Methods for Quantification of Mass Emissions from Leaking Process Equipment When Using Optical Imaging for Leak Detection

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A cost-effective fugitive emission reduction program should focus on locating and repairing the very high leakers. Although these components (such as valves, pumps, compressors, flanges, etc.) represent <1% of the total component count, they are the major contributor to overall mass emissions of volatile organic compounds (VOCs). Optical imaging technologies allow greater efficiencies in simultaneously monitoring large numbers of process piping components. Therefore, locating very high leakers can be done more frequently at reasonable costs and quicker repair of these very high leakers will result in lower overall emissions.

This new approach to leak detection and repair (LDAR), called "Smart-LDAR," will result in better emissions control when compared with current U.S. federal and state work practices. Under Smart LDAR, plants will have the flexibility to implement inspection and maintenance procedures that are based on combinations of leak definitions for repair, monitoring frequencies, and components included. With the adoption of a Smart LDAR emissions control strategy, new approaches for the quantification of fugitive emissions from process components are required. This paper discusses options for such mass emission quantification that could be used for reporting requirements. © 2005 American Institute of Chemical Engineers Environ Prog, 25: 49–55, 2006

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INTRODUCTION

The American Petroleum Institute (API)—in collaboration with the U.S. Environmental Protection Agency (US EPA), the Department of Energy (DOE), and several technology vendors—has been engaged in a multiyear investigation to develop alternatives to the current *leak detection and repair* (LDAR) programs using EPA Reference Method 21. These LDAR programs were designed to control the emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) from large manufacturing and distribution facilities such as petroleum refineries, natural gas processing plants, petrochemical plants, and distribution terminals. The aim of developing alternative work practices is to increase flexibility and improve the cost-effectiveness of the control strategy, while simultaneously reducing fugitive emissions from leaking process components. Despite "conventional wisdom "

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that a subset of "chronic leakers " could be identified for targeted maintenance to significantly reduce emissions, studies conducted by API have concluded that there is no identifiable group of chronic leakers, and that more than 90% of the controllable emissions are contributed by approximately 0.1% of the components (see Figure 1 in API publ. 310) [1]. These findings were confirmed further by the US EPA and various compliance audits undertaken by both the EPA's National Enforcement Investigative Center (NEIC) and the South Coast Air Quality Management District (SCAQMD) in California. It was therefore concluded that an LDAR program focusing on "high leakers" could lead to more effective control compared with that of currently required practices. As a consequence, a new alternative regulatory model for controlling fugitive VOC emissions from process plant piping components is under development. It is based on the findings of the studies discussed above and on the results of an economic analysis of the potential for alternative control practices, as described elsewhere [2].

"Smart LDAR" is a work practice for efficiently locating and repairing the relatively small number of large leakers within the population of components at process plants. Allowing quicker repairs of leaking components will lead to improved environmental performance while allowing flexibility in implementing regulatory requirements. Efforts have focused for the past several years on the development and demonstration of innovative technologies—primarily optical imaging techniques—for the rapid detection of leaking components. These technologies provide real-time imaging, allowing operators to locate leaking components in accordance with regulatory requirements.

The current work practice (CWP) produces monitoring (screening) data using Method 21, and these data can be used both for identifying leaks above a threshold for repair and as indicators for the quantification of total emissions [3–5]. In contrast, although optical imaging techniques being currently tested for Smart LDAR monitoring have the potential of correctly identifying leakers 100% of the time, they do not yet provide a direct quantitative measure of emission rates. Therefore, when these new Smart LDAR work practices are adopted as alternative work practices (AWP), petroleum industry facilities will no longer use Method 21 screening data as an emission quantification method.

This paper provides options that might be available for emission quantification when using Smart LDAR. Both currently available methods and new variants that could be more fully developed are included.

