the IR detectors that were reviewed in this study are in a range from \$2,100 to \$4,800.

7.1.7 Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Description of the Method

Tunable Diode Laser Absorption Spectroscopy (TDLAS) for gas detection is based on the principle that gas molecules absorb energy in narrow bands surrounding specific wavelengths in the electromagnetic spectrum. At wavelengths slightly different than these "absorption lines", there is essentially no absorption. By transmitting a beam of the laser light through a gas mixture sample containing a quantity of the target gas (e.g., methane), tuning the beam's wavelength to one of the target gas's absorption lines, and accurately measuring the absorption of that beam, the concentration of target gas molecules integrated over the beam's path length can be calculated. The fraction of emitted laser power that is transmitted through the gas mixture is monitored with a photo detector.

Extractive measurement path (extractive sampling) is used for direct detection of methane leaks from industrial equipment. The methane concentration is measured within an optical cell installed in a measurement chamber through which the gas is continually drawn. The optical path length within the cell is designed to provide the required sensitivity to the methane gas. A multipass

optical cell (Herriot cell) is utilized to provide a long optical path length within a small volume, in many cases yielding sub-ppm sensitivity with one second or faster response. The light beam ends up making many passes through the sample gas as it bounces back and forth between the spherical mirrors in the chamber. By the time the light exits the sample chamber and hits the detector in the laser chamber it has traveled a physical distance of a few meters. Traveling this distance enhances absorption of the light.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: No
Benzene: No
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

In extractive sampling systems, Tunable Diode Laser Absorption Spectroscopy is a quantitative method. Units of quantification are ppmv. However, it can also be used as qualitative method in "sniffing" devices.

Method Strengths

1. The laser light is selective to methane, and will not false alarm on other hydrocarbons;
2. The TDLAS technology provides immediate response to methane leaks;
3. The TDLAS technology provides the most interference free method of any analytical technique;
4. It provides high sensitivity due to being insensitive to temperature variances, vibrations and humidity and also because of using a multipass optical cell;
5. Measurements of gas concentrations are unaffected by the presence of particles, including rain and snow;
6. One technology provides detection range of 0-100% volume for faster leak classification;
7. There is no "poisoning" or degradation of the instrument with long term exposure to a gas; and
8. The systems are self calibrating and require annual calibration only.

Method Limitations

1. Only one (1) gas can be measured with each instrument; and
2. The method has potential for uncertainty in the gas concentration measurement, since the instrument will not respond to the other constituents of natural gas and so will be in error by an amount equal to the methane deficit. The lower the proportion of methane in the natural gas, the greater the underestimate of gas concentration will be.

Costs

Costs associated with the purchase of a TDLAS detector that was reviewed in this study are approximately \$14,000.

7.1.8 Bubble Tests

Description of the Method

A bubble test is an alternative to the EPA Method 21 screening procedure. This is a qualitative method that detects all hydrocarbon gases. Using this method, up to hundred (100) components can be screened per hour. This method is based on the formation of bubbles in a soap solution that is sprayed on a potential leak source. A pressure sprayer or squeeze bottle may be used to disperse the solution on potential leak sites to determine if any bubbles are formed. If no bubbles are observed, the source is presumed to have no detectable emissions or leaks as applicable. If any bubbles are observed, the EPA Method 21 or alternative instrument techniques need to be used to determine if the leak has emissions of 10,000 ppm or greater.

Pollutants the Method is able to Detect

The bubble test detects all hydrocarbon gases and toxic gases, including hydrogen sulfide.

Type of Detection Qualitative/Quantitative the Method can provide

The bubble test is a qualitative method.

Method Strengths

The bubble test can be used in all cases of equipment leak detection except for those that are described in the Method Limitations paragraph.

Method Limitations

The bubble test cannot be used in the following cases:

1. On potential sources that have continuously moving parts;
2. On potential sources that have surface temperatures greater than the boiling point or less than the freezing point of the soap solution;
3. On potential sources that have open areas to the atmosphere that the soap solution cannot bridge; and
4. On potential sources that exhibit evidence of liquid leakage.

Costs

The soap solution may be a commercially available leak detection solution or it may be prepared using concentrated detergent and water. Therefore, purchase costs for this method are insignificant.

7.1.9 Acoustic Leak Detection

Description of the Method

Acoustic leak detection is based on a principle that when gas moves from a high-pressure to a low-pressure environment across a leak opening, the turbulent flow produces an acoustic signal. A piezoelectric microphone is used to receive sound pressure waves at a specific frequency. Acoustic screening devices are designed to detect either high frequency or low frequency signals. High frequency acoustic detection is used on leaking components that are accessible to a handheld sensor. In this case, the acoustic sensor is placed directly on the equipment orifice to detect the signal. Ultrasound leak detection is an acoustic screening method that detects airborne ultrasonic signals in the frequency range of 20 kHz to 100 kHz. It has been well documented that 40 kHz is the optimal frequency for listening for different kinds of industrial defects, including gas leaks. Ultrasonic detection technology can pinpoint the location of leaks from a distance by having an ultrasonic detector equipped with a hand-held acoustic probe that is aimed from a distance at the potential leak source.

Pollutants the Method is able to Detect

Acoustic leak detection detects all hydrocarbon gases and toxic gases, including hydrogen sulfide.

Type of Detection Qualitative/Quantitative the Method can provide

Acoustic leak detection is a qualitative method.

Method Strengths

1. Acoustic detectors do not measure leak rates; however, they provide a relative indication of leak size - a high intensity or "loud" signal corresponds to a greater leak rate;
2. Acoustic technology provides immediate detection of leaks;
3. Acoustic technology provides high sensitivity of leak detection;
4. High frequency acoustic detection is best applied in noisy environments;
5. Ultrasound detection is directional; therefore, it can be used to pinpoint leaks from distances as great as thirty (30) meters;
6. Ultrasound detection is useful for identifying gas leaks from hard to access equipment components;
7. Acoustic detectors have easy to use controls; and
8. Acoustic detectors do not require calibration or special maintenance.

Method Limitations

1. High frequency waves (those that are far above 40 kHz) do not have sufficient energy to be detectable from reasonable distances. Therefore, high frequency acoustic detection can only be used on leaking components that are accessible to a handheld sensor;

2. Ultrasound detection can not distinguish what compound is leaking (natural gas, instrument air, steam) without tracing lines. Therefore, acoustic techniques are often better used in conjunction with a gas detector that can positively identify the leak;
3. Ultrasonic leak detectors should not be used when the components are wet (e.g., after a rain or from bubble test) or in areas with lots of high frequency process noise;
4. Ultrasound detection may be sensitive to background noise; and
5. Ultrasonic sensors are incapable of determining leakage flow rate.

Costs

Costs associated with the purchase of acoustic leak detectors that were reviewed in this study vary from \$4,700 to \$37,000.

7.1.10 Combined Close Range Detection and Measurement Methods

Gas monitoring applications are generally classified into toxic or combustible range monitoring. Toxic gas monitors are usually used for human health protection and the ranges of the monitors are three (3) to five (5) times higher than permissible exposure limits. For most toxic gases, ranges of measurements are in ppm concentrations. Combustible gas monitors are generally used for process gas monitoring, including fugitive natural gas leak detection. For fugitive natural gas leak detection applications, the gas concentrations are high and are generally in the range of several percent. Therefore, a selected technology/sensor must be able to measure high gas concentrations.

For portable natural gas leak detection, flame ionization (FID) and catalytic combustion (CC) detection methods have served the oil and gas industry over the last twenty (20) years. Pellistor sensors in the catalytic combustion method and flame ionization detectors in the flame ionization method operate gas concentrations on the ppm scale as well as on the %LEL scale. The thermal conductivity method is typically employed to measure high concentrations of gases in the % volume range. Technologies such as solid state (or semi-conductor) and infrared (IR) cover the full gas concentration range of ppm, %LEL and % volume gas concentrations. However, both solid state and infrared methods suffer from major limitations for gas detection such as high cross-responses to the other gases found within the composition of natural gas (over-reading up to 60%) and in some cases cannot be used to detect gases in all concentration ranges. A new optical detection method utilizing tunable diode laser absorption spectroscopy (TDLAS) has become available in recent years and it offers the most interference free method of any analytical technique. The method covers the full gas concentration range of ppm, %LEL and % volume gas concentrations. However, only one (1) gas (methane) can be measured with each instrument. As a result, the method poses a potential for uncertainty in the gas concentration measurement, as it will not respond to other constituents of natural gas. Therefore, there will be error in readings of the total emissions by an amount equal to the methane deficit (the lower the proportion of methane in the natural gas, the greater the underestimate of the gas concentration will be).

There is no simple answer to which technology/method is the best for gas leak detection. Each technology has certain capabilities and limitations and thus the suitability of a given method largely depends on the application in which it is to be used. Therefore, to choose the correct method, firstly one must properly define application requirements. The following guide can be used to select a proper gas leak detection method depending on gases to be monitored:

Monitored gases	Method of Detection
Total hydrocarbons (THC)	Flame Ionization (FI)
Combustible Gases	Catalytic Combustion (CC) Solid-State (SS) Infrared (IR) Flame Ionization (FI)
Volatile Organic Compounds (VOC) Toxic Gases	Photoionization (PI) Solid-State (SS)
Other Gases	Thermal Conductivity (TC)
Methane-Specific Leak Detection	Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Other factors such as the ranges of the monitoring gases concentrations, presence of background gases, temperature ranges in the monitoring areas and the instrument temperature ranges specifications, humidity factor, weather conditions, whether the instrument will be constantly exposed to gas or not, safety, and costs should be considered when determining a method and an instrument for a given application.

In summary, an ideal gas leak detector should:

- be stable and accurate on the ppm, %LEL and % volume scales for natural gas (not simply methane);
- have a fast response time, which will also result in higher component count per hour;
- be specific to natural gas without cross-responding to other flammable vapours;
- be intrinsically safe;
- be rugged and corrosion-resistant;
- be weather- and dust-proof;
- be durable and long-term;
- be operationally stable;
- be easy to maintain;
- be operated by a minimally skilled person;
- be suitable for multi-sensor systems; and
- be of low cost.

Selection of a proper gas leak detector can usually be achieved by combining different detection methods/technologies in one (1) instrument. With respect to the safety performance requirements of the instrument, Appendices C and D of this report contain information pertinent to North American and European Hazardous Area Standards and Approvals and the US ANSI Laser Safety Standard (ANSI Z136).

