IntelliRed™ System for Autonomous Detection of Hydrocarbon Releases

H.M. Abdel-Moati, ExxonMobil Research Qatar, J.M. Morris, Providence Photonics LLC

Identifying fugitive emissions from large scale LNG and gas processing and handling facilities is a time and resource intensive process. Because of the limitations of hand held gas detection devices, and the sheer size and complexity of these facilities, smaller leaks may go undetected and unintended releases may occur when plant personnel are not present or the area monitored. Reducing the total fugitive emissions from a large plant or a regional industry footprint could have an appreciable positive impact on the environment. Further, early detection of hydrocarbon leaks using a continuous monitoring system can reduce the risk of conditions that may lead to safety incidents that can result from unintended ignition of gas plumes.

ExxonMobil Research Qatar and Providence Photonics have partnered since 2009 to develop the IntelliRed™ Remote Gas Detection system that integrates computer vision algorithms and infrared (IR) technology to autonomously scan for and identify small leaks. Efficient identification of these emission sources can lead to better control and maintenance activities.

A single sensor version of the technology utilizes a custom build component based IR camera and integrated cooler assembly, and a computer vision algorithm that analyses the video output from the IR imagers to determine the presence of hydrocarbon plumes. Most hydrocarbon plumes have strong absorption peaks in the narrow mid-wave IR region. The algorithm takes advantage of the difference in contrast between a hydrocarbon plume and the background in each pixel of an IR image and the temporal changes due to plume behavior for the analysis. The algorithm compares sequentially collected IR images and uses a multi-stage confirmation process to confirm the detection and has built-in filters that eliminate interferences like steam, and moving objects. Field tests indicate a 4 lb/hr propane leak could be autonomously detected from a distance of up to 800 feet. Also, rigorous field tests comparing the technology to point and path detectors showed successful detection of leaks, 300 feet away, that barely elicited a response from a point and path detector array only 5 feet away.

A dual sensor version of the technology utilizes two cooled mid-wavelength IR (MWIR) sensors with a common optical path resulting in a differential infrared (DIR) camera. The infrared energy from the scene is split between two sensors and the spectral band pass filtering for the two sensors is chosen so that one sensor can see the hydrocarbon plume while the second sensor cannot. The two sensors are synchronized spatially and temporally to ensure that successive frames are aligned correctly. Image subtraction techniques are used to produce a differential image that eliminates the background, thus filtering out interferences such as dust and steam and allowing for leak detection while the system is in motion without the need for image stabilization.

The IntelliRed™ technology was commercialized in 2014 and has since been deployed at 6 process facilities worldwide. Current research focus is to add quantification capability for use in upstream and downstream LDAR applications through an ongoing research partnership with ExxonMobil Research and Engineering.

Introduction

Leak detection is a fundamental part of safe operations during hydrocarbon exploration, production and processing activities. Hydrocarbon leaks can potentially lead to explosive environments, which may escalate to the point of a high consequence industrial accident. In addition, leaks have impacts on processing efficiency and are undesirable from an environmental perspective as hydrocarbons can be precursors for ozone formation and contribute to poor air quality. Hydrocarbon leaks also have an economic impact as they represent lost product. The petro-chemical industry devotes considerable resources to leak detection to ensure the safety of workers, protection of the environment and to maximize production efficiency. Various methods of autonomous leak detection are employed by the petro-chemical industry, including catalytic combustible gas detectors, point infrared gas detectors, path infrared gas detectors, and acoustic leak detectors. These technologies are mature and provide detection for large hydrocarbon leaks, but early leak detection of small leak rates or fugitive emissions is generally not possible with these legacy technologies.

Hand held flame ionization detectors (FID) are utilized to spot check specific components such as flanges, valves and gauges for small leaks. FIDs are typically used in the United States as part of the Environment Protection Agency (EPA) Leak Detection and Repair (LDAR) program. While the hand held FID can detect small leaks, the process is labor intensive and areas that are difficult to access (such as elevated pipe racks or distillation columns) present logistical challenges when using a hand held FID.

Infrared (IR) optical gas imagers are capable of visualizing hydrocarbon plumes and have become an effective hand held leak detection tool throughout the petro-chemical industry. Gas imagers have been approved for use as part of the EPA LDAR program and allow operators to inspect components much more rapidly. Gas imagers provide the ability to detect hydrocarbons remotely, which enables operators to inspect difficult to reach areas. The remote nature of the gas imagers also makes it possible to inspect multiple components at one time, providing a significant productivity gain when compared with an FID.

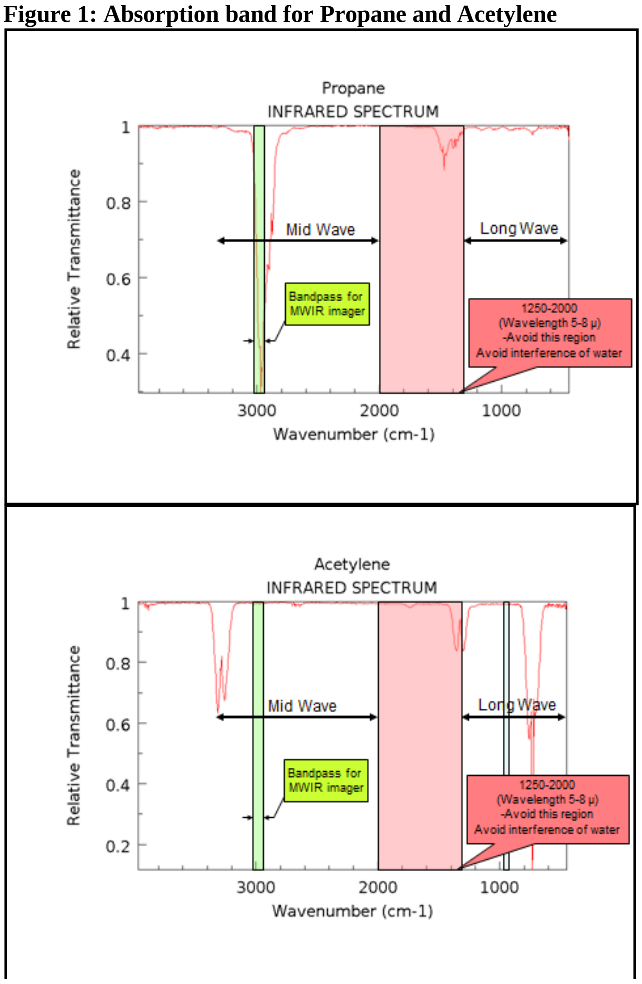
While IR gas imagers provide remote detection capability, they require an operator to view the video and determine whether or not a hydrocarbon plume is present. The innovation of the IntelliRed™ technology is that it replaces the operator with a computer vision algorithm. Field-testing has shown that a single IntelliRed™ system can provide continuous remote leak detection at distances up to 800 feet with leak rates as low as 4 lbs/hour.