REGULATORY CONTEXT

Since the early 1980s, the US EPA has supported the development and eventually required the implementation of LDAR programs for control of fugitive emissions (that is, emissions from piping components such as valves, connectors, pumps, compressors, etc.). Additional state initiatives, and the adoption by the US EPA of the "Refinery MACT Rule" (Maximum Achievable Control Technology) and similar rules for other industry sectors, require nearly every U.S. refinery, natural gas processing plant, and chemical plant to implement an LDAR program for control of fugitive emissions. These programs have been found to be quite burdensome and costly, especially at current regulatory-required low-leak definitions. Programs similar to those that are currently required in the United States are now beginning to be adopted in Europe and other locations worldwide. In most cases, these new programs are based on modifications of the U.S. protocols and monitoring methods.

The current U.S. LDAR monitoring procedure (that is, US EPA Reference Method 21) involves placing a gas-sampling instrument probe at the surface of each piping component seal and measuring the volatile organic compound (VOC) concentration as the probe is moved along the surface of the seal. The instrument readings, referred to as *screening values*, are compared to levels established by the US EPA and/or state environmental agencies to determine whether the components are considered to be leaking. If the measured VOC concentration at a component is above the level defining a leak, the component must be repaired or replaced to reduce the Method 21 measured concentration to the acceptable leak level. Rather than measuring the actual mass leak rate, the Method 21 procedure measures concentration levels only in the vicinity adjacent to the component leak. These screening measurements have been related by a relatively poor correlation to the actual mass emissions rate.

Previous analysis has shown that more than 90% of controllable fugitive emissions come from only about 0.13% of the piping components, with almost all of the emissions attributable to the very few components that are measured to be over 100,000 ppmv [1, 6]. This study showed that major reductions in costs and emissions could be realized if a method can be devised that more economically locates the very high leaking components without having to monitor every individual piping component in the plant using EPA Method 21.

U.S. regulations for control of fugitive emissions contain a provision that allows stakeholders to petition the U.S. EPA Administrator to recognize alternative controls (or work practices, in this case) that will provide equal or better environmental protection when compared to the specific current requirements [7]. Field demonstration testing of potential new fugitive emissions control technology or work practices is potentially quite costly. For this reason, the U.S. EPA Steering Committee for Alternative Leak Detection Work Practices has developed a less costly "demonstration protocol" to provide petitioners with a reasonable idea of what it will take for a new technology or work practice to achieve equivalent control effectiveness and be approved by the U.S. EPA. This demonstration protocol provides an optional "approval process" that includes a combination of laboratory testing, field testing, and mathematical analysis to quantify the performance of an alternative technology and determine whether it can achieve equivalent fugitive emissions control to that achieved using Method 21.

To facilitate this demonstration of emissions control equivalence for a new technology, the U.S. EPA has developed Monte Carlo simulation software to help evaluate technologies or work practices that may be proposed as alternatives for use in LDAR programs [8]. This software may be used during the approval process and is available to any stakeholder interested in assessing an alternative fugitive emissions control technology. The software uses SAS programming to perform Monte Carlo simulations (that is, random statistical simulations) of simultaneous equipment screenings by the current work practice that uses Method 21 and by a proposed alternative monitoring technology such as the optical imaging systems.

Predicted emission reductions are calculated for equipment components identified as leakers to quantify the environmental benefit derived from using either the existing or new technologies in an LDAR program. The environmental benefit equivalent to the current work practice (that is Method 21) is demonstrated when Monte Carlo simulations show that emission reduction for an alternative work practice is the same as, or larger than, the current work practice emission reduction.

An API report titled, “Smart Leak Detection and Repair (LDAR) for Control of Fugitive Emissions” provides further information on the Smart LDAR concept, potential monitoring technologies, plant demonstrations, and laboratory test results [9].

AVAILABLE TECHNOLOGIES FOR OPTICAL IMAGING

Optical imagers offer an operator the ability to monitor components from a distance and instantaneously identify leaking components. The remote sensing and instantaneous detection capabilities of optical imaging technologies allow an operator to scan areas containing tens to hundreds of potential leaking components, thus eliminating the need to visit and manually measure each potential leak source as now required by Method 21 [10, 11].

