Standoff Passive Optical Leak Detection of Volatile Organic Compounds using a Cooled InSb Based Infrared Imager

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ABSTRACT

FLIR Systems has developed and fielded a passive IR imager capable of standoff leak detection of Volatile Organic Compounds (VOCs) in quantities beneficial to both industry and regulatory agencies. The imager, GasFindIR™, has undergone extensive laboratory testing and results are reported. Tests include: minimum resolvable volumetric leak flow rates of multiple VOCs, optical field of view impacts on detection, and imaging methodologies to enhance probability of leak detection. General and specific direct applications of the imager are discussed and guidance is given for its effective use in industrial settings. Potential future paths are discussed.

INTRODUCTION

Infrared spectral imaging of gases and vapors has been widely used in astronomical and geophysical applications for many years. The Infrared Space Observatory, The Atmospheric Infrared Sounder, and The Spitzer Space Telescope are the most notable platforms using IR spectral imaging systems. FLIR Systems has now adapted this space based technology for use in ground based commercial infrared hand held cameras. The GasFindIR™, see figure 1 and table 1, is an infrared spectral imager designed to visualize the absorptive and emissive properties of gases/vapors allowing the user the ability to discern the gas/vapor from its host environment. To wit, the imager "sees" the gas. The camera employs a spectral filter designed to transmit in a region of the IR spectrum that is coincident in wavelength with vibrational/rotational energy transitions of VOC molecular bonds[1,2]. These transitions are typically strongly coupled to the field via dipole moment changes in the molecule[3], and are common to many types of gases and

Figure 1, GasFindIR™

Table 1, Camera Specifications

Specifications	
F-Number	2.3
Thermal Sensitivity	<35mK @ 30C
FPA	InSb 320x240 format 30um pitch
Spectral Range	3-5um
Integration Time	16.6ms and selectable
Power	<6W
Weight & Size	4.6lbs, 10"x5.2"x5.7"
FOV	25mm(22°), 50mm(11°), 100mm(5.5°)
Controls	Push Buttons on Camera and RS232
Outputs	S-Video, NTSC/RS-170, C-Video, PAL
Inputs	RS232

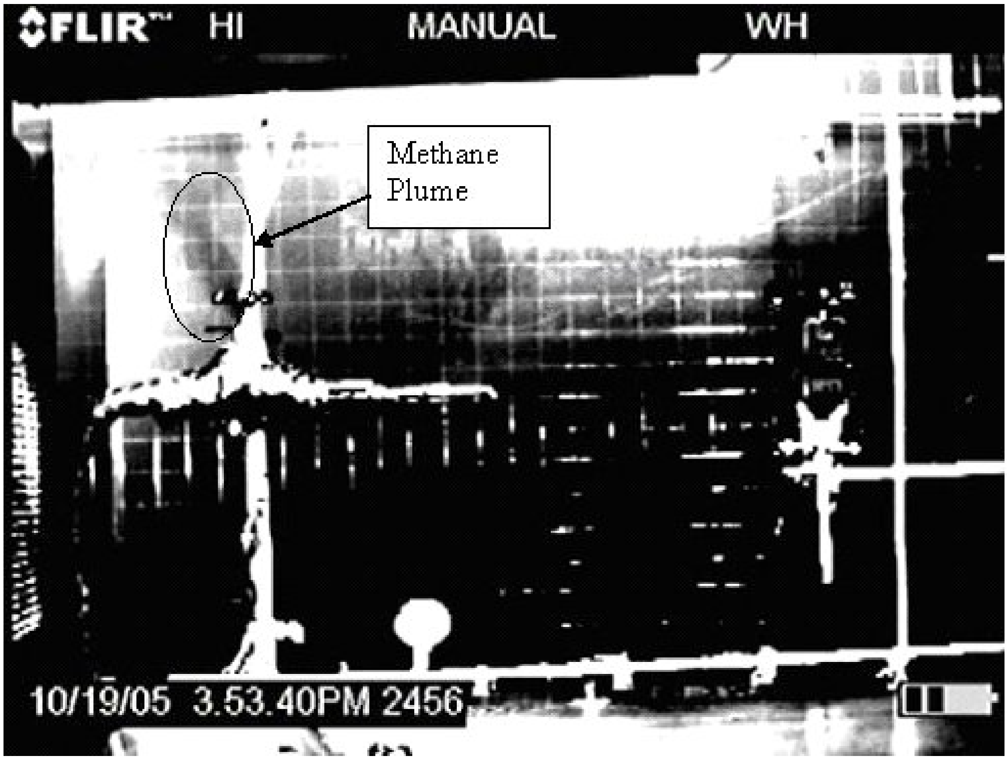
vapors. With this in mind, the camera's detection sensitivity to a wide variety of gases and vapors is extremely small. Thermally, the camera's sensitivity is <35mK when FLIR's adaptive temporal filter is engaged.