The commercially available IntelliRed™ systems are based on a single mid-wave IR imager. Sequential frames from the imager are aligned and the detection algorithm relies upon a temporal analysis for detection. The current frame is compared pixel by pixel to a moving average to determine which pixels are changing. Adjacent changing pixels are combined into candidate blobs and their behavior is studied. Features such as speed, direction, size, shape, texture and aspect ratio are used to determine if the changing pixels are caused by a hydrocarbon plume. This allows the IntelliRed™ system to differentiate between a hydrocarbon plume and common interferences such as people and vehicles. The design and applications for the single and dual sensor IntelliRed™ technologies are presented in this paper.

Background information on Infrared Gas Imagers

Industrial IR gas imagers are generally passive systems relying on the optical energy emitted by objects in the scene. Absorption bands for most hydrocarbons in the MWIR overlap in a narrow region between 3.2 and 3.4 microns. These imagers typically use cooled MWIR Indium Antimonide (InSb) detectors with a narrow band pass filter to exploit the absorption bands of hydrocarbon compounds. This allows a single imager to detect multiple hydrocarbons, although it does not provide the ability to discriminate between hydrocarbons. **Figure 1** shows the absorption band for a compound detectable by these imagers (propane) and a compound non-detectable by these imagers (acetylene)[1].

Figure 1: Absorption band for Propane and Acetylene



These cooled MWIR handheld infrared gas imagers are capable of detecting small hydrocarbon leaks. The detection capability is affected by the energy of the background and the absorption characteristics of the target compound. In general, high temperature backgrounds (such as process equipment) and low temperature backgrounds (such as sky) provide favorable backgrounds for detection. In the case of a warm background, the hydrocarbon plume will absorb a portion of the infrared energy and appear as a dark plume in the image. In the case of a cold background, the hydrocarbon plume will emit IR energy at a level higher than the background and the hydrocarbon plume will appear as a white plume against the dark background.

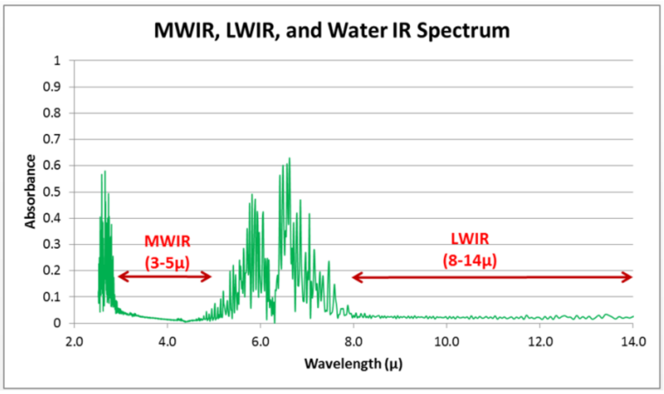
The minimum detected leak rate (MDLR) for a commercially available IR optical gas imager was evaluated in laboratory testing[2] and is reported in **Table 1**.

Table 1 – Minimum Detected Leak Rate	
Compound	**MDLR**
Pentene	5.6g/hr
Benzene	3.5g/hr
Butane	0.4g/hr
Ethane	0.6g/hr
Ethanol	0.7g/hr
Ethylbenzene	1.5g/hr
Ethylene	4.4g/hr
Heptane	1.8g/hr
Hexane	1.7g/hr
Isoprene	8.1g/hr
MEK	3.5g/hr
Methane	0.8g/hr
Methanol	3.8g/hr
MIBK	2.1g/hr
Octane	1.2g/hr
Pentane	3.0g/hr
Propane	0.4g/hr
Propylene	2.9g/hr
Toluene	3.8g/hr
Xylene	1.9g/hr

It should be noted that faster optics available in recent cameras result in a larger aperture, more energy to the sensor and higher sensitivity. This in turn will reduce the MDLR. Correlating these laboratory results to an industrial setting can be difficult as the background temperature and wind conditions are significant variables for the MDLR, as does the distance between the camera and plume.

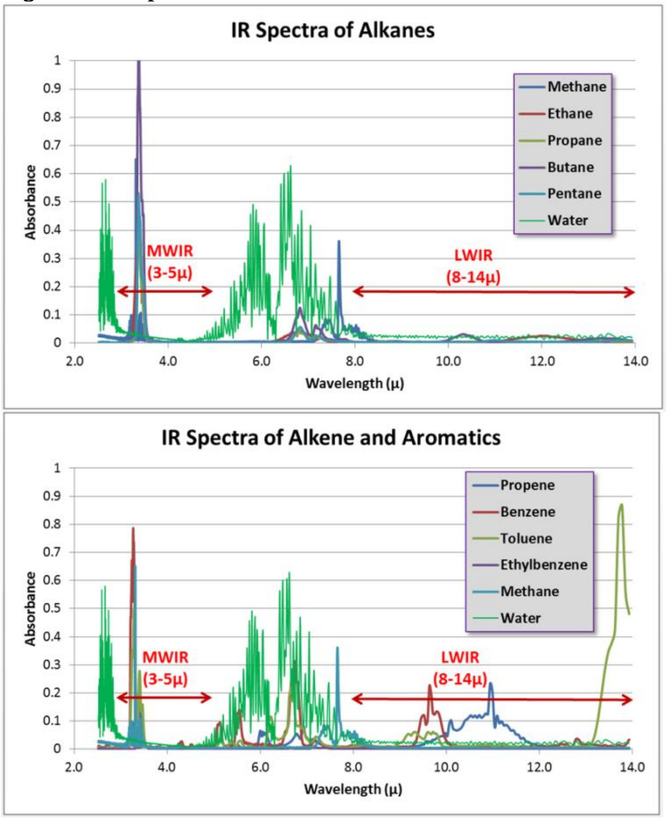
While most industrial gas imagers operate in the MWIR, it is also possible to operate in the Long-wave IR (LWIR). The boundaries for MWIR (3-5u) and LWIR (8-14u) are generally defined by the strong water vapor absorbance regions. **Figure 2** shows the absorbance of water vapor as a function of wavelength. Regions of strong absorbance for water vapor are not suitable for optical gas imaging, as the water vapor in the atmosphere will provide a significant interference.