7.2 Remote Sensing Methods

The current regulatory standards for equipment leak detection at petroleum refineries and organic chemical plants specify Method 21. More recently, remote sensing technologies have been developed and successfully used in detecting pollutants. These technologies have proven that they can enhance the effectiveness of the DI&M programs and also reduce operating costs.

These technologies/methods include:

1. Passive IR Gas Imaging:
 - Thermal Imaging;
 - Image Multi-Spectral Sensing; and
2. Open Path - Tunable Diode Laser Absorption Spectroscopy (TDLAS)

With respect to the gas imaging technologies, on April 6, 2006 the US EPA issued a proposed rule "Alternative work practice to detect leaks from equipment" that would establish use of gas plume imaging technologies as an alternative work practice to Method 21 for compliance with the EPA regulations. In order to compare existing (Method 21) and alternative (gas imaging) work practices ("AWP"), EPA developed a computer model that allowed the simulation of leaks as well as the effect of various leak definitions monitoring frequencies. The model performed a side by side comparison of alternative work practices to the current EPA reference Method 21 based work practice.

Based on a 1993 petroleum industry study, EPA developed a statistical relationship between measured (bagged) mass emissions and the associated measured Method 21 screening values. The statistical relationship was then used to simulate detection of leaks by the Method 21 work practice in the computer model. The modeling program compared the screening value of Method 21 to various leak definitions to determine if a leak would be detected. Similarly, the model assigned a mass rate detection limit to the AWP. The model generated different detection limits for the 500 and 10,000 ppmv thresholds in existing rules (the proposed rule reflects the mass detection limit for 500 ppmv, the more stringent limit which provides equivalency for both leak definitions). The results showed a work practice repeated bi-monthly with a detection limit of 60 g/hr range was equivalent to the existing work practice. The model also showed that a work practice repeated semi-quarterly with a detection limit of 85 g/hr range was equivalent to the existing work practice.

Several laboratory and field studies were also conducted to demonstrate that the optical gas imaging technology can routinely detect a mass rate of approximately 60 g/hr. In both the laboratory and field tests, the technology showed to find leaks. The tests also showed that the imagers could detect a leak with a mass rate of as low as 1 g/hr. It was determined that the imaging technology has negligible variance associated with its ability to detect leaks of 60 g/hr. Based on the modeling results and conducted studies, a leak mass rate of 60 g/hr was determined as the equivalent for an AWP.

Revisions to the regulations are expected to be finalized in 2007.

The above mentioned technologies were reviewed and evaluated in these studies.

7.2.1 Passive IR Gas Imaging

Description of the Method

Passive IR gas imaging is a method that images gas plumes using ambient thermal radiation. Passive methods of chemical detection rely on the imbalance of emission and absorption of chemical species in the field of view (i.e. visual scene) of the instrument. The spectral measurement of the transmitted, reflected, or emitted radiation within the infrared region of the electromagnetic (EM) spectrum reveals signatures due to the vibrational transitions that are unique to each molecule and chemical species. The EM spectrum can be expressed in terms of energy, wavelength, or frequency. Each way of defining the EM spectrum is related to the others in a precise mathematical way. The spectral response of a passive imager may or may not be restricted using filters, and the gas is imaged by adding or attenuating IR radiation in the image. Passive IR gas imaging requires a temperature emissivity product difference between the gas and the background scene in order to produce an image, the magnitude of which depends on the gas concentration, range and the sensitivity of the camera. Cameras/systems that employ this type of gas detection are called passive optical gas imaging cameras.

Method Strengths

1. Passive gas imaging technologies generate information as real time images;
2. Passive gas imaging does not need an artificial light source, such as laser; and
3. Passive gas imaging detection can operate at virtually unlimited range, whereas in active gas imaging the laser power increases as the stand-off distance is increased.

Method Limitations

Passive gas imaging requires a temperature emissivity product difference between the gas, the equipment being inspected and the background scene in order to produce an image.

7.2.1.1 Thermal Imaging

Description of the Method

Thermal IR gas imaging is based on a principle that all objects, including hydrocarbon gases emit infrared radiation as a function of their temperature. Infrared energy is generated by the vibration and rotation of atoms and molecules. The higher the temperature of an object, the more the motion and therefore, the more infrared energy is emitted. This is the energy that is detected by infrared cameras. At absolute zero (-273.16°C), material is at its lowest energy state so infrared radiation is at its lowest level. The cameras do not see temperatures, they detect thermal radiation. The IR camera captures the radiosity of the target it is viewing. Radiosity is the infrared energy coming from a target modulated by the intervening atmosphere, and consists of emitted, reflected and sometimes transmitted IR energy. Hydrocarbon gases have absorption/emission bands at characteristic wavelengths in the mid-wave infrared spectrum (3-5µm). If the gas is above ambient temperature, there is a net emission of radiation at these wavelengths; if the gas is below ambient temperature, there is a net absorption of radiation (Hodgkinson, J., and Pride, R.D., 2005).

The radiation may be imaged onto a detector array to produce a picture of the gas cloud. Infrared Thermography is the technique that is used to produce an image of invisible (to our eyes) infrared light emitted by objects due to their thermal condition. The most typical type of thermography camera resembles a typical camcorder and produces a live TV picture of heat radiation. More sophisticated cameras can actually measure the temperatures of any object or surface in the image and produce false color images that make interpretation of thermal patterns easier. The colors on an IR image vary due to variations in radiosity. An image produced by an infrared camera is called a thermogram. The technique has been further developed to employ gas correlation filters in front of the camera, to compare the detected signals with and without a gas reference.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Thermal IR gas imaging is a qualitative method and is currently waiting for a US EPA approval to become alternative to Method 21.

Method Strengths

1. Thermal imaging works by detecting the heat energy being radiated by objects and requires absolutely no light; therefore, it works under low lighting conditions as well;
2. Thermal imaging has the potential for imaging higher pressure leaks, where the gas cools on expansion and for imaging leaks against a heated background. Large leaks are located quickly and easily;
3. Being a remote sensing device, an IR camera is capable of locating leaks in areas which are considered inaccessible;
4. The camera can survey up to 1000-1500 components per hour, whereas a traditional type of an analyzer can do up to 400 components a day;
5. Surveying a site with the camera will not interrupt operations;
6. An IR camera has the ability to detect leaks in areas where they are not expected to be found; and
7. Field studies have shown that in many cases an IR camera could find leaks easier than a traditional OVA instrument.

Method Limitations

1. Currently, thermal imaging optical gas imaging cameras on the market display leaks in a black and white format; therefore, in areas of little contrast, the gas plume will not be visible;
2. Thermal imaging is not reliable for low-pressure leaks, small fugitive leaks, and leaks from buried pipework or other situations where a temperature difference cannot be guaranteed.

In these circumstances, if there is no image of a gas cloud, it is possible that there is no gas but also that there is no temperature contrast;

3. CO₂ and H₂O as well as fog, dust, smoke, and wind may interfere with the operation of the camera. Therefore, some instruments cannot be used outdoors;
4. Because CO₂ and H₂O have absorption features in the same IR region, the camera will “see” water vapor and CO₂;
5. Strong wind can dissipate the gas quickly and reduce the concentration below the threshold of the camera;
6. A thermal imaging camera cannot differentiate between steam and a leaking hydrocarbon;
7. Solar signature can add scattering or specular reflection signal that can enhance the gas image;
8. Proper training is required for an individual to be able to operate the camera; and
9. Gas imaging cameras are expensive (between \$75,000 -125,000).

Costs

Costs associated with the purchase of a thermal imaging camera that was reviewed in this study are approximately \$94,000 [the base unit (25 mm lens)].

7.2.1.2 Image Multi – Spectral Sensing (IMSS)

Description of the Method

The Image Multi-Spectral Sensing (patented technology 5,479,258) or IMSS is a technology that performs real-time imaging of fugitive hydrocarbon (any kind of gas) gas leaks using a combination of a patented diffractive optical system, the functionality of thermal imaging, and image processing algorithms implemented in real time using field programmable gate arrays (FPGA). The IMSS is based on the principle that diffractive optics have 7 times the chromatic aberration of conventional lenses. The IMSS uses the dispersive power of diffractive optics to disperse the light along the optical axis as well as the light gathering capability of the lens which allows a very high throughput through the instrument. A real-time-image processing function is performed in the embedded FPGA. Therefore, the IMSS is a combination of a diffractive imaging spectrometer and adaptive tunable filter. Using a single lens, the IMSS performs both imaging and dispersion.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: Yes

Type of Detection Qualitative/Quantitative the Method can provide

The Image Multi-Spectral Sensing is a qualitative and quantitative method. A Sherlock camera that employs this method has the ability to quantify and speciate petroleum gases in ppm and

g/hour, but currently these abilities are not implemented in real time in the camera. This ability is expected to be ready in a model that will be released in early 2007.

Method Strengths

1. The IMSS technology has the ability to collect single or multiple chemical species data and also to quantify the emissions;
2. The IMSS technology can process the image and paint the gas in a contrasting color (red or green) and thus display gases that are very low leakers;
3. The IMSS product Sherlock camera can work under low lighting conditions, because it uses the infrared spectral signature of the gas and background;
4. The IMSS can visualize and quantify CO₂ emissions. Dust, smoke, have a distinct spectral signature and can be differentiated from the gas of interest by analysis the spectrum;
5. The IMSS can differentiate between steam and a leaking hydrocarbon;
6. Being a remote sensing device, an IR camera is capable of locating leaks in areas which are considered inaccessible;
7. A camera can survey up to 1000-1500 components per hour, whereas a traditional type of an analyzer can do up 400 components a day;
8. Surveying a site with the camera will not interrupt operations;
9. An IR camera has the ability to detect leaks in areas where they are not expected to be found; and
10. Field studies have shown that that in many cases an IR camera could find leaks easier than a traditional OVA instrument.

Method Limitations

1. Strong wind can dissipate the gas quickly and reduce the concentration below the threshold of the camera;
2. Solar signature can add scattering or specular reflection signal that can enhance the gas image;
3. Proper training is required for an individual to be able to operate the camera; and
4. Gas imaging cameras are expensive (between \$75,000 -125,000).

Costs

Costs associated with the purchase of an Image Multi-Spectral Sensing Sherlock camera that was reviewed in this study are approximately \$125,000.