The camera has been successfully deployed in a wide array of operating environments and settings. The technology has shown itself to be both cutting edge as well as user friendly. Pilot programs in natural gas transmission delivery service companies have documented over $2M savings in annual gas leaks with as few as five finds with the GasFindIR.

TESTING AND VERIFICATION

FLIR Systems has tested the GasFindIR™ camera system at the BP Naperville facility[a]. The testing was sponsored by FLIR, hosted by BP, and conducted by IES[b] under test methodologies developed by IES for the API. A summary of compounds tested and minimum detectable leak rates, (MDLR), is shown in table 2, note wind speed was varied from 0 to 5 MPH. The methodology employed was developed by IES and is reported in their submission to this conference. In brief, a leaking valve was imaged at a fixed distance with a known flow rate of gas being expelled. The flow rate at which minimum detection was achieved was recorded and images were saved. See figure 2 for a generic test image, note this image is not the MDLR for the gas shown. Some gases were also imaged with and without a nitrogen mix, see table 3.

Figure 2, Leaking Valve with Methane Plume



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[a] British Petroleum, Naperville Illinois. Hosted by Dave Fashimpaur, Environmental & Loss Control Specialist.
[b] IES is Innovative Environmental Solutions, Inc., P.O. Box 177, Cary, IL 60013-0177.

Table 2, Minimum Detectable Leak Rates for Compounds

MDLR's in Grams/Hr	Wind Speed in MPH		
Compound	**0**	**2**	**5**
Benzene	3.5	17.5	38.6
Ethanol	0.7	3.5	14
Ethylbenzene	1.5	7.6	17.5
Heptane	1.8	4.8	8.4
Hexane	1.7	3.5	8.7
Isoprene	8.1	14.3	38.8
Methanol	3.8	7.3	24.3
MEK	3.5	17.7	31.8
MIBK	2.1	4.9	13.3
Octane	1.2	3.4	8.7
Pentane	3.0	6.1	17.7
1-Pentene	5.6	19.7	43.8
Toluene	3.8	5.3	14.3
Xylene	1.9	9.1	18.9

Table 3, Minimum Detectable Leak Rates for Gases

MDLR's in Grams/HR	Wind Speed MPH					
Gases, Pure & †N_2 Mixture	**0**		**2**		**5**	
	P	**N_2**	**P**	**N_2**	**P**	**N_2**
Butane	0.4	6.5	1.5	7.3	4.2	13
Ethane	0.6	4.8	1.9	6.3	3.5	10
Methane	0.8	3.4	2.0	6.4	6.0	11
Propane	0.4	3.3	1.3	7.1	1.3	9.3
Ethylene	4.4	31	7.3	52	14	84
Propylene	2.9	14	8.9	30	16	35

†N_2 mixture flow rates were typically 3liters/minute.

