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Field Reliability of Advanced Leak Detection and Repair Technologies: A Technical Analysis of Optical Gas Imaging Against Instrument-Based Screening for Fugitive Emission Identification

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ABSTRACT: Optical gas imaging replaced instrument-based component screening in much of the hydrocarbon sector on the argument that it surveys more components per hour and therefore finds more of what matters. The argument is sound and is frequently made without the qualification that determines whether it holds, namely that detection probability for optical imaging is strongly conditional on emission rate, distance, wind and operator technique, whereas instrument screening is comparatively insensitive to all four. This paper analyses the two approaches as a survey design problem rather than as a technology comparison, on the argument that the relevant question is not which instrument detects better under controlled conditions but which programme finds more of the total emission under field conditions and available resource. Four positions are developed. First, the case for optical imaging rests principally on the extreme skew of the emission distribution across components, which makes coverage rather than per-component sensitivity the dominant determinant of programme performance. Second, the empirical evidence on optical imaging detection probability establishes that manufacturer sensitivity figures describe controlled conditions and that field detection thresholds are substantially higher and highly variable. Third, the two approaches fail in different directions, optical imaging missing small persistent emissions and instrument screening missing large emissions from components not on the survey list, and a programme using either alone inherits its blind spot. Fourth, the quantification problem is common to both and is the reason emission inventories built from component surveys have repeatedly diverged from measurements made at facility scale. The paper closes with implications for survey design in liquefaction facilities and identifies where the evidence base remains thin.

KEYWORDS: leak detection and repair, optical gas imaging, Method 21, fugitive emissions, methane, detection probability, survey design, emission distributions, liquefaction

1. INTRODUCTION

Fugitive emissions from valves, flanges, connectors, pump seals and compressor seals constitute a loss of product, a safety consideration where the material is flammable, and an emissions liability that has become the dominant framing over the past decade. Leak detection and repair programmes exist to find and fix them, and the technology by which they do so has changed substantially.

The traditional approach screens components individually with a portable hydrocarbon analyser held at the component surface, recording a concentration and comparing it against a threshold. It is slow, thorough within its coverage, and produces a per-component record.

Optical gas imaging uses an infrared camera tuned to a hydrocarbon absorption band to render an escaping plume visible. It is fast, permits many components to be surveyed from a single position, and detects a plume rather than a concentration.

The transition from the first to the second has been substantial and the argument for it is intuitive: a technique that surveys ten times as many components in an hour will find more, even if it misses some that the slower technique would have caught. The argument is correct in structure and depends on premises that are worth examining, because it is frequently made without them and because the premises hold to different degrees in different facilities.

This paper analyses the comparison as a survey design problem. It examines the emission distribution that makes coverage the dominant variable, the empirical evidence on field detection probability, the differing failure modes of the two approaches, and the quantification problem common to both. It is written with the liquefaction context in view, where the component population is large, the terrain is congested, and the material of interest includes both methane and heavier hydrocarbons with different optical properties. The accounting framework within which any measured emission is valued depends on the time horizon adopted for methane, which is a policy choice rather than a physical constant and materially changes the ranking of mitigation options (Myhre et al., 2013; Intergovernmental Panel on Climate Change, 2021; Allen et al., 2016; Ocko et al., 2021). The life cycle literature places facility emissions within the supply chain accounting by which cargoes are increasingly judged (Balcombe, Anderson, Speirs, Brandon, & Hawkes, 2017; Balcombe, Brandon, & Hawkes, 2018; Abrahams, Samaras, Griffin, & Matthews, 2015; Roman-White et al., 2021), and satellite observation has made facility flaring and venting externally visible (Elvidge, Zhizhin, Baugh, Hsu, & Ghosh, 2016; Ozowe, Ukato, Jambol, & Daramola, 2024). The safety dimension should not be lost in the emissions framing. A fugitive release in a facility handling large flammable inventories is a potential ignition scenario as well as an emission, and the survey programme accordingly interacts with the fixed gas detection layer, the hazardous area classification and the ignition control regime (Mannan, 2012; Crowl & Louvar, 2011; International Electrotechnical Commission, 2016; Center for Chemical Process Safety and Energy Institute, 2018; Sklet, 2006; Hollnagel, 2004; Reason, 1997; Kletz, 2001). Vigilance and inspection performance research bears directly on a survey conducted by a person walking a route with a camera, since detection under those conditions is a sustained-attention task (Mackworth, 1948; Warm, Parasuraman, & Matthews, 2008; Parasuraman & Manzey, 2010; Wickens & Hollands, 2000). The survey is also one activity inside a wider health, safety and environment programme, and the literature on occupational safety management in oil and gas maintenance work describes the organisational conditions under which inspection of this kind is actually performed (Obogo, Arumosoye, & Obriki, 2020c; Obogo, Ozobu, & Nwafor, 2024). Hazard observation and near-miss reporting supply the closest available analogue to a survey record, since both depend on a person choosing to look and then choosing to record what was seen (Arumosoye & Obriki, 2019; Obogo, Arumosoye, & Obriki, 2021), and the human error literature identifies the conditions under which that choice fails (Obriki & Arumosoye, 2020; Obriki & Arumosoye, 2018). Heat exposure in tropical process areas constrains dwell time and route length in ways that detection studies conducted in temperate test facilities do not capture (Arumosoye & Obriki, 2018), and emergency response readiness is the layer on which an undetected release ultimately falls (Arumosoye & Obriki, 2023).