7.2.2 Open Path Gas Detection from Point Sources

Description of the Method

Open path gas detection is a method that is designed for long distance monitoring in ambient air and fence/perimeter monitoring of gases such as CH₄, H₂S, combustible hydrocarbons and others. For the point source detection, this method holds the following benefits and limitations:

Method Strengths

1. Open path gas detection is extremely sensitive to low concentration clouds of the gases, as the increased path length allows for greater absorption of hydrocarbon specific IR light;
2. Open path gas detection is ideal for detecting gas leaks from afar, reducing survey time and enabling more efficient use of manpower;
3. Open path gas detection is ideal for detecting leaks from inaccessible equipment components and in areas where leaks are not expected to be found;
4. Surveying a site will not interrupt operations; and
5. An average measurement is taken over the total path so that a narrow plume of gas has less chance of escaping detection.

Method Limitations

1. The open path technology cannot pinpoint leaks or differentiate between a small high concentration cloud of hydrocarbon gas or a large low concentration cloud of hydrocarbons and as such, should always be used in conjunction with "point specific" gas monitors; and
2. Very low flowing leaks may produce small to non-measurable plumes; and
3. Weather conditions like high winds and higher temperatures will cause a plume to dissipate faster.

7.2.2.1 Open Path Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Description of the Method

The TDLAS technology is based on utilization of infrared absorption spectroscopy using a laser diode as a light source. A single gas absorption line with no interference is chosen in the near IR spectral range. A single-mode diode laser operating at room temperature scans the single absorption line (methane in a case of hydrocarbon gases) and receives a fraction of the backscatter reflected from a target or from a retro-reflector that is used in some TDLAS system designs. A photodiode detector detects the light absorption caused by the target gas molecules, after which the gas concentration is calculated. The detector measures the path-integrated concentration of methane between the detector and the target, which is termed the methane column density, rather than the concentration at a local point. The column density has the dimensions of the product of the concentration (ppm) and length (m) and is described in units of ppm-m.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: No
Benzene: No
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

In open path applications, Tunable Diode Laser Absorption Spectroscopy is a semi-quantitative method. Units of quantification are ppm-m.

Method Strengths

1. The TDLAS technology provides the most interference free method of any analytical technique (not affected by H₂O vapour, CO₂);
2. The laser light is selective to methane, and will not false alarm on other hydrocarbons;
3. Response times down to 1 (one) second, which allows for fine resolution /control when making measurements;
4. Up to one (1) km measurement path;
5. Very low detection limits (ppb or low ppm);
6. Most systems have an internal reference cell; therefore, the system is self calibrating. As a result, it has low maintenance and low operating costs;
7. There is no "poisoning" or degradation of the instrument with long term exposure to a gas;
8. Proven reliable technology; and
9. Instruments are light and portable.

Method Limitations

1. Using TDLAS technology, only one (1) gas can be measured with each instrument;
2. When heavy dust, steam or fog blocks the laser beam, the TDLAS system will not be able to take measurements. This is also the case when a person or vehicle blocks the path;
3. Direct sun and ambient light adds detected background photons;
4. Surface types such as concrete will spread the leak and create spot leaks through surface cracks and holes;
5. Abrupt motion, change in terrain, or distance may cause an instrument to give a short low detection; and
6. Strong reflections of certain types of surfaces such as black garbage bags, water droplets, glass, polish surfaces, stones, etc may give a false detection (overly strong returns).

Costs

Costs associated with the purchase of the TDLAS open path instruments that were reviewed in this study are approximately \$26,000 and \$35,500.

7.3 Airborne Sensing Methods (Pipeline Inspections)

7.3.1 Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Description of the Method

Tunable Diode Laser Absorption Spectroscopy (TDLAS) for gas detection is based on the principle that gas molecules absorb energy in narrow bands surrounding specific wavelengths in the electromagnetic spectrum. At wavelengths slightly different than these "absorption lines", there is essentially no absorption. By transmitting a beam of the laser light through a gas mixture sample containing a quantity of the target gas (methane in a case of a hydrocarbon gas), tuning the beam's wavelength to one of the target gas's absorption lines, and accurately measuring the absorption of that beam, the concentration of target gas molecules integrated over the beam's path length can be calculated. The fraction of emitted laser power that is transmitted through the gas mixture is monitored with a photodetector.

The TDLAS technology that utilizes an extractive measurement path (or in other words extractive sampling) technique can be used to detect and measure methane leaks from buried pipelines in either a stationary, portable, vehicle or air frame mounted configuration. In all configurations, a portable fibre coupled instrument is connected with an external optical probe. A fibre-optic cable carries the laser light to the external probe through which ambient air (gas) is continually freely passing. The optical path length within the probe is designed to provide the required sensitivity to the methane gas. A multipass optical cell (Herriot cell) is usually utilized to provide a long optical path length within a small volume, in many cases yielding sub-ppm sensitivity with one second or faster response. The light beam ends up making many passes through the sample gas as it bounces back and forth between the spherical mirrors in the cell. By the time the light exits the sample cell and hits the detector it has traveled a physical distance of a few meters. Traveling this distance enhances absorption of the light.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: No
Benzene: No
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

In extractive sampling systems, Tunable Diode Laser Absorption Spectroscopy is a quantitative method. Units of quantification are ppmv.

Method Strengths

1. The laser light is selective to methane, and will not false alarm on other hydrocarbons;
2. The TDLAS technology provides immediate response to methane leaks;
3. The TDLAS technology provides the most interference free method of any analytical technique;
4. It provides high sensitivity due to being insensitive to temperature variances, vibrations and humidity and also because of utilizing a multipass optical cell;

5. Measurements of gas concentrations are unaffected by the presence of particles, including rain and snow;
6. One technology provides detection range of 0-100% volume for faster leak classification;
7. There is no "poisoning" or degradation of the instrument with long term exposure to a gas; and
8. The systems are self calibrating and require annual calibration only.

Method Limitations

1. Only one (1) gas can be measured with each instrument;
2. The method has potential for uncertainty in the gas concentration measurement, since the instrument will not respond to the other constituents of natural gas and so will be in error by an amount equal to the methane deficit. The lower the proportion of methane in the natural gas, the greater the underestimate of gas concentration will be;
3. Natural gas with lower proportions of methane can have a greater proportion of higher hydrocarbons, which will lower the %LEL of the mixture; and
4. Costs of surveys can be high.

Costs

Airborne pipeline survey costs are in a range from approximately \$50 to \$100/km.

7.3.2 Airborne Differential Absorption LIDAR (Airborne DIAL)

Description of the Method

LIDAR (Light Detection and Ranging; or Laser Imaging Detection and Ranging) is a technology that determines distance to an object or surface using laser pulses. The range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. Any LIDAR system consists of two major parts: transmitter and receiver. The transmitter is a laser or laser-based source of optical radiation. Light generated by the transmitter is emitted into the atmosphere as a collimated beam. As this beam propagates away from the source, some of the radiation will be scattered back toward the receiver by particles and aerosols in the atmosphere. A system of mirrors and lenses is used to direct laser pulses toward the target gas and focus the backscattered light onto a sensitive detector.

DIAL (Differential Absorption Lidar) is a development of LIDAR. It is an example of an active remote sensing technology. Each chemical has a unique set of absorption frequencies or lines called "spectral fingerprint". In the DIAL method, the transmitter generates light at two (2) optical frequencies. One frequency called "on-line" is chosen to coincide with a particular absorption line of the chemical of interest. The other frequency called "off-line" is tuned away from the absorption peak and serves as a reference. The return energy at the "on-line" and "off-line" is compared and the concentration of the chemical is determined as a logarithmic function of the ratio of energy returns at on- and off-lines. For DIAL detection of hydrocarbons, including volatile organics, the laser source is tuned onto the mid-IR (3-5 μm) spectral region where many hydrocarbon gas molecules have strong and well defined absorption features.

In the airborne operation, the laser beam is transmitted down from the aircraft to illuminate the area on the ground above and around the buried pipe. The light reflected from the ground is collected by the sensor's receiver, and the amount of received energy is measured. If the laser beam passes through a gas plume emanating from a pipeline leak, the received energy will be diminished due to the absorption of laser light in the plume. This absorption signature is used to locate the leak and to assess its magnitude.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: No
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Airborne DIAL is a semi-quantitative method. Units of quantification are ppm-m.

Method Strengths

1. The Differential Absorption LIDAR (DIAL) technology provides a very high sensitivity in remote gas detection;
2. Being an active remote sensing technology, DIAL is particularly advantaged when the desired wavelengths are not sufficiently provided by the sun, such as portions of the mid-wave IR;
3. DIAL provides real-time read-out capability of hydrocarbon gases, regardless of the time of day or season. Concentrations of the pollutants can be reported within a few minutes. Full reports can be delivered within an hour of inspection;
4. When combined with a high resolution imaging camera and a GPS receiver, a DIAL system can precisely locate a leak. The DIAL system is sufficiently sensitive to detect even the smallest pipeline leaks;
5. The airborne DIAL provides over ten (10) to hundred (100) times faster surveys than ground surveys. It can inspect up to 100 miles on a typical day when integrated with a helicopter and up to 1,000 pipeline miles when integrated with a fixed aircraft;
6. The airborne DIAL provides full coverage of the right-of-way; and
7. The airborne DIAL technology eliminates worries about rough terrain by relieving strain on vehicles and people involved in a ground survey, as well as worries about crops, fences, herds and permits. It is also non-disruptive to private landowners.

Method Limitations

1. Large DIAL lasers require hundreds of watts of power to operate, as well as liquid nitrogen to cool down the laser cell;
2. Rain, strong wind, fog, and extreme dust can interfere with the DIAL operations;
3. A DIAL system incorporates a very complex system design, components, integration and data analysis; therefore it requires highly skilled people to operate it and interpret the results of a conducted survey; and

4. Costs of surveys can be high.

Costs

Airborne pipeline survey costs are approximately \$200/km.

7.3.3 Gas Filter Correlation Radiometry (GFCR)

Description of the Method

Gas Filter Correlation Radiometry (GFCR) for gas detection is based on the principle that a target gas is detected by its IR signature viewed through a bandpass filter centered at one of its strongest bands. Two (2) groups of the GFCR techniques are used in the airborne gas detection application: active and passive. The active detection technique requires a broadband power source to illuminate a scene, whereas the passive technique uses sun light reflected off the ground.

For either detection technique, the IR Gas Filter Correlation Radiometry (GFCR) method is used to allow highly selective measurement of gases such as methane and ethane. The GFCR method is based on broad band IR radiation from a light source alternately passing through one (1) of two (2) gas filters. One contains inert gas such as nitrogen and the other contains the gas of interest. When the inert gas filter is in position, no absorption takes place. When the gas of interest filter is in position, absorption takes place reducing the intensity in the beam at the characteristic wavelengths for the gas of interest. The temporally spaced beams then pass through a narrow band pass filter which limits the IR region to a specific part of the absorption spectrum and then into the sample cell. When radiation that has passed through the inert gas filter passes through the sample gas containing the gas of interest, absorption occurs according to Beer's law and produces a reduction in the detector signal. Radiation that has passed through the gas of interest filter has had the intensity at the characteristic wavelengths significantly reduced and so further absorption in the sample cell is small. However, the energy which is transmitted makes an excellent reference signal as it has the same spectral distribution as the measure signal.