Figure 2: MWIR, LWIR and Water IR Spectrum



The primary benefit for using a LWIR imager for optical gas imaging applications is the ability to speciate the compound. In the MWIR, absorbance bands for hydrocarbons are common, meaning a single detector can image multiple compounds but will not be able to speciate. In the LWIR, the absorbance bands spread out allowing the possibility to detect a specific compound or family of compounds. **Figure 3** shows the IR Spectra of Alkanes, Alkenes and Aromatics.

Figure 3: IR Spectra of Alkanes



As shown in **Figures 3,** absorbance bands for Alkanes, Alkenes and Aromatics overlap in the MWIR at about 3.3u. A MWIR imager with spectral filtering to exploit this band will be quite versatile, as it will detect all of the hydrocarbons with absorbance in this region. However, in the LWIR the absorption bands have regions that do not overlap. A hyper spectral LWIR imager can exploit this feature and detect the relative signal of a specific compound. This is difficult to do for the Alkanes (example: Methane, Ethane, Propane, Butane, Pentane) due to the poor absorbance in the LWIR, however it is easier for some Alkenes (example: Propene) or Aromatics (example: Benzene). A hyper spectral imager operating in the LWIR could be an effective tool for detecting and identifying Propene or Benzene. In general, the versatility and higher sensitivity of the MWIR imagers make them more suitable for general hydrocarbon leak detection when the target compounds are not known.

Single sensor system

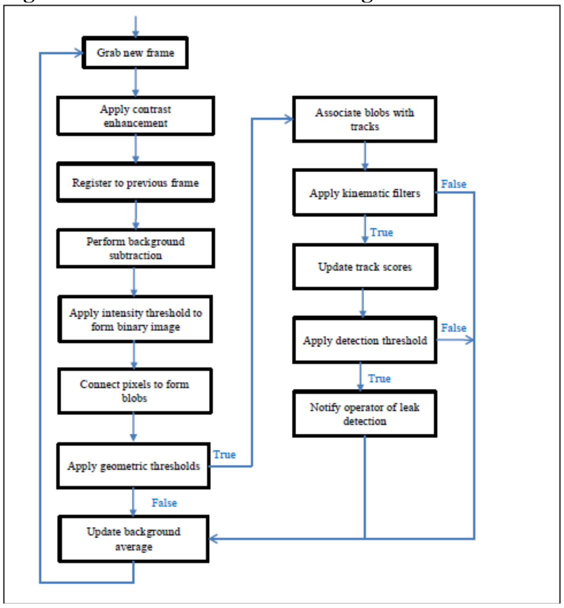
The single sensor IntelliRed™ technology comprises a lone MWIR sensor mated with a custom continuous zoom 25mm to 100mm lens with an optional 2X optical doubler which extends the focal range to 200mm. This optic can be remotely zoomed and focused, enabling a single camera installation to monitor a variety of objects at different distances.

At the heart of the single sensor IntelliRed™ technology is the computer vision algorithm which processes the video stream from a single IR optical gas imager. The detection algorithm analyzes sequential frames from the infrared video to detect a hydrocarbon plume and generate an alarm. Early versions of the detection algorithm utilized an analog 8-bit 320 by 240 resolution video stream. The analog video was encoded and transmitted wirelessly to a server running the detection algorithm. Later versions utilized an 8-bit HDMI video stream and a 14-bit 640 x 512 stream. **Figure 4** describes the steps of the computer vision algorithm.

The first step for the detection algorithm is to pre-process the video stream. This process includes contrast enhancement using histogram equalization and de-noise using a bilateral smoothing filter. The enhanced image is then registered to the previous frame. The detection algorithm studies the changes in pixels over time, so it is important to register each frame prior to processing. Techniques employed to achieve registration and stabilization include feature point extraction using Shi-Tomasi corner detector3 and associating pairs of feature points using Pyramidal Lucas-Kanade optical flow method4. In addition, affine transformation modeling is implemented to fit the geometric changes between image frames utilizing random sample consensus (RANSAC) to remove outliers. The registration process can be enhanced by using edge detection (Canny edge detector) to mask edges in the scene and reduce noise due to improper registration. The result from utilizing these techniques is a series of frames with improved contrast and good spatial registration.

Once the image has been registered, the algorithm will compare the current frame to a moving average of the background. An intensity threshold is applied to determine which pixels are changing relative to the moving average. This process reduces the image to binary data, with each pixel classified as changing or not-changing. Adjacent changing pixels are then grouped to form blobs and additional spatial thresholds are applied to the candidate blobs. The blobs are subjected to minimum and maximum sizes (in terms of pixels). The minimum blob size threshold removes noise in the image, while the maximum size threshold removes blobs caused by dramatic changes in scene intensity which affect most pixels (such as occurances when a cloud moves to reveal direct sunlight). A bounding box is drawn around candidate blobs and thresholds are applied to the aspect ratio of the bounding box (height vs. width) as well as the fill ratio of the bounding box (ratio of pixels inside the box which are changing to those which are not changing). If a candidate blob survives these spatial filters, it is considered to be a foreground object and it is associated with blobs from previous frames using Global Nearest Neighbor (GNN) technique. If it does not survive the spatial filters, it will be considered a background object and is not considered for subsequent processing.

Figure 4: IntelliRed™ Detection Algorithm



A track is established for each foreground object to track the movement across multiple frames. A blob is associated with an existing track by comparing the location of the center of the bounding box with the most recent blob in the existing tracks. Thresholds are applied to limit the acceptable distance between the current blob and the previous blob in an existing track. A second threshold is applied to limit the acceptable distance between the current blob and the origin of an existing track. If the blob cannot be associated with an existing track, a new track is established for the blob in the current frame for subsequent processing. The detection algorithm is capable of monitoring hundreds of tracks simultaneously.

Once the blobs are segmented into tracks, each track receives a score which describes the likelihood that the track represents a plume. A blob can increment the score of the track if it passes additional filters. The distance traveled between the current blob and the previous blob is used to calculate an average speed for the track. If the track represents a collection of blobs which is relatively static it is not likely to be a plume (more likely to be a person). Similarly, if the average speed of the track is relatively high, it is not likely to be a plume (more likely to be a vehicle). These thresholds are correlated to the distance between the camera and the scene and are typically very loose.

One of the most important thresholds to filter out non-gaseous blobs is the degree to which the blob is changing shape relative to previous blobs in the track. The algorithm describes the shape of the blob using a combination of the first, second and third order moments. Moments of a blob can be used to uniquely describe the information contained in the blob. The lower order moments represent some well-known fundamental geometric properties of the image. For example, zero, first and second order moments represent respectively the area, the mass center of the blob and the orientation of the principal axes of the blob. While there are other shape comparison methods available (such as blob correlation and blob matching), the algorithm uses moments because they are fast to compute.