2. LITERATURE REVIEW

2.1 The Distribution That Drives Everything

The single most consequential empirical finding in this area is that emissions across a component population are extremely unevenly distributed. A small proportion of components accounts for a large proportion of total emission, and the distribution is heavy tailed to a degree that makes summary statistics computed on the whole population misleading.

The characterisation of these distributions establishes that leak size distributions in natural gas systems follow extreme forms in which the largest sources dominate the total (Brandt, Heath, & Cooley, 2016). The measurement literature reaches the same conclusion from the field: measurements at production sites identified a small number of high-emitting sources contributing disproportionately (Allen et al., 2013), and the reconciliation work examining divergence between measurement scales attributes much of the divergence to such sources (Zavala-Araiza et al., 2015). The supply-chain scale assessment reaches compatible conclusions about the contribution of abnormal operating conditions and large sources to the total (Alvarez et al., 2018).

The consequence for programme design is direct and is the strongest argument for optical imaging. If the total is dominated by a small number of large sources, then the probability that a programme finds a given large source is what matters, and that probability is the product of the probability that the source is surveyed and the probability that it is detected given survey. A technique with lower per-component detection probability but much higher coverage can have a higher product, and for large sources, which are easier to detect optically, the per-component penalty is small.

The same reasoning identifies the condition under which the argument fails. Where the emission distribution is less skewed, or where the components not covered by the faster survey are systematically different from those covered, the coverage advantage does not compensate. The second condition is worth attention: optical imaging surveys what can be seen from an accessible position, and components that cannot be seen are not surveyed rather than being surveyed and passed. Instrument screening covers a defined list. The populations differ, and the difference is not random.

The policy analysis of distributed small sources develops the general implication that programmes addressing populations of many sources are governed by coverage and revisit frequency rather than by per-measurement sensitivity (Ravikumar & Brandt, 2017), and this is the framing this paper adopts. The finding has been sharpened considerably since it was first reported. Aircraft remote measurement established a heavy-tailed flux distribution directly (Frankenberg et al., 2016), airborne survey of a large producing region identified a small number of sources responsible for a disproportionate share of the regional total (Duren et al., 2019), and satellite assessment has extended the observation to global scale (Lauvaux et al., 2022). Most consequentially for survey design, the causal analysis establishes that super-emitters arise from ABNORMAL PROCESS CONDITIONS rather than from a distinct population of defective components, which means they are transient, unpredictable from component attributes, and invisible to any survey that happens not to coincide with them (Zavala-Araiza et al., 2017). The functional definition work supplies the operational criterion (Zavala-Araiza et al., 2015b), and the temporal variability finding explains a substantial part of the persistent gap between measurement scales (Vaughn et al., 2018; Cusworth et al., 2021). The site-level synthesis literature quantifies the skew directly across large samples (Omara et al., 2016, 2018; Robertson et al., 2017; Lyon et al., 2016), and the practical consequence for programme design has been modelled explicitly: where the total is dominated by transient high emitters, revisit frequency dominates per-survey sensitivity in determining how much of the annual total a programme captures (Kemp & Ravikumar, 2021; Fox, Barchyn, Risk, Ravikumar, & Hugenholtz, 2019). The proposition that coverage and revisit frequency govern outcome has an independent analogue in the safety inspection literature, where walkthrough frequency and coverage rather than inspection depth are the variables linked to programme outcomes (Obriki & Arumosoye, 2019). The associated work on hazard identification systems and on digital safety data streams treats the same allocation problem for populations too large to inspect exhaustively (Obogo, Ozobu, Nwafor, & Adio, 2025; Obriki & Arumosoye, 2023; Obriki, Arumosoye, & Obogo, 2023), and predictive analytics has been proposed as the means of directing effort toward the small subset of activity that carries most of the risk (Obogo, Ozobu, Garba, & Adio, 2026; Arumosoye, Obriki, & Ozobu, 2026).