Pollutants the Method is able to Detect

Methane: Yes (with gas filter change)

NMVOC: Yes (C₂H₆)

Benzene: Yes (Future Plan)

Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Gas Filter Correlation Radiometry is a semi-quantitative method. Units of quantification are ppm-m.

Method Strengths

1. Only a single IR region is required for the measurement. That is, a single narrow band IR filter defines the region of interest. Therefore, the technology provides a high selectivity and sensitivity for a specific gas;

2. Any changes in spectral content due to source aging (in case of an active source aging), window contamination and any other broad band interference occur equally for both measure and reference beams and thus cancel out in the differential measurement. The greater the spectral similarity of the two beams, the greater the immunity from interferences, as both would be affected equally by any absorption;
3. Many natural gas pipeline leak detection systems just detect methane, which does not truly validate the presence of a leak. Because there are many sources of methane such as landfills, animal feedlots, rotting vegetation, detecting both methane and ethane or just ethane (which is not naturally occurring in the atmosphere) provides a better indication of the presence of a leak;
4. When combined with a high resolution imaging camera and a GPS receiver, a PGFCR system can precisely locate a leak. The PGFCR system is sufficiently sensitive to detect even the smallest pipeline leaks; and
5. The PGFCR technology was developed in Alberta.

Method Limitations

1. The PGFCR technology requires sunny days to operate. Therefore, it will not work for emergency applications;
2. Weather conditions such as fog, dust, cloudy and windy days will interfere with the operations;
3. A PGFCR system incorporates a complex system design, components, integration and data analysis; therefore it requires highly skilled people to interpret the results of a conducted survey. However, the field operation of the instrument does not require any highly skilled operators and will typically be operated by the pilots themselves; and
4. Costs of surveys can be high.

Costs

Airborne pipeline survey costs are in a range from approximately \$50 to \$100/km.

8.0 Point Source Quantification Methods

The method/technologies presented in Section 7 are useful for detecting leaks and in some cases can provide a concentration reading. However, in order to quantify the emissions, a suitable method must be used to measure the actual leakage rate. In order to obtain this, the following flow measurement methods can be applied:

1. Bagging;
2. Hi-Flow Sampler;
3. Rotameters and other flow measuring devices; and
4. Tracer gas.

A summary of the findings for this category is provided in Table 2 of the accompanying Excel-based Information Tool.

8.1 Bagging

Description of the Method

Bagging techniques are commonly used to measure flow rates from equipment leaks. The leaking component or leak opening is enclosed in a "bag" or tent. An inert gas such as nitrogen is conveyed through the bag at a known flow rate. Once the carrier gas attains equilibrium, a gas sample is collected from the bag and the methane concentration of the sample is measured. The leak flow rate from the component is calculated from the purge flow rate through the enclosure and the concentration of methane in the outlet stream. Two (2) to three (3) samples per hour can be measured when using this method.

Application:

This method can be applied on most accessible components. However, it may not be suitable for unusually shaped components or very large leaks.

Approximate Costs

Costs by utilizing would be under \$10,000, depending on sample analysis cost (US EPA. Lessons Learned, 2003). For component bagging, the testing could be done with a cylinder of ultra pure air and an FID (that was used for component screening). This eliminates the need to collect samples and have them analyzed at a lab. In this case, the equipment costs are very low (\$200 for a large air cylinder and the cost of renting an FID). The real cost in this method is that of labor since it is a relatively slow method.

8.2 Hi-Flow Sampler

Description of the Method

High flow samplers capture all emissions from a leaking component to accurately quantify leak flow rates. Leak emissions, plus a large volume sample of the air around the leaking component, are pulled into the instrument through a vacuum sampling hose. High volume samplers are equipped with dual hydrocarbon detectors that measure the concentration of hydrocarbon gas in the captured sample, as well as the ambient hydrocarbon gas concentration. Sample measurements are corrected for the ambient hydrocarbon concentration, and the leak rate is calculated by multiplying the flow rate of the measured sample by the difference between the ambient gas concentration and the gas concentration in the measured sample. Methane emissions are obtained by calibrating the hydrocarbon detectors to a range of concentrations of methane-in-air. High volume samplers are equipped with special attachments designed to ensure complete emissions capture and to prevent interference from other nearby emissions sources. The hydrocarbon sensors are used to measure the exit concentration in the air stream of the system. The sampler essentially makes rapid vacuum enclosure measurements. Up to thirty (30) samples per hour can be measured when using this method.

Application:

This method can be applied on most accessible components with leak rate not exceeding 14 m³/hr.

Approximate Costs

Costs associated with the purchase of a Hi-Flow Sampler that were reviewed in this study are approximately \$21,800.

8.3 Rotameters and other Flow Metering Devices

Description of the Method

The rotameter is an industrial flowmeter used to measure the flowrate of liquids and gases. The rotameter consists of a tube and float. The float response to flowrate changes is linear, and a 10-to-1 flow range or turndown is standard. The rotameter has a linear scale, a relatively long measurement range, and low pressure drop. It is simple to install and maintain. The rotameter's operation is based on the variable area principle: the flow raises a float in a tapered tube, increasing the area for passage of the fluid. The greater the flow, the higher the float is raised. The height of the float is directly proportional to the flowrate. With liquids, the float is raised by a combination of the buoyancy of the liquid and the velocity head of the fluid. With gases, buoyancy is negligible, and the float responds to the velocity head alone. The float moves up or down in the tube in proportion to the fluid flowrate and the annular area between the float and the tube wall. The float reaches a stable position in the tube when the upward force exerted by the flowing fluid equals the downward gravitational force exerted by the weight of the float. A change in flowrate upsets this balance of forces. The float then moves up or down, changing the annular area until it again reaches a position where the forces are in equilibrium. To satisfy the force equation, the rotameter float assumes a distinct position for every constant flowrate. However, it is important to note that because the float position is gravity dependent, rotameters must be vertically oriented and mounted. Three (3) to six (6) samples per hour can be measured when using this method.

Application:

This method can be applied to measure very large leaks. It is the best when it is used for open-ended lines and compressor seals where the entire flow can be channeled through the meter. Rotameters and other flow metering devices can supplement surveys using bagging or high volume samplers. Rotameters are not often useful in quantifying fugitive equipment leaks because flows are frequently unsteady or intermittent. Totalizing flow meters (diaphragm or roots meters) are a better choice. The meter can be set up to measure the flow over an extended period of time to get an accurate average. This also permits the measurement of small leaks by totalizing over a relatively long period of time. However, at very low rates, positive displacement meters tend to experience some slippage so emissions will tend to be underestimated. For very large emissions from open-ended lines (e.g. vent stacks) a flow velocity profile can be measured with an insertion probe such as a pitot tube, thermal anemometer or vane anemometer. Knowing the velocity profile and cross-sectional area, the emission rate can be calculated.

Approximate Costs

Purchase costs by utilizing this method would be under \$1,000 (US EPA. Lessons Learned, 2003).

8.4 Tracer Gas

Description of the Method

Tracer gas leak detectors are used to test any component that can be pressurized. If smaller leaks are sought, a tracer gas method should be considered. Tracer gas leak detectors operate by drawing air from near a suspected leak, and the concentration of a specific gas "tracer" is measured. A component or vessel is filled or partially filled with the tracer gas and sealed. The amount of tracer gas detected is proportional to its leak rate and therefore to the size of the leak. Tracer gas detectors are usually available in two configurations: hand-held, portable instruments, and systems that use chambers or enclosures surrounding the test component and capture any leak within the enclosure. With the hand-held instruments, the component to be tested is pressurized with a known gas mixture, and all suspect leak positions are probed directly. In the system approach, the component is injected with a tracer gas mixture and placed into a specially designed chamber, or hood. The test chamber is then ventilated, and air is forced or evacuated across the possible leak site of the component and passed into the detector. The detector provides a measure of tracer concentration, which, in turn, provides a measure of the total leak rate from the component. Helium, argon, nitrogen, sulfur hexafluoride (SF₆) and R12 are a few of the options available as a "tracer" gas. Two (2) to three (3) samples per hour can be measured when using this method.

Application:

This method can be applied on most accessible components. It may not be suitable for unusually shaped components or very large leaks.

Approximate Costs

Purchase costs by utilizing this method would be greater than \$10,000.

9.0 Area Source Leak Detection and Quantification Technologies

Area sources of fugitive emissions may include: industrial processes, product storage and handling areas, waste treatment and disposal facilities (landfills, land farms and wastewater lagoons), surface spills, and subsurface contamination such as contaminants in subsurface contaminated soils and groundwater (plume).

One of the currently employed methods used to quantify area emissions is tracer gas. This method can quantify emissions from large or open sources that can not be quantified by other means. Some examples include tailings pond outfalls and floating roof storage tanks. In this method, a tracer gas (a compound that is not found in the emission source such as SF₆) is released at the emission source. The plumes of the emission source and tracer gas are assumed to coincide and samples are collected at a point downwind. Knowing the flow rate and concentration (100%) of the tracer gas and the pollutant at the source and the concentration of the pollutant and tracer downwind, the emission rate can be inferred by simple ratio (CAPP, 1999).

There have been significant technological advances in recent years in the area of fugitive detection and emissions quantification from area sources. These advances dramatically

improved capabilities to monitor fugitive emissions from area sources. Some of the technologies (Spectrasyne DIAL and AIRDAR) directly measure all parameters that are necessary to calculate an emission rate (mass/time), but most of them measure the ambient concentration and must use an interpretation such as dispersion modeling to determine the associated emission rate (i.e., TDLAS and FTIR systems). There are also methods that calculate the pollutant concentration in a manner where the emission is not directly related to a given area or time interval. These technologies typically use air dispersion modeling to infer the emission rate responsible for the emission concentration measured given the unique source, dispersion, and transport conditions of the testing.

Several factors determine which technology or combination of technologies will be appropriate for evaluating a given site. These factors include: a prior estimate of compounds emitted and emission rate, the level of effort available to determine these emission rates, the degree of accuracy required; and the complexity of the source. Some sources are a combination of sources (i.e., point and area sources or multiple area/fugitive sources) and might require several assessment technologies in order to generate representative emission rate data.