Once the blobs have been processed and track scores have been updated, the moving average of the background will be updated. Foreground objects and background objects both influence the moving average but at different rates. A background object will typically influence the background moving average at a higher rate than the foreground objects. The rate at which foreground and background objects update the moving average can be adjusted dynamically by the algorithm. For example, the conditions of the scene may set the weight of background objects to 5% (meaning the current frame counts 5% towards the new average value while the previous frames count 95%) and the weight of foreground objects to 1%. This approach allows the algorithm to adapt to a changing scene as a foreground object that becomes stationary will eventually become part of the background, such as occurances when a vehicle drives into the scene and stops.

A final threshold is applied to the score for each track. When the track score exceeds this threshold the algorithm declares that a plume has been detected. The location of that confirmation is recorded and the scores are reset. Depending on the sensitivity settings on the algorithm, a notification may be sent immediately or multiple confirmations may be required before notification. The nature of the notification can be an email (with an embedded still image of the leak), fax, multi-media text message, analog voltage, analogy current, or Modbus TCP alarm.

The detection algorithm utilizes multiple thresholds to achieve detection. Some of these thresholds can be set during installation of the camera, such as those related to the distance between the camera and the objects which are monitored. Other thresholds must be set dynamically by the algorithm in response to changing factors in the scene. For example, at night energy levels in the scene tend to decrease so the intensity threshold applied to changing pixels needs to be lowered. Still other thresholds trade-off detection sensitivity with the false alarm rate and can be set by the user, such as the confirmation score for a track. The combination of these thresholds allow for the deployment of a complex detection algorithm to a variety of environments, providing continuous autonomous remote leak detection capability.

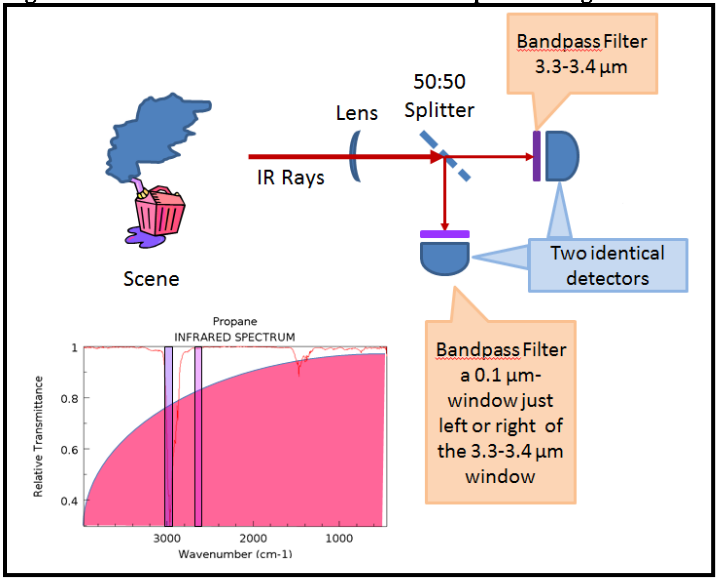
One limitation of the current single sensor IntelliRed™ technology is that the temporal analysis requires careful alignment of sequential frames from the imager. A "step and stare" inspection technique covers a large field of view with a series of automated steps, with the imager remaining stationary at each step. If the imager is moving or shaking during detection then the frames must first be aligned using registration techniques prior to detection. These frame alignment techniques can be resource intensive and generally require several high contrast features in the image.

Another limitation of the current single sensor IntelliRed™ technology is that certain interferences can be difficult to filter out. For example, a steam plume will present a signal in a MWIR imager that behaves in a manner similar to a hydrocarbon plume. One effective technique to distinguish between steam and hydrocarbon is to use the polarity of the plume. A steam plume consists of water droplets that are generally at a higher temperature than the background and therefore the plume appears "white" in an infrared image. A hydrocarbon plume generally absorbs a portion of the energy from the background and appears darker than the background. This simple polarity test is effective, but a more robust filter is provided by the dual sensor IntelliRed™ technology currently undergoing qualification.

Dual sensor system

The working principle of the IntelliRed™ DIR camera is illustrated by **Figure 5**. The IR energy coming from a scene is reimaged onto a beam splitter positioned in the optical path. As a result, a portion of the IR energy from the scene passes through the splitter to reach one MWIR detector and a portion of the IR energy from the scene is reflected to the second MWIR detector. This beam splitter can be a simple broadband splitter with reflectance and transmittance of approximately 50%. This design evenly splits the energy with approximately 50% reaching each detector. Alternatively, the splitter can be dichroic allowing for wavelength specific reflectance and transmittance. Careful design of the spectral filtering and dichroic splitter can provide each detector with nearly 100% of the energy in its respective wavelength.

Figure 5: IntelliRed™ Differential Infrared Optical Design



The unique feature of the dual sensor IntelliRed™ design is that the specific wavelengths selected for the bandpass filters make one detector sensitive to hydrocarbon plumes while the second detector is not. The detector sensitive to hydrocarbon gas operates with a bandpass filter in the 3.3u to 3.4u range and is referred to as the Gas Band (GB) imager. The second detector is referred to as the Reference Band (RB) imager and has a bandpass filter that is shifted to the right or left of the GB imager. Since the RB imager is still operating in the MWIR region, it provides a spatially and temporally registered reference image that is very similar to the GB but insensitive to hydrocarbon gas. **Figure 6** shows the raw unprocessed data from a single frame of a dual sensor IntelliRed™ imager.