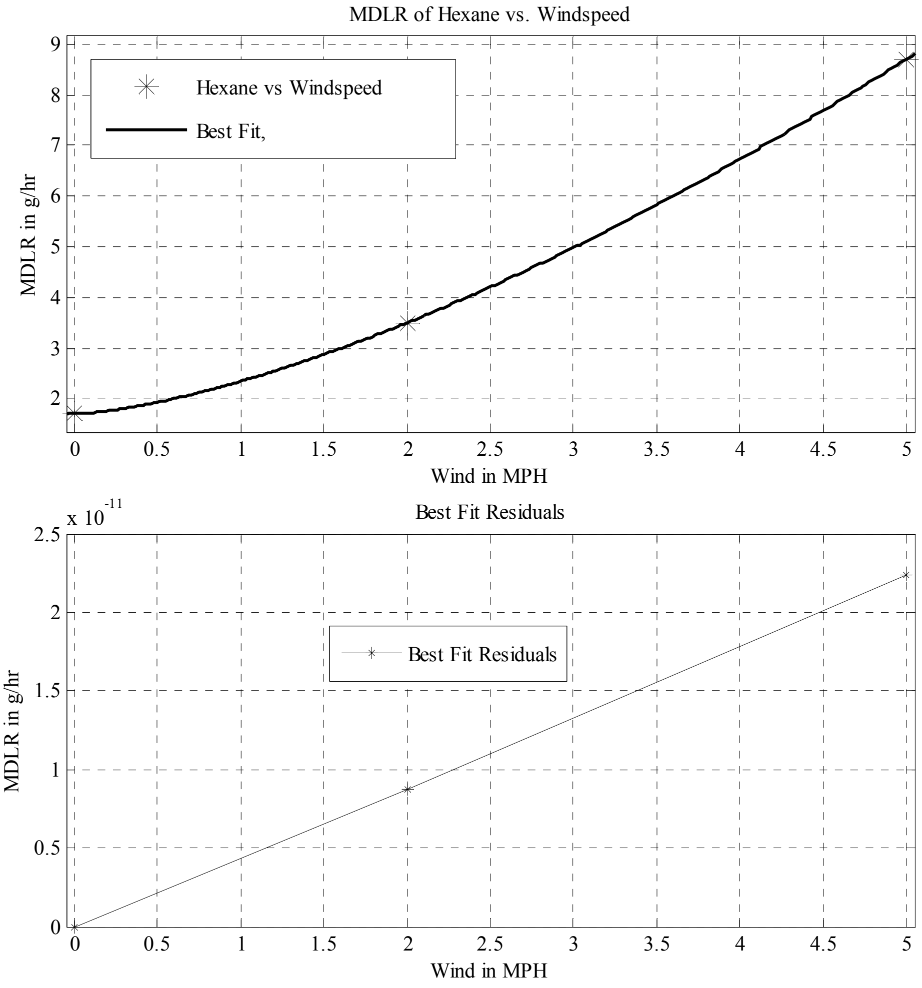
The data suggest a rough power law correlation between constant wind speed and MDLR, see equation 1, figure 3, and table 4. The experimental setup could not generate wind gusts therefore it is impossible to numerically estimate the effect of gusting on MDLR. From practical field experience however, gusting is a primary mechanism by which leak detection can be achieved. As the wind ebbs and flows in gusts around pipes, valves, junctions, etc.., the vortices, currents, and eddies generated allow gas plumes to be discerned far easier then a constant wind source alone. The lab data can and should be used as an upper limit rule of thumb for leak detectability in the field in the presence of variable winds.

Equation 1, power law fit of MDLR as a function of wind speed.

$MDLR(w) = \alpha * w^{\beta} + X$, Where α, β, and, X, are variables in the fit.

The power law fit of MDLR as a function of wind speed is a simplistic approach to a highly complex physical process. The fundamental physics of the observable phenomenon is a multivariable problem of both hydrodynamics, namely flow mixing in the presence of turbulent or highly nonlinear geometries[4], coupled with the quantum mechanical photonic emissive and absorptive properties of molecular bonds[5] whose host molecules are in a state of non thermodynamic equilibrium with their environment. This power law fit simply attempts to approximate a much more complex function over a small range of only one variable. The fact that the fit turns out to be quite reasonable, see figure 3, is a statement that most of these variables can be ignored or at least held to a constant over a small range of wind speeds. Additionally, from a mathematics perspective, we are fitting only three data points to three degrees of freedom, namely our three fit parameters. Under those conditions a multitude of functional equations can be shown to fit the data. To be any more deterministic one would need to take more data over a larger wind speed span. Since the fit itself is only an approximation to reality, taking mountains of data would seem to be overkill.