A summary of the findings for this category is provided in Table 3 of the accompanying Excel-based Information Tool.

9.1 Differential Absorption LIDAR (DIAL)

Description of the Method

LIDAR (Light Detection and Ranging; or Laser Imaging Detection and Ranging) is a technology that determines distance to an object or surface using laser pulses. The range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. Any LIDAR system consists of two major parts: transmitter and receiver. The transmitter is a laser or laser-based source of optical radiation. Light generated by the transmitter is emitted into the atmosphere as a collimated beam. As this beam propagates away from the source, some of the radiation will be scattered back toward the receiver by particles and aerosols in the atmosphere. A system of mirrors and lenses is used to direct laser pulses toward the target gas and focus the backscattered light onto a sensitive detector.

DIAL (Differential Absorption Lidar) is a type of LIDAR. It is an example of an active remote sensing technology. Each chemical has a unique set of absorption frequencies or lines called "spectral fingerprint". In the DIAL method, the transmitter generates light at two optical frequencies. One frequency called "on-line" is chosen to coincide with a particular absorption line of the chemical of interest. The other frequency called "off-line" is tuned away from the absorption peak and serves as a reference. The return energy of the "on-line" and "off-line" is compared and the concentration of the chemical is determined as a logarithmic function of the ratio of energy returns at on- and off-lines. With DIAL, the laser source is tuned onto the mid-IR (3-5 μm) spectral region where many hydrocarbon gas molecules have strong and well defined absorption features.

There is only one (1) commercially operated unit in the world and that is the Spectrasyne DIAL in United Kingdom (UK). The Spectrasyne DIAL unit contains two laser systems, one operating in the IR spectrum to measure methane and C_2 hydrocarbon emissions and another - in the UV spectrum to measure benzene emissions.

The Spectrasyne DIAL is a twelve (12) metre mobile DIAL unit operated out of a big trailer bus. It is based on two (2) high energy (1.4J), 10Hz pulsed Nd:YAG pumped dye lasers. Tunable ultraviolet and visible radiation is generated in one of the laser sets by selective use of frequency doubling and tripling crystals. The second laser set, which has an injection seeded Nd:YAG, is used to generate tuneable IR by means of the unique IR source assembly. The DIAL is single ended and its output beam is directed by means of a mirror steering system which rotates in two planes. The backscattered light, which returns along the same path, is collected in a cassegrain-type receiving telescope and delivered to the appropriate detector through a multi-dichroic, beam splitting, collimating and focusing system. A high speed data communication network has been developed in parallel with a unique PC based software package to collect, store, handle and process the DIAL signals. The vehicle is also equipped with an extendible meteorological mast and a number of portable telemetric stations, which are used along the DIAL scan lines to measure wind speed and direction, temperature and humidity. These data are displayed in real time and digitally logged for subsequent use with DIAL concentration data to produce mass emission fluxes in kg/hr (Chambers, A. ,2004).

A few hours of scans are required to calculate time weighted average of a single area and two (2) or three (3) days to do measurements of emissions from an entire gas plant, depending on a size of a plant.

Pollutants the Method is able to Detect

Methane: Yes

NMVOC: Yes

Benzene: Yes

Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

DIAL is a quantitative method. Units of quantification are kg/hr and/or mg/m³.

Method Strengths

1. The DIAL technology can remotely measure the concentration of hydrocarbon gases in the atmosphere up to two (2) km distant with detection limits in the order of parts per billion;
2. Being an active remote sensing technology, DIAL is particularly advantaged when the desired wavelengths are not sufficiently provided by the sun, such as portions of the mid-wave IR;
3. DIAL is the only measurement technique available that enables mass emission fluxes to be obtained directly. By combining DIAL measured 2D concentration maps with measured wind speed, the mass emissions of the species in a plume in kg/hr can be calculated;
4. DIAL provides real-time read-out capability, regardless of the time of day or season. Concentrations of the pollutants can be reported within a few minutes;
5. As separate emission plumes can be seen in the DIAL results, the DIAL unit can be used to assist in locating leaks by performing successive scans closer to the source;
6. DIAL can quickly find leaks in restricted access areas - e.g. the top of high stacks; and
7. The DIAL technology does not interfere with facility operations.

Method Limitations

1. DIAL lasers require hundreds of watts of power to operate, as well as liquid nitrogen to cool down the laser cell;
2. Rain, strong wind, fog and extreme dust can interfere with the DIAL operations;
3. There is only one (1) commercially operated unit in the world and that is the Spectrasyne DIAL in UK;
4. The Spectrasyne DIAL incorporates a very complex system design, components, integration and data analysis; therefore it requires highly skilled people to operate it and interpret the results of a conducted survey;
5. Costs of a survey by the Spectrasyne DIAL, including shipment of the unit from UK to Canada and operating costs will be very high; and
6. DIAL measurements of a single area of a plant require a few hours of scans to calculate time weighted average for the area. Measurements of emissions from a gas plant of any size usually require two (2) or three (3) days. Therefore, it should be noted that if the DIAL short term measurement results are used to estimate annual fugitive emissions from a facility, they will not represent actual annual average plant emissions.

Costs

Costs associated with the use of the Spectrasyne DIAL service would be: \$60,000 - transportation costs to bring the Spectrasyne unit to Canada and \$20,000 - \$25,000 per day. Costs include survey and reporting time and living expenses.

9.2 AIR Detection and Ranging (AIRDAR)

Description of the Method

The AIRDAR (AIR Detection and Ranging) technology detects and ranges emission sources using compounds that travel in the air. AIRDAR provides a measure of fugitive emissions for the overall facility as well as the location and characteristics of important leaks. The AIRDAR system makes continuous point measurements at a series of locations around the facility of air concentrations of compounds that have been emitted from sources and driven by wind. It uses these results to track plumes back to the sources and characterize emission rates. By detecting increased concentrations of compounds and combining collected data with measured wind speed and direction data, the AIRDAR system produces emission rate of the species from a source in units of E^3m^3/yr .

The AIRDAR system consists of the following components:

1. Permanently installed field sampling with an FID analyzer and timers; and
2. Mapping algorithm that combines the composition data with sample positioning and local speed and direction data to create site maps to show positions of any leakage.

Four (4) to eight (8) sampling towers are usually installed at several locations around a plant to collect ambient air samples. Polyethylene 1/4" tubing, which is strung around the facility connects the towers with a hydrocarbon gas measuring device (FID analyzer) located in one of the plant's

buildings. Pump-driven ambient air is continuously analyzed by the FID analyzer and the data is continuously logged. The collected data is processed next day remotely from the DS Prince Consulting Ltd. office in Edmonton, AB. At the end of each month, monthly data is summarized and processed to generate monthly emissions maps that provide the locations and information on emitting sources.

Current application of AIRDAR focuses on fugitive emissions of methane because they are valuable and there is a benefit in GHG reductions. With further fine tuning AIRDAR could be used to characterize all emissions.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: Yes
Benzene: Yes
Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

The AIRDAR technology provides a quantitative method of measurement of fugitive emissions. Units of quantification are $E^3m^3/year$.

Method Strengths

1. The AIRDAR technology provides continuous unmanned surveillance of fugitive emissions. It monitors site emissions using long-term, low intensity data collection combined with sophisticated data analysis;
2. AIRDAR quantifies and locates fugitive emission sources using an innovative analysis of air concentration data. Total hydrocarbon concentrations (THC) in air and wind speed and direction are measured;
3. AIRDAR provides a facility wide emission rate and because of the long term measure it provides a better estimate of total annual fugitive emissions from a facility;
4. Because of its true surveillance, AIRDAR can find leaks from unexpected fugitive sources;
5. AIRDAR can accurately predict location as well as characteristics of larger fugitive emissions sources. In conducted field studies, actual fugitive sources were confirmed and compared;
6. The AIRDAR technology has an ability to estimate the location of large leaks to within five (5) meters, which allows for rapid pinpointing of the actual leak location using other point source detection technologies/methods;
7. AIRDAR can track plumes of much lower concentration like those associated with odours;
8. AIRDAR uses inexpensive and uncomplicated equipment. Except for equipment setup and its maintenance, it does not require manpower onsite;
9. The technology does not interfere with facility operations; and
10. The AIRDAR technology was developed and is readily available in Alberta.

Method Limitations

1. Currently, the AIRDAR technology does not provide a real-time response to new emissions;
2. AIRDAR can locate and characterize any emitting source as long as the emission contains a compound that can be detected at levels distinguishable above background concentrations. However, the AIRDAR's detection limit is unknown;
3. AIRDAR may not be convenient in providing a quick spot check of a small facility; therefore, it is more suited for a medium to large size plants;
4. The supplier company currently consists of one (1) individual who is in charge of conducting the entire survey, including set up of AIRDAR systems, providing maintenance for them as well as fugitive emission assessment/data analysis;
5. Because the fugitive emission assessment analysis is very sophisticated, cost of implementation is high. However, implementation costs may be offset through cost savings associated with early detection of identified leaks;
6. Because many meters of aboveground polyethylene tubing are run throughout a plant area, AIRDAR systems must be periodically inspected to ensure that that tubing maintains its integrity; and
7. The AIRDAR technology has not yet been evaluated by a third party.

Costs

Costs (combined capital, maintenance, and operational costs per year) associated with the use of the AIRDAR technology would be in a range from \$200,000 to \$300,000 depending on a size of a facility.

9.3 Open Path, Path-Integrated Optical Remote Sensing (PI-ORS)

Open path gas detection is a method that is designed for long distance monitoring in ambient air and fence/perimeter monitoring of gases such as CH₄, H₂S, combustible hydrocarbons and others. Open path, path-integrated optical remote sensing (PI-ORS) is a technique that employs open-path technologies to obtain path-integrated concentration (PIC) data from area sources. In other words, the PI-ORS technique identifies and quantifies airborne pollutants.

For non-point (area source) detection, the open path detection method holds the following benefits and limitations:

Method Strengths

1. Open path gas detection is extremely sensitive to low concentration clouds of the gases, as the increased path length allows for greater absorption of hydrocarbon specific IR light;
2. Open path's sensitivity to high volume/low concentrations hydrocarbon clouds makes this method ideal for perimeter monitoring of fuel gas storage facilities and boundary monitoring between a process plant and operational areas; and

3. An average measurement is taken over the total path so that a narrow plume of gas has less chance of escaping detection.

Method Limitations

1. Open path detection cannot pinpoint leaks or differentiate between a small high concentration cloud of hydrocarbon gas and a large low concentration cloud of hydrocarbons and as such, should always be used in conjunction with "point specific" gas monitors. However, it can identify "hot" spots;
2. Very low flowing leaks may produce small to non-measurable plumes; and
3. Weather conditions like high winds and higher temperatures will cause a plume to dissipate faster.