With optical imaging technologies an entire process area is scanned from a distance of 5 to 10 m and gas plumes from high emission leaking components appear as a black plume on a TV monitor [12]. This technique allows the quick and cost-effective identification of the largest leakers that contribute the vast majority of the fugitive emissions. Currently available technologies fall into two general classes, active and passive. The active type uses a laser beam that is reflected by the background. The attenuation from passing through a hydrocarbon cloud provides the optical image. The passive type uses ambient illumination to detect the difference in heat radiance of the hydrocarbon cloud.

The principle of operation of the active system is the production of an optical image by reflected (backscattered) laser light, where the laser wavelength is such that it is strongly absorbed by the gas of interest [13]. The system illuminates the scene with infrared light and a video camera–type scanner picks up the backscattered infrared light. The camera converts this backscattered infrared light to an electronic signal, which is displayed in real time as an image. Because the scanner is sensitive to illumination only from the infrared light source and not from the sun, the camera is capable of displaying an image in either day or night conditions.

The passive instrument has a tuned optical lens, which is in some respects like “night-vision” glasses [14]. It selects and displays a video image of light of a particular frequency range and filters out the light outside of that frequency range. In one design, by superimposing the filtered light (at a frequency that displays VOC gas) on a normal video screen, the instrument (or camera) displays the VOC cloud in real time in relationship to the surrounding process equipment. The operator can see a plume of VOC gas emanating from a leak.

This technology area continues to develop with additional plant tests and applications as well as new technology approaches. Papers presented at a recent conference provide additional information on the equipment now being tested, the U.S. regulatory approval process, plant test results, and preferred application techniques [15].

Mass Emission Rates

A calibration process normally assigns values that relate the concentrations or mass emission rates to the response of the instrument. For an optical imaging system, relating the image densities of the leaking gas plumes to the amount of gas leaking from the process equipment would be a potential approach. The new optical imaging instruments, however, are not yet sufficiently developed to provide a quantitative measure of the amount of gas that is leaking. Future versions of these instruments are expected to have the ability to correlate image density with mass emission rates. While this aspect of the technology is being advanced, there is a need to develop alternative emissions quantification methodologies for plant application of the optical imaging systems. The alternative methods could be based on existing leak data and are available to determine VOC mass emission rates when optical imaging is used for Smart LDAR.

ALTERNATIVE METHODS FOR MASS EMISSIONS QUANTIFICATION

There are a number of alternative emission-quantification methods that can be applied when using optical imaging to find leaks. Some are applicable for immediate use, whereas others depend on further technology development. The choice of a method will depend on the available plant data and the planned use of the emission estimate.

Method A: Average Expected

Three potential variants of the classical average expected quantification method are available. All are based on the EPA procedures outlined for average emission factors [3].

Option A.1: EPA Average Emission Factors

Under this option mass emissions are computed using plant component counts—by equipment type—and multiplying them by the appropriate EPA average emission factors. This provides an estimate of total plant emissions. However, this is likely the least representative of the methods because it is not based on plant measurements, and the average emission factors are not plant specific. Typically, this method will not enable the documentation of year-to-year decreases in total plant emissions, with improved leak detection and repair (LDAR) performance, unless new emission factors are derived or the plant reduces its component count.

Option A.2: Plant-Specific Average Emission Factors

To apply this option the plant must have screening data for components. A new set of average emission factors by equipment type is developed using the EPA correlation equations. Total plant emissions would then be calculated as in Option 1 (component counts by equipment type are multiplied by the appropriate site-specific average emission factors). This option is likely more representative than Option A.1 because the plant component mass emission rate distribution is used to derive the average emission factors. However, as in Option 1, total plant emissions will not decrease with improved LDAR performance, as long as the same factors are used and the component population remains the same.

Option A.3: Lookup Tables Based on Monte Carlo Simulation of Mass Emissions

This option relies on using Monte Carlo simulations to develop average emission factors, which would be provided in tables (or spreadsheets) for different leaker distributions, monitoring frequencies, and leak definitions. Monte Carlo simulations could be performed using existing SAS software that has been developed by the U.S. EPA [8] to compare different work practices, and would be based on a large enough number of simulations to provide robust statistical results. The simulation will be based on different CWP scenarios with corresponding assumptions about the monitoring intervals for the AWPs.