Figure 3, MDLR of Hexane versus wind speed



As can be seen in figure 3, the fit is reasonable with small residuals. This is the case for all compounds fit. Table 4 shows the fit parameters for each compound, the mean and standard deviation for the power law term, β, are also given. In addition to determining MDLRs as a function of wind speed, the MDLR was measured as a function of magnification (optical FOV, Field of View) and standoff distance.

Table 4, MDLR Best fit parameters for all compounds

MDLR Best Fit Parameters	**Fit Parameters from Equation 1**		
Compound	α	β	X
Benzene	6.985	1.003	3.5
Ethanol	0.862	1.700	0.7
Ethylbenzene	2.941	1.052	1.5
Heptane	1.652	0.861	1.8
Hexane	0.664	1.482	1.7
Isoprene	1.849	1.746	8.1
Methanol	0.919	1.929	3.8
MEK	8.428	0.753	3.5
MIBK	0.981	1.513	2.1
Octane	0.870	1.338	1.2
Pentane	0.955	1.699	3.0
1-Pentene	6.634	1.088	5.6
Toluene	0.344	2.124	3.8
Xylene	3.759	0.938	1.9
Mean		**1.373**	
Standard Deviation		**0.431**	

The GasFindIR has a standard F/2.3 lens with a fixed focal length of 25mm. This generates a 21.74° horizontal FOV. Additional lenses with fixed focal distances of 50mm and 100mm were also tested. Horizontal FOVs for these lenses are 10.97° and 5.50° respectively. These lenses are offered by FLIR as optical accessories. The MDLR as a function of FOV for standoff distances of 3 to 12 meters is shown in table 5, and figure 5. For the 3 meter standoff distance images of each FOV are displayed in figure 4. The gas delivery system employed for the test was challenged by the GasFindIR with 100mm telescope at 3 meters distance. Unfortunately the delivery system could not deliver gas at small enough rates to accurately determine the MDLR. The camera began seeing "puffs" of gas, which was taken as an indication the system was at its lower limit.

Figure 4, MDLR vs. optical FOV at 3 meters.