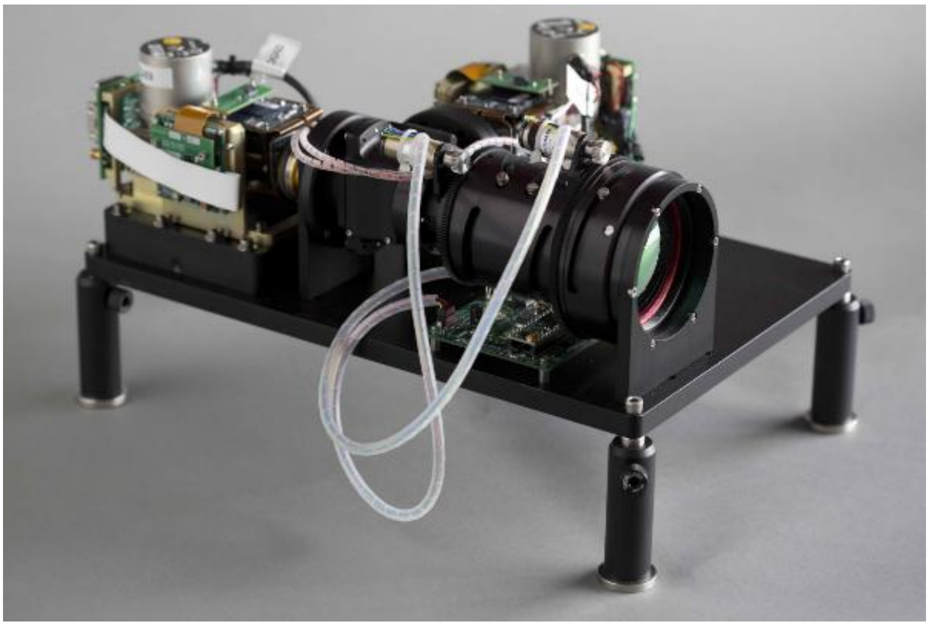
Figure 6: IntelliRed™ Differential Infrared Frame

The left side of the image in **Figure 6** shows the GB imager and the right side shows the RB imager. Notice the presence of a hydrocarbon plume in the GB image and the absence of the plume in the RB image. Other interferences, such as people and steam, are present in both images. In a simple sense, a pixel-by-pixel subtraction will reveal the presence of a hydrocarbon plume. In reality, more complex processing is required but field-testing has shown that this design can achieve autonomous detection within a single frame. With single frame detection, new applications such as aerial pipeline surveys are now possible. The hydrocarbon plume represented in this image was generated by a Propane leak at the rate of 1.5 lb/hour and imaged from a distance of 300 feet.

Field Testing IntelliRed™ DIR System

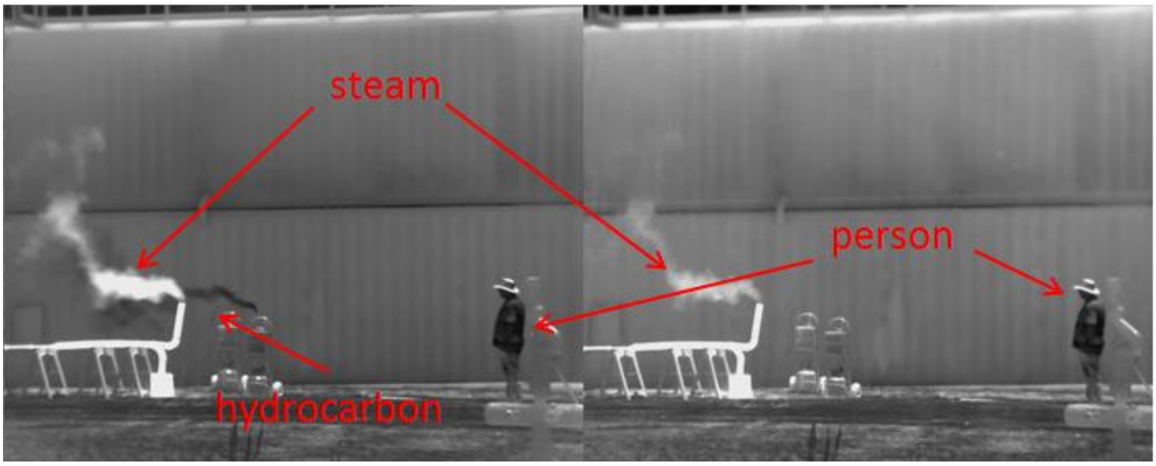
A prototype DIR imager was constructed using two cooled MWIR imagers with a common optical path. Each imager provides 640x512 pixels streaming video at 30 frames per second. A synchronized master clock provides temporal registration between the two imagers assuring good alignment for moving objects. The optic for the prototype DIR is a 25mm to 100mm F1.5 continuous zoom lens with motorized zoom and focus controls. **Figure 7** shows a picture of the prototype imager.

Figure 7: Prototype IntelliRed™ DIR System



Field-testing the prototype DIR camera and algorithm demonstrated the ability to identify a hydrocarbon plume and distinguish it from common interferences such as people and steam. In the following sample frame collected during field-testing shown in **Figure 8**, you can see the image from the gas band on the left and the reference band on the right.

Figure 8: Spatially registered frame from gas band (left) and reference band (right) of DIR camera



Notice that the hydrocarbon plume appears as a dark shape in the gas band and is not present in the reference band. The white steam plume is present in both the gas band, though at a higher intensity in the gas band. The person appears in both the gas band and the reference band. Applying the techniques described above, the signal of the hydrocarbon plume is separated from the steam plume and other background objects. **Figure 9** shows the resulting image with the hydrocarbon plume autonomously recognized and highlighted by colorizing the pixels red.

Figure 9: Resulting frame from DIR algorithm

A significant benefit of these techniques is that the detection is accomplished in a single frame of video. This allows for a much simpler computer vision algorithm architecture that requires minimal processing power to function. The dual sensor algorithm is compact enough that it could be deployed directly into the firmware of the IR camera, significantly reducing ancillary equipment requirements. Another benefit is that it allows leak detection to occur from a moving camera platform, lending itself to vehicle, marine or aerial based surveys. These results were repeated with multiple field tests utilizing various backgrounds and leak scenarios. The thresholds and techniques applied continue to develop with additional field-testing improving the sensitivity and false alarm rejection rate.

Pilot Deployments

Deploying these IR imagers into industrial settings requires rugged camera enclosures to protect against the elements. Temperature, dust and humidity can all adversely affect the performance and lifetime of the equipment. **Figure 10** depicts a rugged enclosure developed for the deployment into an industrial setting.