In assessing options A.1, A.2, and A.3, it is recognized that they all lend themselves to easy computation of mass emissions, with the differences among the options being the specificity of the average emission factors used. This set of methods is less representative than others presented in the EPA Protocol because no new measurements will be obtained, and an individual plant's mass emissions may not be represented by the distribution used to derive the average emission factors used. The Monte Carlo simulation look-up table method will be the most representative among these options. These average emission factors will account for leak-rate distributions, monitoring and repair intervals used, and the definition of leak thresholds.

Method B: Leak/No-Leak

Leak/No-Leak emission factors are average factors for a certain range of screening values. Commonly, the Leak/No Leak factors currently in use are based on a Method 21 leak definition of 10,000 ppm, as the delineation between leaking and nonleaking components. In the case of optical imaging, they would be developed based on the camera's ability to find leaks of a certain rate. This method would allow plants that have fewer leaks over time to quantify their reduced emissions.

Option B.1: Leak/No-Leak Emission Factors

This method will require the development of new leak/no-leak factors that correspond to the ability of the optical imaging equipment to detect leaks above a certain range. The average emission rates for the leak and no-leak component groups can be used to develop the required factors. Several data sets are available to achieve this, including those for both controlled [1] and uncontrolled [3, 7] facilities. Plant component counts for leakers and nonleakers—by equipment type—are multiplied by the appropriate Leak/No-Leak emission factors to derive an estimate of total plant emissions. Estimates made using this method are somewhat more accurate than those made using the average emission factors described in Method A.

Option B.2: Plant-Specific Leak/No-Leak Factors

This option is a variant that relies on the availability of a complete set of Method 21 screening data for a plant, either from new on-site monitoring data or from existing data from previous years. To apply this method a plant must determine its counts of leakers and nonleakers at the specified leak definition. The plant needs to derive average emission factors for the leakers and nonleakers separately by using measured leak rates for the various equipment types. This option is more accurate than Option B.1, given that the estimated mass emissions will be based on the plant's distribution of leak rates.

Option B.3: Generic Leak/No-Leak Factors for Different Leak Definitions

In this approach Monte Carlo simulations are used to develop generic Leak/No-Leak emission factors. Several scenarios can be anticipated such as different leak rates, monitoring frequencies, and leak definitions. The Monte Carlo simulations could be performed by the approach developed by the U.S. EPA [8]. The simulations of plant mass emission rate distributions will be based on using EPA's correlation equations and applied to appropriate screening value data sets. The implementation of this method will benefit from the use of current refinery screening value distributions that are representative of refineries across the United States.

Under the Leak/No-Leak approach (Method B), Option B.2 is the most representative for a specific plant.

Method C: Random Sample Screening

Method C is based on using Method 21 to screen a randomly selected group of components periodically. Results would be extrapolated by equipment type and service to estimate total plant emissions. The steps to be taken include:

1. Mass emissions will be calculated for the randomly screened components using the correlation equation.
2. An average emission factor will be calculated for each of the component types.
3. The same factor will be multiplied by the number of unscreened components of the same type.
4. The two sums will be combined to obtain total emissions per component type.

This approach assumes that leaking components occur randomly in any process unit or another physical "area" of a plant and that the leakers' frequency is the same across all equipment types and services. The inherent variability and uncertainty of Method 21 measurements may lower the representativeness of this method. This is especially true if there are insufficient screening measurements.

Option C.1: Random Sample Screening and EPA Correlation Equations

Component counts and leaker frequencies would be used in statistical calculations for specified confidence and precision levels to determine the number of random samples. In some cases the sample size required for screening could be quite large, to achieve a statistically robust estimate (arising from the small proportion of leakers). In this method the estimates will be based on periodically measured data that rely on Method 21 and it will allow documenting decreases in total plant emissions with improved LDAR performance.

Option C.2: Random Sampling and Use of Plant-Specific Correlation Equations

Site-specific correlation equations developed from plant-specific screening/bagging data pairs are used in lieu of the US EPA correlation equations. Emission estimates are based on correlation equations that relate site-specific screening values to mass emission rates.