9.3.1 Open Path Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Description of the Method

The TDLAS technology is based on utilization of infrared absorption spectroscopy using a laser diode as a light source. A single gas absorption line with no interference is chosen in the near IR spectral range. A single-mode diode laser operating at room temperature scans the single absorption line (methane in the case of hydrocarbon gases) and receives a fraction of the backscatter reflected from a target or from a passive retro-reflector that is used in TDLAS systems designed for area source monitoring applications. A photodiode detector detects the light absorption caused by the target gas molecules, after which the gas concentration is calculated. The detector measures the path-integrated concentration of methane between the detector and the target, which is termed the methane column density, rather than the concentration at a local point. The column density has the dimensions of the product of the concentration (ppm) and length (m) and is described in units of ppm-m. By utilizing the TDLAS technology, measurement lengths can be up to one (1) km.

Pollutants the Method is able to Detect

Methane: Yes
NMVOC: No
Benzene: No
Hydrogen Sulfide: Yes.

Type of Detection Qualitative/Quantitative the Method can provide

Open path Tunable Diode Laser Absorption Spectroscopy is a semi-quantitative method. Units of quantification are ppm-m.

Method Strengths

1. The TDLAS technology provides the most interference free method of any analytical technique (not affected by H₂O vapour and CO₂);
2. The laser light is selective to methane, and will not false alarm on other hydrocarbons;

3. Response times down to 1 (one) second, which allows for fine resolution /control when making measurements;
4. Up to one (1) km measurement path;
5. Very low detection limits (ppb or low ppm);
6. Most systems have an internal reference cell; therefore, the system is self calibrating. As a result, it has low maintenance and low operating costs;
7. There is no "poisoning" or degradation of the instrument with long term exposure to a gas;
8. Proven reliable technology;
9. A TDLAS system can be used together with Optical Remote Sensing-Radial Plume Mapping (ORS-RPM) technique to provide real-time on-site information on emissions of fugitive gases from many different types of area sources by identifying "hot spots" and measuring emission fluxes;
10. Low associated operational and maintenance costs; and
11. Instruments are lightweight and portable.

Method Limitations

1. Using the TDLAS technology, only one (1) gas can be measured with each instrument;
2. When heavy dust, steam or fog blocks the laser beam, a TDLAS system will not be able to take proper measurements. This is also the case when a person or vehicle blocks the path; and
3. Direct sun and ambient light adds detected background photons.

Costs

Approximate costs associated with the installation of a single TDLAS unit (GasFinder by Boreal Laser Inc.) that was reviewed in these studies are: \$50,000 (for compressor stations and batteries) and \$80,000 (for gas plants). Boreal Laser equipment is custom tailored to each installation and is modular in design. Therefore, an upper limit to costs cannot be specified.

9.3.2 Open Path Fourier Transform Infrared (FTIR) Spectroscopy

Description of the Method

Fourier Transform Infrared (FTIR) Spectroscopy is a method of spectroscopy that uses a Michelson interferometer to measure the spectrum of an infrared light beam. The signal from the interferometer is called an interferogram. It is subsequently Fourier transformed to generate an intensity spectrum. Gas concentrations are determined by measuring the attenuation or addition of infrared spectral intensity that they cause. FTIR systems employ two (2) types of gas detection techniques: passive and active. In passive detection, gases can attenuate radiation from a remote surface or they can radiate additional spectral radiation above that from the remote surface, depending on their relative temperature to that of the surface. This occurs at distinctive wavelengths, allowing the gas to be detected. Active detection requires the presence of a broad

band IR light source in order to create the necessary source spectrum. FTIR systems that use an active detection technique are available in two different configurations: bistatic and monostatic. Bistatic monitoring is a method wherein an IR signal from a remote source makes a single pass through the sample area on its way to the IR spectrometer. Monostatic monitoring refers to a technique where the IR signal originates at the interferometer, makes a double pass through the sample area on its way to and from a retro-reflector, and is received near its origin by a detector.

FTIR systems with passive detection technique configuration are primarily intended for qualitative analysis while the active bistatic and monostatic can be used for quantitative analyses as well.

By utilizing the FTIR technology, measurement lengths can be up to 1.5 km.

Pollutants the Method is able to Detect

Methane: Yes

NMVOC: Yes

Benzene: Yes

Hydrogen Sulfide: No

Type of Detection Qualitative/Quantitative the Method can provide

Open path FTIR Spectroscopy is a semi-quantitative method. Units of quantification are ppm-m.

Method Strengths

1. Open path FTIR spectroscopy provides real-time, simultaneous detection, quantification and speciation of hundreds of chemical compounds, including all BTEX compounds;
2. Very low detection limits (ppb or low ppm);
3. Results can be obtained in seconds;
4. Up to 1.5 km measurement path;
5. FTIR systems are designed to continuously operate unattended, over long periods, under a wide range of climatic conditions;
6. Most systems have an internal reference cell; therefore, the system is self calibrating. As a result, its maintenance and operating costs are relatively low;
7. There is no "poisoning" or degradation of the instrument with long term exposure to a gas;
8. Proven reliable technology; and
9. A FTIR system can be used together with Optical Remote Sensing-Radial Plume Mapping (ORS-RPM) technique to provide real-time on-site information on emissions of fugitive gases from many different types of area sources by identifying "hot spots" and measuring emission fluxes.

Method Limitations

1. Because H₂O and CO₂ have absorption features in the same IR region that a FTIR system uses to analyze for the target compounds and the concentration of these two (2) potential

interferants is usually much greater than the concentration of the compounds of interest, the presence of H₂O and CO₂ can make analyzing for the target compounds difficult;

2. Because all regions of the spectrum are observed simultaneously, if noise occurs in one part of the radiation from the infrared source, it will be spread throughout the spectrum in a FTIR system;
3. When heavy dust, steam or fog blocks the IR beam, a FTIR system will not be able to make proper measurements. This is also the case when a person or vehicle blocks the path;
4. Direct sun and ambient light add detected background photons; and
5. High electrical power is required to operate a FTIR system and liquid nitrogen to cool down the detector.

Costs

Costs associated with the installation of a RAM2000 by EDO Corporation can range from \$80,000 to \$250,000 depending on options such as positioner, autofill, weather station, multiple reflectors, cryocooler, and service requested. Because maintenance of the system is not required, service costs for it would be optional.

9.3.3 Radial Plume Mapping (RPM)

Radial Plume Mapping (RPM) is a methodology that uses a novel, yet simple, configuration of non-overlapping radial beam geometry to map the path-integrated concentration (PIC) distributions in a plane. It requires only a single open path instrument (such as TDLAS or FTIR) that scans horizontally in a radial pattern to several retro-reflecting mirrors located along different path lengths. Using optimization algorithms, a method was developed to convert the path-integrated concentration data collected during the radial scans onto spatially-distributed concentration maps that could identify “hot spots” of fugitive emissions over an area source (US EPA, Optical Remote Sensing, 2006).

Three (3) RPM methodologies have been developed:

1. Horizontal Radial Plume Mapping (HRPM);
2. Vertical Radial Plume Mapping (VRPM); and
3. One Dimensional Radial Plume Mapping (1D-RPM).

The Horizontal Radial Plume Mapping (HRPM) methodology was designed to map pollutant concentrations in a horizontal plane. The Vertical Radial Plume Mapping (VRPM) was designed to measure flux of pollutants through a vertical plane, downwind from an emission source. The One Dimensional Radial Plume Mapping (1D-RPM) was designed to profile pollutant concentrations along a line-of-sight (e.g., along an industrial site fence line).

The HRPM methodology utilizes multiple non-intersecting beam paths in a horizontal plane and optimizing algorithms to give a time-averaged surface concentration filed plumes of contaminants. This methodology is used to locate “hot spots” close to the ground.

The VRPM methodology utilizes multiple non-intersecting beam paths in a vertical plane downwind from the emission source to obtain a mass-equivalent plume map. This map, in conjunction with wind speed and direction, is used to obtain the flux of pollutants through the vertical plane. The measured flux is then used to estimate the emission rate of the upwind source being characterized.

The 1D-RPM methodology utilizes multiple beam paths along a line-of-sight to obtain concentration profiles downwind of a source (e.g., along an industrial site fence line). The peak concentration position along the line-of-sight can be incorporated with wind direction to estimate the location of an upwind fugitive emission source.

All these methodologies use an open path, path-integrated optical remote sensing system (PI-ORS) in multiple beam configurations to directly identify “hot spots” and measure emission fluxes. The user-selected PI-ORS system collects spectral data. There are no true “samples” that require preservation, storage, transport, extraction, digestion, or concentration. The chemical concentration of each gas species of interest along each beam path is obtained following the measurement and analysis procedures for the instruments being used.

10.0 GOSAT – Greenhouse Gases Observing Satellite

A profile of global greenhouse gas concentrations has been mapped from measurement data obtained through ground and airborne observations. However, the number of observation points and observation coverage are limited and are not distributed evenly around the world.

The Greenhouse gas Observing SATellite (GOSAT) has been designed to observe global distribution of GHG concentration from space, and is expected to contribute to international efforts in preventing global warming by acquiring current absorption and emission levels of GHGs. The GOSAT was jointly developed by the Japan Aerospace Exploration Agency (JAXA), Japan's Ministry of the Environment, and the National Institute for Environmental Studies (NIES) to observe the levels of carbon dioxide.

GOSAT is designed to observe infrared energy radiated from the Earth. Concentrations of GHGs in the atmosphere can be estimated by comprehensive analysis of this infrared energy. GOSAT is designed to measure the distribution of GHGs on a near global basis, while orbiting the planet every 100 minutes and obtaining data for the same regional point every three (3) days. Accordingly, the satellite will provide much more complete measurement data and will allow more accurate estimations of the GHG levels for the various regions around the world. Unlike ground and airborne observations, GOSAT will make global observations with a single sensor, allowing for the comparison of data in a single engineering scale. Observations of methane are also being considered for the satellite.

The GOSAT is in full-scale development and is scheduled for launch in 2008. There may be an opportunity in the future for GOSAT to assist companies in the early detection of fugitive hydrocarbon emissions through its observations from space.