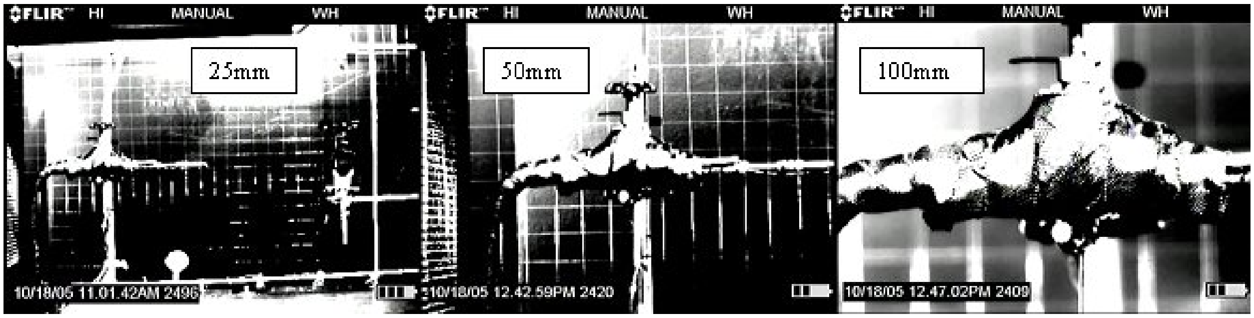


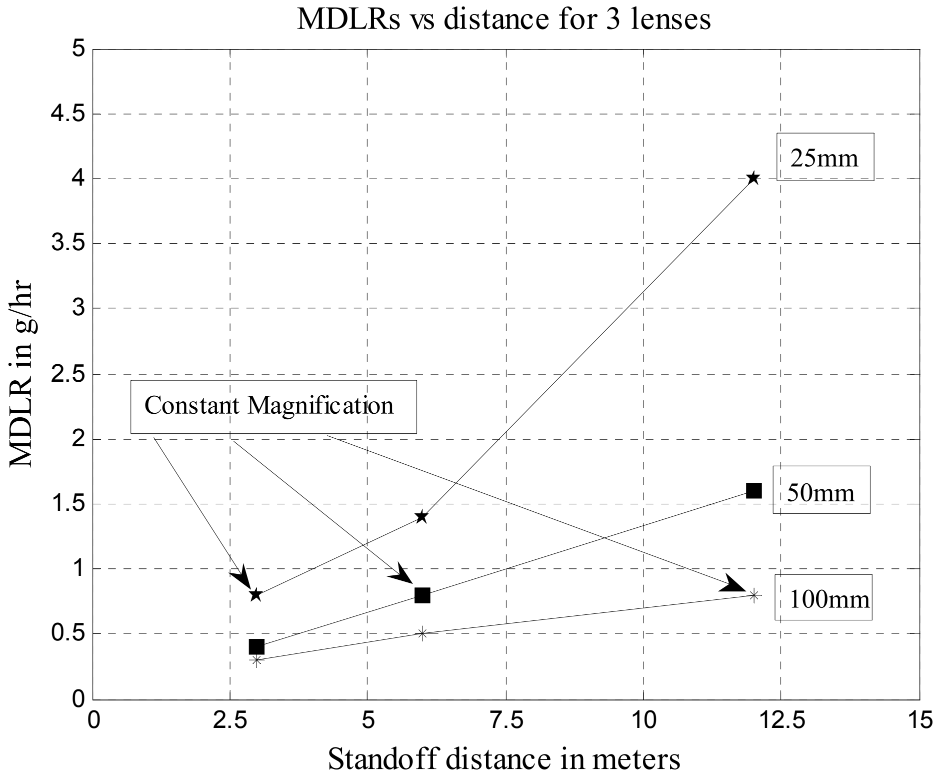
Table 5, MDLR vs. Optical FOV for methane

[†]MDLR in g/hr	**Lens Back Focal Distance in mm**								
Gas	**25**			**50**			**100**		
Standoff distance (m)	**3**	**6**	**12**	**3**	**6**	**12**	**3**	**6**	**12**
Methane MDLR	0.8	1.4	4.0	0.4	0.8	1.6	[‡]*0.3*	0.5	0.8

[†] *MDLR was measured at 0 wind speed with no N_2 mixing.*
[‡] *Lower limit of delivery system.*

The data in table 5 and figure 5 indicate a nearly linear relationship between optical FOV and MDLR. The leaking valve under constant magnification was consistently found to have a near constant MDLR. For instance, the 3 meter standoff 25mm lens data shows a MDLR of 0.8g/hr. Both the 50mm at 6 meters and the 100mm at 12 meters show the exact same 0.8g/hr MDLR. These 3 points of course all have the same scene magnification.