This approach will require the development of statistical tables and special guidance for implementing the process of random selection of components and the proper extrapolation to the rest of the components of the same type and service. Although this approach seems feasible in theory, it will impose a very large implementation burden in practice. It will require maintenance of two sets of instruments, optical imaging along with Method 21, including training of personnel, equipment maintenance and calibrations, as well as data management systems.

Method D: Periodic Screening

This method relies on using the Method 21 technique to periodically screen all the refinery components and use these data to estimate emissions. This approach is the same as that of the current practice. (Component repairs are based on leaks found by optical imaging, but Method 21 is used for emission quantification.) This option is based on periodic screening of all plant components using Method 21. It could entail using Method 21 once per year. This approach relies on well-established methods and provides the needed information in a familiar format.

To avoid duplication of the current requirements of using Method 21, this method will require the establishment of special monitoring frequencies. It is not the intent to use Method 21 in addition to optical imaging. It requires the availability of two types of monitoring instruments and would entail additional complexity in data management and reporting.

Method E: High-Leakers Sniffing

This method incorporates the use of Method 21 in conjunction with optical imaging. It is based on identifying leakers by optical imaging, followed immediately by screening the leaking component using Method 21. Although this approach appears reasonable in theory, in practice the leaks detected with optical imaging usually have been above the screening instrument's range, resulting in "flameout" of the unit.

Option E.1: Screen Leaking Components Identified by Optical Imaging

This option uses well-established methods and techniques and in theory enables the use of existing US EPA correlation equations with Method 21 screening data. In addition, it focuses efforts on high leakers, which are the primary contributors to plant emissions.

Option E.2: "Bagging " Leaking Components Identified by Optical Imaging

This method uses a whole sample capture— or "bagging" method—to quantify mass emission rates for high leakers identified by optical imaging. This approach could be used to conduct "bagging" on only a few representative components and thus use the data to generate a new correlation equation relating optical imaging data directly to mass emission rates. This optional approach will lead to higher accuracy estimates. It could be implemented either by deriving new correlation equations that represent the industry or by site-specific applications. Using this approach with the higher measurement precision of optical imaging could avoid some of the uncertainty associated with the existing correlation equation approach, which is primarily attributed to Method 21 variability.

Method E addresses the high leakers and thus could account for about 90%, or more, of the emitted mass. It is based on an inherent assumption that those components not detected by optical imaging will follow similar screening value distributions as those previously derived from Method 21 screening. This approach, however, would impose a high implementation burden because it relies on the availability of dual-monitoring techniques with appropriate technician training and availability of compatible data management systems.

Method F: Instrument Mass Reading

This method requires further development of the technology and internal data processing capabilities for the optical imaging instruments. This technology is not currently available or anticipated in the near future. It would use direct reading of digitized signals from the optical image obtained from the leaking component. This image, with proper calibration, would be used to determine mass emission rates directly from an optical imaging system. Because it has the potential to read mass emission rates directly, it could avoid the use of correlation equations to relate concentrations to mass emissions. However, its usefulness will depend on the development of appropriate calibration curves and special routines that could be programmed to quantify emissions of classes of compounds or individual chemicals. Technical challenges will need to be overcome for direct instrument quantification of emissions.

Table 1. Summary of alternative quantification methods.