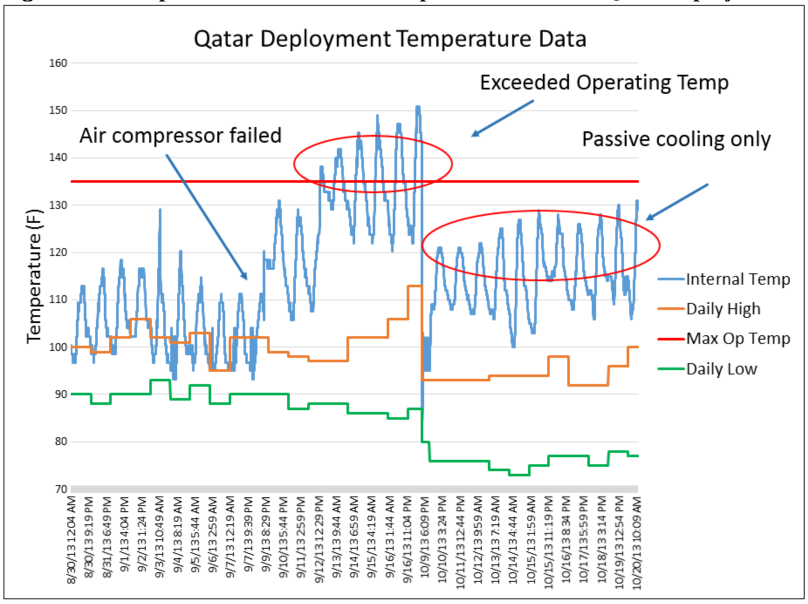
Figure 10: Rugged enclosure for IR Optical Gas Imager

This enclosure is sealed, pressurized and temperature controlled. A thermostatically controlled Vortex cooler converts high pressure, high temperature instrument air into low pressure, low temperature air to cool the enclosure. An integrated pressure switch monitors the pressure differential between the enclosure and ambient pressure and will disconnect power to the enclosure if the pressure differential drops below a set threshold. In addition to the infrared imager, a visible camera is co-located in the enclosure. All of the power systems, control signals and video streams are combined to a single mil-spec plug, providing a unified Ethernet connection and single 48V DC power supply. This allows the operator to control the camera assembly with a web-based interface utilizing Ethernet protocols. This system has been deployed in Qatar since July of 2013 and similar systems have been deployed to facilities in Saudia Arabia and the United States. **Figure 11** shows the deployed system in Qatar (left) and the United States (right).

Figure 11: Deployed IntelliRed™ systems in Qatar (left) and the United States (right)

One significant challenge for the deployment in Qatar was keeping the enclosure interior temperature below the operating temperature for the imager and electronics. For deployments in the United States, thermoelectrically cooled enclosures were sufficient to provide continuous operation. However, environmental testing showed that the thermoelectric coolers would not provide sufficient cooling for the harsh Qatar climate. A new cooling system was designed to meet this challenge. A thermostatically controlled Vortex cooler uses high pressure (100 psi), high temperature (40C or higher) instrument air to generate low pressure, low temperature air to cool the enclosure. While this introduces the need for instrument air at the deployment site, it provides a very robust cooling solution. Throughout the Qatar deployment, the system maintained operating temperature with a reliable instrument air supply. There were occasions when the air compressor supplying the instrument air failed. **Figure 12** shows temperature data collected before and after a failure of the air compressor.

Figure 12: Temperature data for air compressor failure at Qatar deployment site



As the temperature data shows, the enclosure is kept well within operating temperature limits with a supply of instrument air. When the instrument air supply failed, the interior temperature of the enclosure exceeded the operating temperature for the imager causing the system to shut itself off. Once the ambient temperatures dropped, the system was able to operate without instrument air and passive cooling only. This field data showed that the system can be operated continuously in the extreme climate of Qatar with a reliable instrument air supply. Another version of this enclosure has achieved ATEX EX II 1 G Exp IIA T3 (Zone 1) certification, enabling deployment in hazardous electrical environments. The ATEX certified version of the enclosure was deployed into Qatar in the third quarter of 2015. Based on the results of this pilot deployment, a new sensor platform with a high temperature imager has been developed which can achieve continuous operation in Qatar with passive cooling only (no instrument air needed). That version is currently offered as an option for the single sensor IntelliRed™ systems. This innovation will reduce the costs of deployed IntelliRed™ systems as the site preparations will be reduced to a single power supply and a single Ethernet connection.

Comparison to existing technology

The most prevalent technologies currently used for leak detection are catalytic point combustible gas detectors, IR point detectors and IR path detectors. Catalytic point combustible gas detectors rely on the principle that when gas oxidizes it produces heat. The sensor generally includes two heating elements, with one element embedded in a catalyst. The surface of the catalyst reacts exothermically in the presence of hydrocarbons. This reaction generates heat, which changes the resistance of the embedded coil. The resistance of the embedded coil is measured via a standard Wheatstone Bridge-type circuit and compared to the reference coil. The change in resistance is proportional to the gas concentration. One potential drawback of the catalytic combustible gas detectors is that the catalyst requires oxygen to operate. An oxygen deficient environment will reduce the efficiency of the oxidation and hence the sensor's accuracy. The catalyst can also be contaminated by dust, oil, grease and certain chemical compounds, such as silicones and sulfurs. This failure mode may not be easily detectable and so requires frequent calibrations of the sensor.

IR point combustible gas detectors have generally replaced traditional catalytic detectors for detecting lower explosion limit (LEL) hydrocarbon vapor measurement. The basic measurement principal of an IR point detector uses an infrared source to illuminate a volume of gas that has diffused into a measurement chamber. If hydrocarbons are present in the measurement chamber, they will absorb certain wavelengths of infrared energy as the light passes through the chamber while other wavelengths pass through completely unattenuated. Two optical sensors with different spectral sensitivity measure the change in intensity of the absorbed light compared to the non-absorbed light. This change in intensity is related to the concentration of the hydrocarbons in the measurement chamber. The point infrared detectors are sometimes deployed in pairs utilizing voting logic to reduce false alarms. A potential issue with infrared point detectors is insensitivity or signal drifting caused by water and water vapor in the measurement chamber.

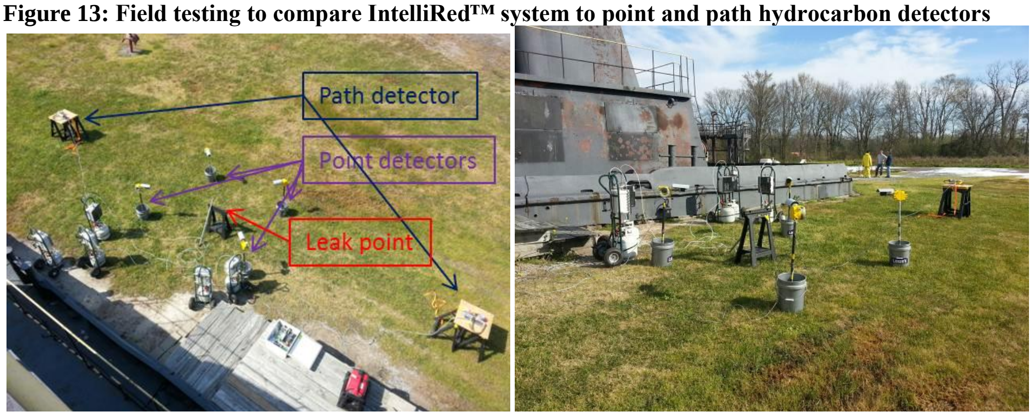
While IR point detectors rely on wind conditions to bring the hydrocarbon plume to the point detector, IR open path detectors can cover a wider area. The technology relies on an infrared source and receiver, which are mounted at some distance from each other. The source and receiver are carefully aligned and calibrated to establish the response in the absence of a hydrocarbon plume. The distance between the source and receiver can be several hundred feet. After calibration, the IR open path detector continuously monitors the signal from the source. If a hydrocarbon plume passes between the source and receiver, it will absorb certain wavelengths of IR energy. The receiver will detect the reduced energy level caused by the absorption of the hydrocarbon vapor. Due to the nature of open path measurement, the units of the detector are concentration by unit of distance, typically LEL-meters. Most industrial IR open path detectors use multiple spectral filters to eliminate the interference from water vapor exhibited by IR point detectors. As a result, IR open path detectors can operate in high humidity conditions, including rain or fog. A potential issue for IR open path detectors is obstruction or misalignment of the infrared source.