Figure 5, MDLR vs Standoff Distance for 3 FOVs

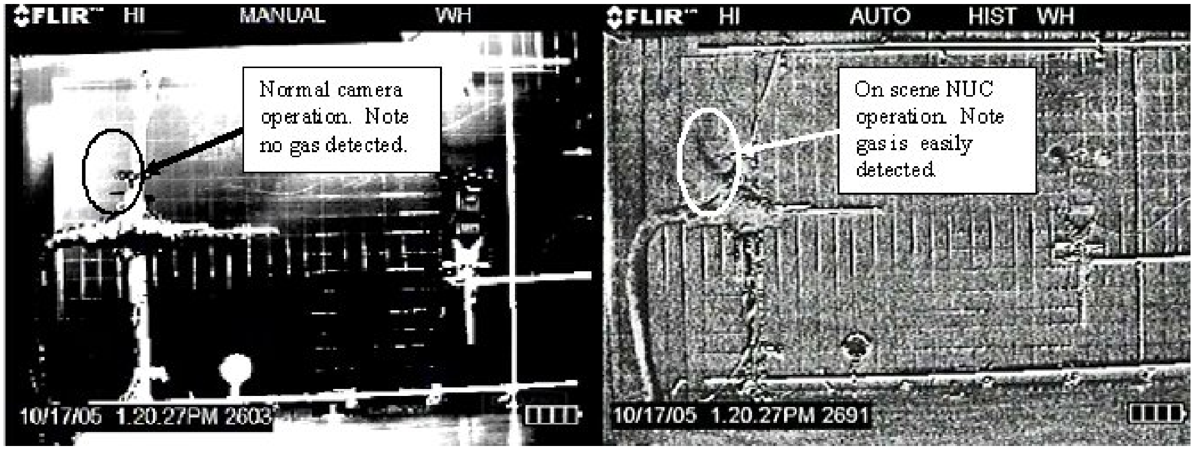


GAS DETECTION METHODOLOGIES

During the test and measurement phase at BP the camera was utilized in an on scene NUC, non-uniformity correction, mode. This was done in an effort to maximize the potential of the camera to detect gas. The on scene NUC allows the camera's internal histogram equalization algorithm to effectively stretch and display any time dependant scene based variables. To wit: It sees gas and vapor plumes at levels far below the normal mode of operation as they change spatial position and concentration over time.

We set up 2 identical cameras both viewing the same leak at the same time and simultaneously captured video from each. We set the leak rate to the detection limit, and then verified the limit was the same for each camera. We then on scene NUC'd one of the cameras and the leak became clear. See figure 6.

Figure 6, On scene NUC



The on scene NUC is a useful tool when attempting to identify suspected leaks at very small levels. The camera requires a sturdy position from which to operate, like a tripod or similar mount. This mount holds the scene contents constant in the view space of the imager, therefore after a NUC the image will look "embossed". NUCing on a scene requires both practice and patience but the detection levels available when this methodology is employed are incredibly small. Again, we were limited by the smallest leak rate available to the delivery system and could not measure the MDLR in on scene NUC mode.

APPLICATIONS AND GUIDANCE

Pilot programs in the natural gas transmission industry have found failed rupture disks, crankcase vent leaks and numerous vent stack leaks. Vent stacks are difficult, if not impossible, to find with TVA's due their inaccessibility. Leak volumes were documented using the bagging technique. See figures 7 and 8.

Figure 7, Compressor crankcase vent leak. Quantified annual leak rate of $150K

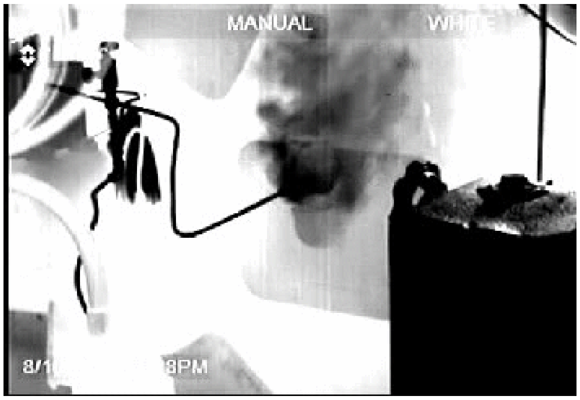
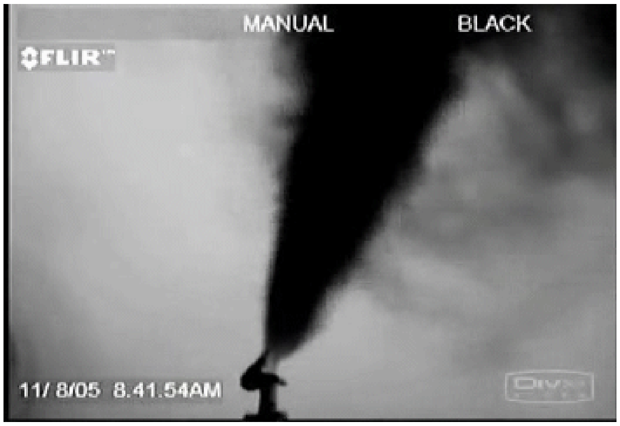


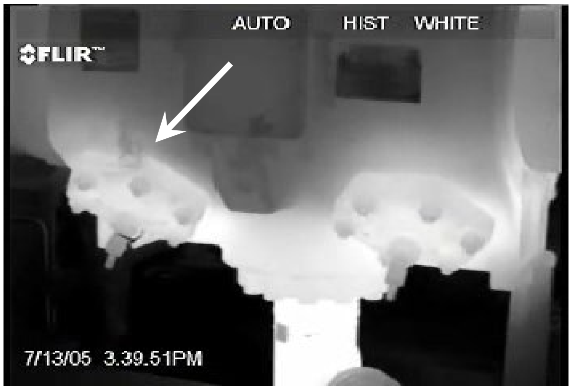
Figure 8, Failed rupture disk. Quantified annual leak rate of $1M.