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Wikipedia, a multilingual free-content encyclopedia on the Internet (<http://en.wikipedia.org>)

Appendix A

List of Technology / Product Suppliers Contacted

List of Technology / Product Suppliers Contacted

Company	Name	Method/Product Discussed
Avensys Solutions	Jim Cornish	Photovac FID, Crowcon Triple Plus + IR and LMD
Bacharach of Canada	Steve Paquette	Leakator 10, Gas Pup, Hi-Flow Sampler
Bascom-Turner Instruments	Dennis N. Crouse	Gas-Sentry, Gas-Ranger, and Gas-Explorer
Boreal Laser Inc.	John Selby	GasFinder
Boreal Laser Inc.	Hamish Adam	GasFinder
Concept Controls Inc.	Ben Karst	MultiRAE Plus, Rae Systems Instruments
Concept Controls Inc.	Brent Yaschuck	RAESystems Instruments
Crowcon Detection Instruments Ltd.	Brendan OSullivan	LMD
CTRL Systems Inc.	Benjamin Fried	Ultrasonic CTRL UL101
Draegersafety	Brent Gingras	Drager X-am 7000, Drager Multi-PID 3
Draegersafety	Jeff Ambrosio	Drager X-am 7000, Drager Multi-PID 3
Draegersafety	Tim Goodwin	Drager X-am 7000, Drager Multi-PID 2
DS Prince Consulting	Dennis Prince	AIRDAR
Entevys Ltd.	Steve Lepp	ATV system (Boreal Laser and Sensit LMD)
FLIR Systems Canada	Greg Bork	FLIR GasFindIR
FLIR Systems Canada	Ken Waters	FLIR GasFindIR
Gas Imaging Technology	Michelle Hinrichs	Sherlock Camera
Guillevin International	Steve Eddy	TLV Sniffer
HETEK Solutions Inc.	Dave Keeling	GMI Leak Surveyor, RMLD
HETEK Solutions Inc.	Rebecca Hennigar	PPM Gasurveyor 500, Leak Surveyor
ITT Industries-Space Systems Division	Daniel Brake	ANGEL Service
ITT Industries-Space Systems Division	Steven Stearns	ANGEL Service
KASSAY Field Services, Inc	Steve Perry	RAM2000
LaSen Inc.	Bob Reich	LaSen ALPIS
LaSen Inc.	Igor V. Degtiarev	LaSen ALPIS
Midac Corporation	Mark Derenthal	FTIR Midac system.
Physical Acoustics Corporation	Carlton P. Gonsalves	VPAC/5131
PKL Technologies Inc.	Perry Kain	Spectra-1 system
Reliant Safety Equipment Inc.	Stuart McAulay	RAE Systems Instruments
Spectrasyne Ltd.	Jan Moncrieff	Spectrasyne DIAL unit
Spectrum Instruments	Brian Hickey	SDT Ultrasound Equipment
Synodon Inc.	Adrian Banica	Airborne realSens
Tevalco Ltd.	Daniel Livingstone	Sensit LMD, SensitR Gold CGI, SensitR HXG-2
Thermo Electron Corporation	Nilesh Davé	TVA 1000A, TVA 1000B, Innova
Tyco/Scott Health & Safety	Shaun Endsley	TLV Sniffer

Appendix B

Instructions for Using the “AutoFilter” Function in Excel Spreadsheets

Appendix B

Instructions for Using the “AutoFilter” Function in Excel Spreadsheets

Filtering is a quick and easy way to find and work with a subset of data in a range. A filtered range displays only the rows that meet the filtering criteria you specify for a column. Unlike sorting, filtering does not rearrange a range. Filtering temporarily hides rows you do not want displayed. When Excel filters rows, you can edit, format, chart, and print your range subset without rearranging or moving it.


When you use the AutoFilter command, AutoFilter arrows  appear to the right of the column labels in the filtered range. AutoFilter then displays only those rows that contain the filtered parameter that you select for that column.

You can also use “custom” AutoFilter to display rows that meet more than one condition for a column; for example, you might display rows that contain values within a specific range.


Click a cell in the range you want to filter.

On the Data menu, point to **Filter**, and then click **AutoFilter**.

▼ Filter a range for rows that contain specific text

1. Click the arrow  in the column that contains the numbers, and click (**Custom**).
2. In the box on the left, click **equals**, or **does not equal**, **contains**, or **does not contain**.
3. In the box on the right, enter the text you want.
4. To add another criteria, click **And** or **Or**, and repeat the previous step.

▼ Filter for numbers greater than or less than another number

1. Click the arrow  in the column that contains the numbers, and click (**Custom**).
2. In the box on the left, click **is greater than**, **is less than**, **is greater than or equal to**, or **is less than or equal to**.
3. In the box on the right, enter a number.
4. To add another criteria, click **And** or **Or**, and repeat the previous step.

When you apply a filter to a column, the only filters available for other columns are the values visible in the currently filtered range.

For more information regarding the capabilities of Excel, please refer to the program’s Help.

For an online tutorial on using Excel’s filtering capabilities, please follow the link below:

<http://office.microsoft.com/training/training.aspx?AssetID=RC011459671033>

Appendix C

North American and European Hazardous Area Standards and Approvals

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North American and European Hazardous Area Standards and Approvals

Industrial process and production areas at upstream oil and gas facilities involve the use of highly flammable and toxic gases. These areas are often classified as hazardous locations. Industrial facilities in which potentially explosive gas atmospheres exist or may exist must utilize proper explosive proof protection methods when using fugitive gas leak monitoring instruments.

Flammable Gas Hazards

Combustion is a chemical reaction in which oxygen is combined rapidly with another substance resulting in the release of energy. This energy appears mainly as heat, sometimes in the form of flames. The igniting substance is normally, but not always, a hydrocarbon compound and can be solid, vapor or gas. If an igniting source is gases or vapors, three (3) factors are always needed to cause combustion:

1. A source of ignition;
2. Oxygen; and
3. Fuel in the form of a gas or vapor.

There is only a limited band of gas/air concentration which will produce a combustible mixture. This band is specific for each gas and vapor and bounded by a lower level, called the Lower Explosive Limit (LEL) or Lower Flammable Limit (LFL) and an upper level, known as the Upper Explosive Limit (or the UEL) or Upper Flammable Limit (UFL).

The Lower Explosive Limit (LEL) or Lower Flammable Limit (LFL) is the minimum concentration of gas or vapor mixed with air (percent by volume, at room temperature) that will cause the propagation of flames when it comes in contact with a source of ignition. The Upper Explosive Limit (or the UEL) or Upper Flammable Limit (UFL) is the maximum concentration of gas or vapor mixed with air (percent by volume, at room temperature) that will cause the propagation of flames when it comes in contact with an ignition source. At levels below the LEL, there is insufficient gas to produce an explosion (i.e. the mixture is too "lean"), whilst above the UEL, the mixture has insufficient oxygen (i.e. the mixture is too "rich"). The flammable range therefore falls between the limits of the LEL and UEL for each individual gas or mixture of gases. Outside these limits, the mixture is not capable of combustion.

Flammable gases also have a temperature where ignition will take place, even without an external ignition source such as spark or flame. This temperature is called the ignition temperature. Instruments for use in hazardous area must not have a surface temperature that exceeds the ignition temperature. The instruments are therefore marked with a maximum surface temperature or T rating (T4 – suitable for gases or vapors with ignition temperatures greater than 135°C).

North American Hazardous Area Standards and Approvals

The North American system for the certification, installation, and inspection of hazardous locations equipment includes the following elements (Honeywell Analytics, 2006)

- Installation Codes: e.g. NEC, CEC;
- Standard Developing Organizations (SDOs): e.g. UL, CSA, FM;
- Nationally Recognized Testing Laboratories (NRTLs): Third Party Certifiers e.g. ARL, CSA, ETI, FM, ITSNA, MET, UL; and
- Inspection Authorities: e.g. OSHA, IAEI, USCG.

The installation codes in North America are the NEC (National Electric Code) for the USA, and the CEC (Canadian Electric Code) for Canada. In both countries, these codes are accepted and used by most authorities as the final standard on installation and use of electrical products. Details include equipment construction, performance and installation requirements, and area classification requirements.

The Standards Developing Organizations (SDOs) work with industry to develop the appropriate overall equipment requirements. Certain SDOs also serve as members of the technical committees charged with the development and maintenance of the North American installation codes for hazardous locations.

The Nationally Recognized Testing Laboratories (NRTLs) are independent third-party certifiers who assess the conformity of equipment with these requirements. The equipment tested and approved by these agencies is then suitable for use under the NEC or CEC installation standards.

In the United States of America, the inspection authority responsible is OSHA (Occupational Health and Safety Administration). In Canada, the inspection authority is the Standards Council of Canada. To confirm compliance to all national standards both countries require an additional indication on products tested and approved. As an example, CSA approved product to USA standards must add "NRTL/C" to the CSA symbol. In Canada, UL must add a small "c" to its label to indicate compliance to all Canadian Standards.

National Electric Code (NEC) articles 500-503 employ a class and division system. Classes identify the type of hazard present as gases or vapors, combustible dusts, and flammable fibers. Divisions define the condition under which the hazardous material may be present. The devices designed and manufactured for these hazardous locations should be tested and approved for use by a nationally recognized laboratory such as Underwriter's Laboratories (UL), Factory Mutual (FM), or Canadian Standards Association (CSA). The NEC 500 hazard classifications are as follows:

- Class I - Flammable gases or vapors;
- Class II - Combustible dusts;
- Class III - Easily ignitable fibers and flyings.

Each class is divided into two (2) divisions according to the probability that a hazardous atmosphere will be present. The divisions are as follows:

- Division 1, where ignitable concentrations of gases, vapors, dusts, and fibers can exist all the time or some of the time under normal operating conditions; and

- Division 2, where ignitable concentrations of gases, vapors, dusts, and fibers do not exist under normal operating conditions. Hazardous conditions only exist in the event of abnormal conditions, such as accidental rupture or breakdown of a container, storage tank, etc.

Class I is divided into four (4) groups: A through D. Groups are based on flame propagation characteristics, ignition temperature, and pressure generated during explosion of various gases and vapors. These groups are as follows:

- Group A - acetylene;
- Group B - acrolein, butadiene, ethylene oxide, formaldehyde, hydrogen, propylene oxide, and propyl nitrate; and
- Groups C and D - all other combustible gases belong to Groups C and D.

Class II is divided into three (3) groups: E, F and G. These groups are as follows:

- Group E – metal dust;
- Group F – coal dust; and
- Group G – grain and non-metallic dust.

Class I, division 1, groups A, B, C, and D locations are those in which hazardous concentrations of flammable gases or vapors may exist under normal conditions. Class I, division 2, groups A, B, C, and D are those in which hazardous concentrations of flammable gases may exist only under unlikely conditions of operation. Any instrument considered for use in potentially hazardous environments must be classified as intrinsically safe for class I, division 1 and class II, division 1 conditions at a minimum.