A series of field tests were conducted to compare the detection capability of the IntelliRed™ remote gas detection system to existing point and path infrared technology. A representative sensor was selected for the two most common technologies (IR point detectors and IR open path detectors) based on a survey of the devices deployed at various facilities. Four point detector units were purchased and were calibrated to Propane (0 – 100% LEL). Each unit has a response (T50 – time to 50 percent of range) of 4.5 seconds. A short-range path detector (15 to 130 feet) with a measurement range from 0 to 5 LEL-meters was chosen with a response time (T90 – time to 90% of range) of 3 seconds. An alignment tool was also purchased to provide for calibration in the field.

The IntelliRed™ system was deployed with a 25mm to 100mm F1.5 continuous zoom lens. The zoom lens was set to the longest focal length (100mm) for each scenario. The algorithm thresholds and sensitivity settings were identical for each scenario, although three different backgrounds were selected. The IntelliRed™ algorithm was challenged with interferences (people) before each test to ensure that the sensitivity settings were reasonable for continuous deployment. The IntelliRed™ system was operated in autonomous mode during each leak scenario with no human interaction to facilitate detection. For the purposes of these field tests, the IntelliRed™ system was required to achieve three confirmations to successfully detect a leak.

In total, 11 field tests were conducted comparing the point and path detectors to the IntelliRed™ system. Propane gas was released at rates varying from 15 l/min to 60 l/min. The point detectors (4) were arranged in close proximity to the release point at a distance of 5 feet. The path detector was arranged to intersect with the plume at a point in close proximity to the release point. The IntelliRed™ system was positioned at distances ranging from 275 to 320 feet from the release point. **Figure 13** shows images of a typical field test, with point detectors arranged in a diamond pattern around the release point and the path detector intersecting with the release point. The leak duration for each scenario was 10 minutes.

Figure 13: Field testing to compare IntelliRed™ system to point and path hydrocarbon detectors



Prior to each field test, the point and path detector were calibrated. For the point detectors, a 50% LEL calibration gas was used to calibrate and then demonstrate the response of each detector. For the path detector, an alignment tool was utilized to ensure good signal and calibration performed using optical filters. The IntelliRed™ system successfully confirmed the leak in each of the 11 scenarios. The cumulative results from the point and path detectors are shown in **Table 2**.

The alarm levels for the IR point detectors are user defined, but common practice is to set the alarm value at 50% LEL (approximate midpoint of the instrument range). With that threshold, none of the point detectors produced an alarm throughout the field-testing. The highest reading from a point detector (37.8 % LEL) was achieved during scenario 7 with a leak rate of 60 l/min at a distance of 5 feet from the leak source.

The open path detector alarm thresholds are also user defined. Common practice is to set the alarm value at approximately 50% of the detection range, or 2.5 LEL-m. With that threshold, the path detector did not alarm during any of the field tests. The highest response (1.9 LEL-m) was achieved during scenario 1 with a leak rate of 45 l/min and the path detector arranged to interact with the plume approximately 1 foot from the release point.

Table 2: IR point and path detector response

Leak Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Leak Rate (l/min)	**45**	**60**	**30**	**15**	**15**	**15**	**60**	**60**	**60**	**45**	**45**
Point 1 Response (% LEL)	0.6	0	3.0	3.5	0	0	0	0	0	0	0
Point 2 Response (% LEL)	0	0	0	0	0	0	0	0	0	0	0
Point 3 Response (% LEL)	0	0.2	0	0	0	0	0	0.9	0	0	0.2
Point 4 Response (% LEL)	0	0	7.5	0	0	0	0	37.8	18	0	0
Path Response (LEL-m)	1.9	0	1.6	0.8	0	0	0	0.9	0	0	0

While these results are anecdotal, they show that the IntelliRed™ technology is capable of remotely detecting hydrocarbon leaks at levels that are well below the detection capability of existing technologies. IR point detectors are a mature technology and relatively inexpensive sensors, but they must come into contact with the hydrocarbon plume to achieve detection. In these field tests the point detectors were placed as close as 5 feet to the release point and rarely elicited a response from the small amount of propane released. In an actual deployment, the distance between the point detector and the leak source can be much greater as it is not practical to deploy point detectors every few feet. While the IR point detectors we placed in close proximity to the leak source, the IntelliRed™ system was positioned 300 feet away and achieved detection in each scenario.

The open path detector achieved more consistent results than the point detector, eliciting a response in 4 of the 11 scenarios. However, in each scenario the open path detector was positioned to intersect with the hydrocarbon plume 1-2 feet from the release point. As with the point detectors, in an actual deployment it will be rare that the path of an open path detector intersects with a leak within 2 feet of the source.

Quantitative optical gas imaging (QOGI)

The U.S. Environmental Protection Agency (EPA) has promulgated regulations governing the detection and repair of equipment leaks that cause fugitive emissions of volatile organic compounds (VOC). These regulations are embedded in various emission standards and are generally referred to as Leak Detection and Repair (LDAR) programs. Similar regulations exist for many regions globally, with associated LDAR surveys being performed regularly in these regions (including Europe).