Method	Advantages	Limitations	Current status
Method A: Average expected			
Option 1			
EPA average emission factors	• Easily computed	• Not representative of specific plant performance • Estimated emissions expected to be higher than actual • Continued monitoring is required to document improved performance	• Available now
Option 2			
Plant-specific average emission factors	• Based on existing site monitoring data	• Continued monitoring is required to document improved performance	• Needs development
Option 3			
Lookup table based on Monte Carlo Simulation of mass emissions	• Statistical simulations will provide robust results	• For small-leaker frequency (e.g., 2% or less), many runs are required to simulate mass emission rates variability	• New simulations are needed for usable lookup table
Method B: Leak/no-leak			
Option 1			
EPA leak/no-leak factors	• Established method • Factors already exist • More realistic estimate of plant emissions	• Existing emission factors may not be representative • Average factors over a screening value range	• Available now
Option 2			
Plant-specific factors	• Established method • Factors based on plant monitoring data	• Average factors over a screening value range • Need to know screening value distributions in each range	• Needs development
Option 3			
Generic leak/no-leak factors for different leak definitions	• Established method • Factors could be easily developed • Can be applied for applicable leak definitions at plant	• Need to develop factors for different leak definitions. • Average factors over a screening value range • Screening value distributions may not represent plant	• Needs development
Method C: Random sample screening			
Option 1			
Random sample screening by Method 21 with the application of EPA correlation equations	• Established method • Random sampling is well established • Do not have to screen entire plant	• Optimum size of sample may be too large—burdensome • Need plant-specific randomization scheme • Method 21 monitoring in addition to optical imaging	• Available now
Option 2			
Random sample screening by Method 21 with the application of plant-specific correlation equations	• Established method • Random sampling is well established • Do not have to screen entire plant • Uses plant-specific data	• Optimum size of sample may be too large to prevent burden. • Need plant-specific randomization scheme • Method 21 monitoring in addition to optical imaging	• Available now
Method D: Periodic screening			
Periodic screening of all the plant with Method 21 sniffers	• Uses existing method • Recognized in applicable regulation	• Require maintenance of two types of monitoring instruments • Increases complexity of data management and reporting • Resource intensive • Minimizes the benefits of optical imaging	• Available now
Method E: High leaker sniffing			
Option 1			
Screen highly leaking components identified by optical imaging with Method 21 sniffers	• Focuses on high leakers that contribute the bulk of plant emissions • Enables use of existing correlation equation with Method 21 screening	• Addresses only the high leakers • Assumes that those components not detected by optical imaging will follow the same distribution as previously derived from Method 21 screening • Would require continued reliance on Method 21 • Many high leakers cause flameout of instrument	• Available now
Option 2			
"Bag" highly leaking components identified by optical imaging	• Enables higher accuracy in determining emissions • Representative of site specific conditions	• Time consuming • Costly to implement • Extremely cumbersome for routine application	• Available now
Method F: Instrument mass reading			
Option 1			
Direct reading of digitized signal from optical image	• Allows direct reading of mass emission rate • Avoids use of factors or correlation equations	• Instrument sensitivity varies with identity of chemical species • Field operations will require highly trained technicians to properly calibrate and tune instrument	• Not yet developed

METHODS SELECTION

These potential emission quantification methods represent techniques that range from average emission factors to new approaches relying on Monte Carlo simulations or the use of calibrated optical imaging devices. Some of the methods considered retain the use of organic vapor analyzers ("sniffers"), as currently used under Method 21, in addition to optical imaging devices.

All the methods described above have some advantages and some limitations. They are summarized in Table 1. Some may tend to overestimate plant emissions but are very simple to implement; others are resource intensive but potentially will provide a more representative emissions estimate. Each plant operator will have to make an individual assessment when selecting the approach that best fits the plant's needs. Factors that will need to be considered will depend on data needs and their intended use, including:

1. *Operational complexity* for implementation of the various emissions quantification techniques available.
2. *Assurance of compliance* and verifiability of the data.
3. *Level of accuracy* for the resulting plant emissions inventory.

CONCLUSIONS

Options for alternative emissions quantification methods that can be used in conjunction with "Smart LDAR" practices that rely on optical imaging techniques have been developed. Each of the methods has advantages and limitations. In evaluating the feasibility of implementing quantification methods that are suitable for alternative work practices, it is important to assess regulatory compliance and operational aspects.

All of the methods evaluated may have a role to play and could be useful in specific circumstances. However, the main consideration should be the ability to obtain representative estimates of emissions. This is ascribed to the fact that total facility emissions are used in assessing its emission fees; evaluating its community impacts; and determining permitting requirements.

Maintaining Method 21 as a tool for determining emissions will result in inconsistencies between the monitoring methods, and thus it is not recommended. For the near term, Method B provides the best balance between generating a representative emission estimate and avoiding excessive costs and burden. In the longer term, technology developments are expected to make Method F feasible.

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