Petrochemical facilities such as refineries offer a target rich environment for VOC leaks. The remote imaging capabilities of IR cameras such as the GasFindIR dramatically reduce the task of finding leaks. Even when gases have a low contrast with their surroundings, the movement of the gas in a static environment makes finding small leaks, or larger leaks at greater distances feasible. Figures 9 and 10 show some examples of refinery applications.

Figure 9, LPG pumping station transfer line leak, dark cloud just above arrow.

Figure 10, LPG compressor flange leak, darker area just off arrow tip.



Refined product leaks can also be found. Figure 11 shows vapors released during pumping gasoline into a vehicle. In all these examples viewing live video makes it much easier to spot the leaks than the still images in this publication. In the gasoline pump video, the operator is seen leaning back when the wind blows the fumes toward his face. The video is compelling imagery of why we should have vapor recapture devices and why we shouldn’t smoke or have open flames while filling our tanks.

Figure 11, Gasoline fumes cascading from fill spout onto pavement.

Applications of passive IR imaging continue to be developed in the LDAR setting. Moreover, we believe these applications truly start at the well head, continue through the entire transmission distribution system, and end only after the VOC has been used and it's by-products examined. This even includes gas meter and vapor recovery inspections at your local gas station. IR is a powerful tool. GasFindIR adds an all together new level of inspective capability to any technicians tool bag. Whether LDAR technicians use a TVA to try and measure concentration levels or use the GasFindIR to "see" the source and magnitude of the VOC leaks, tools are essential to detect, locate, diagnose, repair, and report the hazardous conditions.

FUTURE PATHS

The use of passive infrared technology has many benefits that require exploration. Although GasFindIR is a "new" technology for many LDAR technicians, IR imaging itself has proven to be a mandatory diagnostic tool across a multitude of disciplines. From predictive maintenance (PdM), medical diagnoses, and even climate control, hundreds of new applications continue to be found for IR imaging everyday. Based on FLIR's extensive history in IR, we are highly confident that VOC leak detection will mature at a rapid rate and join the many other industries that enjoy the full potential that IR imaging brings to bear.

The ability to quantify leaks appears to be the next technological hurdle to overcome. Perhaps speciation will soon be a standard feature in passive IR systems. This type of technologic growth in the IR industry has historically followed the needs of the consumer, and therefore doesn't beg the question if it will happen but rather when.

In addition to detecting VOC's that spectrally fall within the current GasFindIR's 3-5µm waveband, there are many other chemicals and gases of significant importance that fall outside this band. Many applications can be served by passive IR systems that utilize different IR bands to detect other VOC's or greenhouse gases, such as SF_6.

Other potential follow-on cameras could include automation capability to monitor critical areas. One of the keys to gas plume detection is motion of the gas. A fixed mounted camera looking at a static environment could use image differencing to reliably alarm on even small gas leaks.

CONCLUSIONS

Infrared imaging technology promises a bright future for environmental quality improvement through finding and documenting fugitive emission of volatile organic compounds. Companies will also reap the significant benefit of retaining quantities of VOC's improving the bottom line of their businesses. Infrared imaging cameras are sensitive to numerous VOC's in small quantities and can rapidly detect large and small leaks at ranges from a few feet to a few thousand feet. Infrared imaging cameras are easy to use, rugged and enable the operator to find leaks fast.

The technology of IR in LDAR environments will continue to grow as the needs and requirements of the user community become realized to the IR industry. As technical advances take place, both the end user as well as the IR provider will benefit. The greatest potential benefit however will not be realized by the current generation of users or IR developers. It will be realized by the next generation who will enjoy a safer, healthier, and more stable planet. This is the legacy of the IR LDAR work we do today.

ACKNOWLEDGMENTS

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The authors would like to acknowledge the AEDC/EPA's online spectral database. This collection of online IR spectra was invaluable in the engineering of this camera. http://www.epa.gov/.

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