Two methods for LDAR surveys are currently being used:

- Sniffing (Method 21)
  - Developed to reduce fugitive VOC emissions at time when there was no better method; contributed to VOC reduction throughout decades
  - Not intended for accurately quantifying emission of each leak
  - Significant uncertainties
  - Labor intensive
- Optical gas imaging (OGI)
  - Higher productivity – can find significant leaks faster than Method 21
  - Provides today qualitative result only (i.e., image), no estimate of emissions
  - Widely used as a fast response visual tool, but limited use for LDAR compliance

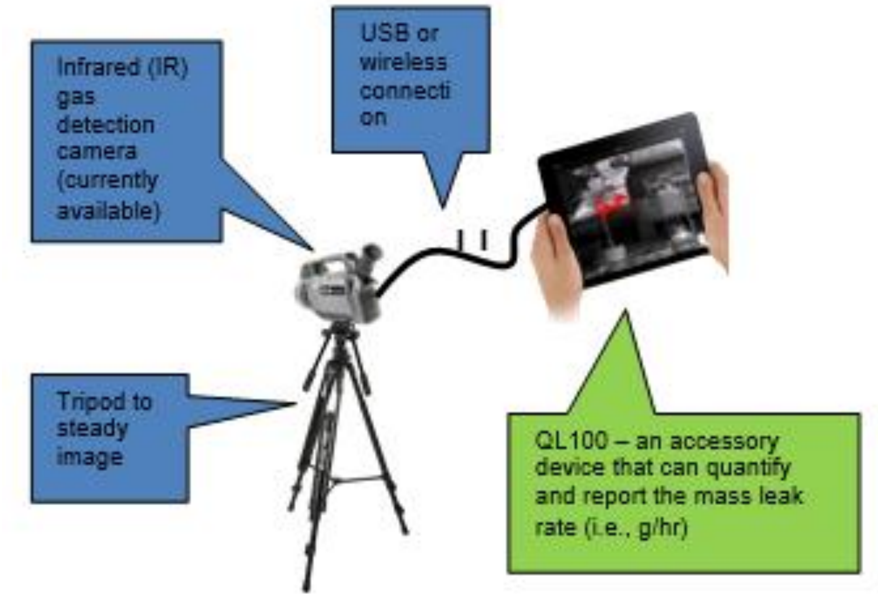
IR sensors are very effective in detecting leaks, but do not provide a quantitative measurement of leak rate. This has been one of the shortcomings of OGI from a regulatory perspective, thereby hindering its adoption as a true alternative to Method 21. Based on the research done to develop the IntelliRed™ single and dual sensor technology, the research team developed a quantitative OGI (QOGI) technology. If the IR camera detects a leak, then, the operator can apply the QOGI technology to quantify the mass leak rate from the captured video images as shown in **Figure 14**.

The working principle of QOGI can be briefly described as follows:

- IR images of a leak are analyzed for intensity on a pixel-by-pixel basis
- Each pixel represents a column of hydrocarbon vapor between the camera and the background
- Pixel contrast intensity is a function of temperature difference between the background and the plume (ΔT)
- At a given ΔT, the intensity is proportional to the hydrocarbon molecules in the vapor column

• Leak rate drives both pixel intensity and number of pixels. Inversely, the combination of the two factors determines leak rate.

Figure 14: QOGI Technology



Based on the above referenced methodologies, a computer program (QL-100) has been developed that captures raw IR data from an IR camera and analyzes it for leak rate. The IR camera must be radiometrically calibrated to make it capable of measuring temperature at the pixel level. To analyze the IR images, the user must also input a measured ambient temperature and distance from the component being tested to the IR camera. All other variables required for determining leak rate are pre-programmed into the computer program. With the captured IR images and the two user-provided input parameters, the program will calculate the mass leak rate in grams per hour (g/hr).

Work to date has measured component leak rate using the QOGI technology on accurately controlled releases, with the focus on propane. The IR camera was positioned 3 meters away from the release point. All of the tests performed to date (80 total) were conducted in an outdoor, open air environment. The types of backgrounds tested included a uniform temperature controlled metal board, building wall, and gravel. These tests included sunny and cloudy days, in sunlight and in shade, ambient temperatures from 3-35°C), relative humidity from 50% to 90%, and various moderate wind conditions. Because the true leak rates were known in these tests, the accuracy of this method can be assessed by comparing the true leak rate and the leak rate measured by QOGI. Within these 80 tests, the measured leak rates were between -17% and +25% from the true values.

Conclusion

IR optical gas imagers have proven to be an effective remote leak detection technology and are becoming widely used in recent years throughout the industry as hand held detectors. The IntelliRed™ autonomous detection system extends the capabilities of optical gas imagers enabling autonomous remote leak detection. Combining this technology with rugged enclosures and advanced optics, it is possible for a single camera installation to cover a wide field of view providing continuous autonomous remote leak detection with detection limits that outperform existing technologies. Existing IR point and open path detectors are quite effective at detecting large hydrocarbon clouds, but IntelliRed™ technology can provide a means for early detection of much smaller leaks, reducing the probability of a high consequence event. IntelliRed™ technology is uniquely suited to monitor areas that are difficult to cover with existing technologies, such as elevated pipe racks or distillation columns. It can also provide a means to detect difficult leak scenarios, such as corrosion under insulation or periodic releases. While existing IR point and open path detectors can alert an operator to the presence of hydrocarbons if the concentrations are high enough and wind conditions are favorable, IntelliRed™ technology provides an alert as well as a high contrast real time visual image to help the operator safely respond to the alarm. In addition, the ability to remotely stream the results of an IntelliRed™ system over an Ethernet protocol provides the operator with a real-time tool to investigate leak alarms without putting personnel into harms way.

The advancement of a dual sensor (DIR) IntelliRed™ system opens up new applications. DIR is capable of generating an alarm in a single frame, providing immediate notice to the presence of a hydrocarbon plume. A frame-by-frame reference also provides very low false alarm rates, enabling applications where the IntelliRed™ system could be integrated into fire suppression systems. Single frame alarming also opens up applications for detection from a moving platform. Aerial pipeline surveys with a dual sensor system could be achieved, as well as surveys form vehicles and boats. The dual sensor IntelliRed™ system is undergoing qualification with multiple pilot deployments underway. Once commercially available, the dual sensor IntelliRed™ system will offer detection limits lower than the single sensor IntelliRed™ systems with a lower false alarm rate.

In addition to process safety, IntelliRed™ technology can extend the capabilities of LDAR programs and has the potential to reduce fugitive emissions and improve air quality[3]. In traditional LDAR programs, a FID or hand held IR optical gas imager is used to manually inspect components once per quarter. If the component begins leaking it will go undetected between inspections. Using autonomous IntelliRed™ technology allows for increased monitoring frequency without the additional labor costs associated with traditional LDAR monitoring. Providing continuous monitoring allows a facility to quickly identify and correct large leak sources, which typically constitute 95% of fugitive emissions.

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