European Hazardous Area Standards and Approvals

European countries, as well as a majority of other nations of the world, have been influenced by the International Electrotechnical Commission's (IEC) three-tiered zone approach. The IEC separates the potentially explosive atmosphere into Zones 0, 1, and 2 based on the probability of occurrence and length of time a potential explosive mixture may be present. Instruments designed for use in these areas are usually tested and approved for use by the European Committee for Electrotechnical Standardization (CENELEC) test authorities using Euronorm (EN) standards. The division of these three (3) zones is:

- Zone 0 - an area in which an explosive gas atmosphere is continuously present for long periods;
- Zone 1 – an area in which an explosive gas atmosphere is likely to occur in normal operation;
- Zone 2 – an area in which an explosive gas atmosphere is not likely to occur in normal operation, and if it does, it will exist for a short period only.

In accordance with their explosive properties, the combustible gases and vapors are divided into temperature classes and explosion protection subgroups. There are no direct comparisons between the current NEC and IEC standards. National Fire Protection Agency (NFPA) in

America adopted article NEC 505 which is comparable to IEC standards. A brief comparison of IEC (world), CENELEC (Europe) and NEC (USA) are as follows (IEC/NEC Classification Comparator):

1. Condition: hazardous conditions exist continuously or for long periods of time:
 - NEC 505: Class 1, Zone 1;
 - NEC 500: Class 1, Division 1;
 - IEC: Zone 0; and
 - CENELEC: Zone 0.

2. Condition: hazardous condition is likely to occur in normal operation:
 - NEC 505: Class 1, Zone 1;
 - NEC 500: Class 1, Division 1;
 - IEC: Zone 1; and
 - CENELEC: Zone 1.

3. Condition: hazardous condition is not likely to occur in normal operation and if it does, only infrequently and for a short period.
 - NEC 505: Class 1, Zone 2;
 - NEC 500: Class 1, Division 2;
 - IEC: Zone 2; and
 - CENELEC: Zone 2.

Instrument Design

To ensure the safe operation of electrical equipment in flammable atmospheres, several design standards have been introduced. These design standards have to be followed by the manufacturer of an instrument sold for use in a hazardous area and must be certified as meeting the standard appropriate to its use. Equally, the user is responsible for ensuring that only correctly designed equipment is used in the hazardous area.

For gas detection equipment, the two (2) most widely used classes of electrical safety design are “flameproof” (sometimes known as “explosion-proof” and with an identification symbol Exd) and “intrinsically safe” with the symbol Exi. There are two (2) types of intrinsic protection. The highest is Exi (a) which is suitable for use in zone 0, 1 and 2 areas, and Exi (b) which is suitable for use in zone 1 and 2 areas. A letter E in front of Exd and Exi represents that a monitoring device meets the Euronorm (EN) standards.

A flameproof instrument is designed so that its enclosure is sufficiently rugged to withstand an internal explosion of flammable gas without suffering damage. This could possibly result from the accidental ignition of an explosive fuel/air mixture inside the equipment. The dimensions of any gaps in the flameproof case or box must be therefore calculated so that a flame can not propagate through to the outside atmosphere. This type of protection is most commonly used for gas monitoring applications and can meet the requirements of:

- NEC 505: Class 1, Zones 1 & 2, AExd;
- NEC 500: Class 1, Division 1 & 2;
- IEC: Exd; and
- CENELEC: EExd.

An intrinsically safe instrument is designed so that the maximum internal energy of the instrument and interconnecting wiring is kept below that which would be required to cause ignition by sparking or heating effects if there was an internal fault or a fault in any connected equipment. To meet this requirement, safety barriers or other devices limiting the electrical energy are placed on the wires to limit the electrical energy allowed to flow through the circuit before the wire enters into the hazardous location. Safety barriers are a combination of zener diodes, power resistors, and fuses which are designed to limit the amount of electrical energy allowed to flow through the wires. Various approved and certified safety barriers are available as standard electrical components. These are limited to low power device applications only. This method of protection can meet the requirements of:

NEC 505: Class 1, Zones 0, 1 & 2, AExi (a)

NEC 500: Class 1, Division 1 & 2;

IEC: Exi (a); and

CENELEC: EExi (a).

Appendix D

Laser Safety

Appendix D

Laser Safety

A laser is a light source that can be dangerous to the people exposed to it. Even low power lasers can be hazardous to eyesight. A person exposed to invisible laser radiation, in particular, may be unaware that damage is occurring. Some lasers are so powerful that even the diffuse reflection from a surface can be hazardous to the eye. Laser radiation predominantly causes eye injury via thermal effects on the retina. A transient increase of only 10°C can destroy retinal photoreceptors.

Classification

Lasers have been classified by wavelength and maximum output power into four (4) classes and a few subclasses since the early 1970s. The classifications were intended to categorize lasers according to their ability to produce damage in exposed people. In the United States the following safety classes have been established in consensus standards (IEC 825, later IEC 60825, and ANSI Z136.1) and in Federal and state regulations (the international classification is slightly different):

Old System (2000)

class I

Inherently safe; no possibility of eye damage. This can be either because of a low output power (in which cases eye damage is impossible even after hours of exposure), or due to an enclosure that cannot be opened in normal operation without the laser being switched off automatically, such as in CD players.

class II

The blinking reflex of the human eye (aversion response) will prevent eye damage, unless the person deliberately stares into the beam. Output powers up to 1 mW. This class contains lasers that emit visible light only. Some laser pointers are in this category.

class IIa

A region in the low-power end of Class II where the laser requires in excess of 1000 seconds of continuous viewing to produce a burn to the retina. Supermarket laser scanners are in this subclass.

class IIIa

Lasers in this class are mostly dangerous in combination with optical instruments which change the beam diameter. Output powers 1–5 mW. Maximum power density in the beam is 2.5 mW/square cm. Many laser pointers are in this category.

class IIIb

Will cause damage if the beam enters the eye directly. This generally applies to lasers powered from 5–500 mW. Lasers in this category can easily cause permanent eye damage from exposures of 1/100 th of a second or less depending on the strength of the laser. A diffuse reflection is generally not hazardous but specular reflections can be just as dangerous as direct exposures. Protective eyewear is always recommended when

experimenting with IIIb lasers. Lasers at the high power end of this class may also present a fire hazard and can lightly burn skin.

class IV

Highly dangerous. Lasers in this class have output powers of more than 500 mW in the beam, or produce intense pulses of light. These are cutting, etching and surgical lasers and can cause damage without being magnified by the optics of the eye. Diffuse reflections of the laser beam can be hazardous to skin or eye within the Nominal Hazard Zone.

The laser powers mentioned above are typical values; the classification is also dependent on the wavelength and on whether the laser is pulsed or continuous. In addition a laser of any power may be classified as a Class 1 Laser Product if it is enclosed so that there can be no access to laser radiation during normal use.

Revised System

In 2002 the system of Laser Classes was revised as part of a revision of the international laser safety standard, IEC 60825. The revision was based on the greater knowledge of lasers that had accumulated since the original classification system was devised, and was intended to permit certain types of lasers to be recognized as having a lower hazard than was implied by their placement in the original classification system. The revised system is expected to be adopted for use in the US in the next revision of the ANSI Laser Safety Standard (ANSI Z136). The FDA, which regulates lasers offered in commerce in the United States, does not object to its use on imported laser products' labels and markings.

class I

A class 1 laser is safe for use under all reasonably-anticipated conditions of use; in other words, it is not expected that the maximum permissible exposure (MPE) can be exceeded. This class may include lasers of a higher class whose beams are confined within a suitable enclosure so that access to laser radiation is physically prevented.

class IM

Class 1M lasers produce large-diameter beams, or beams that are divergent. The MPE for a Class 1M laser cannot normally be exceeded unless focusing or imaging optics are used to narrow down the beam. If the beam is refocused, the hazard of Class 1M lasers may be increased and the product class may be changed.

class II

A class 2 laser emits in the visible region. It is presumed that the human blink reflex will be sufficient to prevent damaging exposure, although prolonged viewing may be dangerous.

class IIM

A class IIM laser emits in the visible region in the form of a large diameter or divergent beam. It is presumed that the human blink reflex will be sufficient to prevent damaging exposure, but if the beam is focused down, damaging levels of radiation may be reached and may lead to a reclassification of the laser.

class IIIR

A class 3R laser is a continuous wave laser which may produce up to five times the emission limit for Class 1 or class 2 lasers. Although the MPE can be exceeded, the risk of injury is low. The laser can produce no more than 5 mW in the visible region.

class IIIB

A class 3B laser produces light of intensity such that the MPE for eye exposure may be exceeded and direct viewing of the beam is potentially serious. Diffuse radiation (i.e., that which is scattered from a diffusing surface) should not be hazardous. CW emission from such lasers at wavelengths above 315 nm must not exceed 0.5 watts.

class IV

Class 4 lasers are of high power (typically more than 500 mW if cw, or 10 J/cm² if pulsed). These are hazardous to view at all times, may cause devastating and permanent eye damage, may have sufficient energy to ignite materials, and may cause significant skin damage. Exposure of the eye or skin to both the direct laser beam and to scattered beams, even those produced by reflection from diffusing surfaces, must be avoided at all times. In addition, they may pose a fire risk and may generate hazardous fumes.

(From The Physical and Theoretical Chemistry Laboratory Oxford University)
(<http://ptcl.chem.ox.ac.uk/MSDS/>)

Protective Eyewear

Laser goggles

Inside an environment with exposed laser beams, it is recommended that everyone wears suitable eye protection.

In the U.S., guidance for the use of protective eyewear, and other elements of safe laser use, is given in the ANSI Z136 series of standards. They are:

ANSI Z136.1 - Safe Use of Lasers;

ANSI Z136.2 - Safe Use of Lasers in Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources;

ANSI Z136.3 - Safe Use of Lasers in Health Care Facilities;

ANSI Z136.5 - Safe Use of Lasers in Educational Institutions; and

ANSI Z136.6 - Safe Use of Lasers Outdoors

In the European Community, eye protection requirements are specified in the European norm EN 207. In addition to the EN 207 norm, there is the European norm EN 208 norm that specifies requirements for goggles for use during alignment. These transmit a small fraction of the laser light in order to allow the operator to see where the beam is. The latter does not provide sufficient protection against a direct hit of the laser beam. Finally, the European norm *EN 60825* specifies the required optical densities in extreme situations.