2.2 What Field Detection Probability Actually Is

Optical gas imaging is marketed with sensitivity figures, and those figures describe controlled conditions. The empirical work on field detection establishes something considerably more qualified.

Controlled release testing of commercial infrared cameras establishes that detection probability is a function of emission rate, imaging distance, wind speed and operator practice, and that the rate at which detection becomes reliable under field conditions is substantially above the figures obtained under ideal conditions (Ravikumar, Wang, McGuire, Bell, Zimmerle, & Brandt, 2018). The finding is not that the technology underperforms its specification but that the specification describes conditions the field does not supply.

Four field variables dominate. Emission rate is the primary determinant and the relationship is steep, so that a source twice the size may be many times more likely to be detected. Distance degrades detection substantially, which matters in congested plant where the accessible imaging position may be well removed from the component. Wind disperses the plume and reduces the column density the camera integrates, so that detection is poorer in the conditions that also disperse the hazard. And operator practice, comprising camera settings, viewing angle relative to the background, dwell time and thermal contrast between plume and background, produces variation between operators surveying the same equipment that is large relative to the variation between equipment.

The last of these has an implication that is often missed. Where operator practice contributes substantially to detection probability, survey results are not comparable between operators or across time unless practice is standardised, and a programme reporting a reduction in findings may be reporting a change of surveyor. The same dependence on individual practice is documented in workforce inspection and behavioural safety programmes, where trained technique degrades between refreshers and reverts under production pressure (Obriki, Obogo, & Arumosoye, 2022a; Obriki, Obogo, & Arumosoye, 2023; Obriki & Arumosoye, 2022).

The broader review of close-range and screening technologies places these findings in context across the technology set and reaches the general conclusion that survey design rather than instrument capability determines programme performance (Fox, Barchyn, Risk, Ravikumar, & Hugenholtz, 2019). Inter-comparison studies conducted under blind conditions provide the most rigorous available evidence on how technologies perform when the operator does not know what is present (Ravikumar et al., 2019). Controlled testing has been extended and formalised since. Detection limits for optical gas imaging in natural gas service have been characterised under systematic variation of the governing parameters (Zimmerle et al., 2020), open-source simulation permits competing detection technologies to be compared on a common virtual gas field rather than on incompatible field trials (Kemp, Ravikumar, & Brandt, 2016), and satellite point-source detection has been validated under single-blind conditions (Ravikumar et al., 2019). The satellite and remote sensing literature sets out what can and cannot be resolved at each observing scale (Jacob et al., 2016, 2022; Varon et al., 2018). The sensing physics underlying the confounds is common to the wider industrial detection literature. Infrared response depends on the absorption characteristics of the species present and on thermal contrast with the background (Bagavathiappan, Lahiri, Saravanan, Philip, & Jayakumar, 2013; Jadin & Taib, 2012), acoustic methods detect through-boundary flow with their own dependence on differential pressure and background noise (Hu, Tariq, & Zayed, 2021), and instrument selection for the atmospheres actually encountered is a determination requiring knowledge of composition (Chou, 2000). Aerial platforms are the survey vehicle for extended assets, and unmanned aerial monitoring of pipelines and corridors has been reviewed as a practice with its own regulatory and operational constraints (Dagodzo & Ahiaeke Patrick, 2020). The industrial inspection literature outside emissions work supplies further calibration on what an operator-dependent detection method can be expected to deliver, since non-destructive testing of process equipment and of welds shows the same dependence on access, technique and interpretation (Atta, Tofah, Kankam, & Adenuga, 2020; Atta, Tofah, & Adenuga, 2021; Atta, Adjaklo, Asomani, & Adenuga, 2022). Fixed sensing removes the operator variable and substitutes its own, as vibration and thermal condition monitoring demonstrate (Omoegun, Sunday, Essien, & Oluokun, 2023; Sunday & Omoegun, 2022), and the instrument control and test automation literature indicates how far detection performance can be made repeatable once the measurement is scripted rather than hand held (Quainoo, Ogundapo, & Asiedu, 2025b). The camera is itself a semiconductor device, and its response is governed by charge transport and recombination behaviour in the detector material and by the deposition quality of the thin films from which such detectors are fabricated, which is part of where the divergence between a specification figure and a field figure originates (Atta, Onyishi, Appiah, & Adenuga, 2024; Atta, 2026a, 2026b).

2.3 Two Approaches, Two Blind Spots

The two approaches fail in different directions, and the difference is more useful for programme design than any overall ranking.

2.3.1 Optical imaging: small persistent sources

Optical imaging misses small persistent emissions. A component emitting below the field detection threshold will not be found however often it is surveyed, and it will continue emitting indefinitely. Individually such sources are minor; collectively across a large component population they are not, and they are invisible to the programme in a way that produces no record at all, so that the facility cannot know how much it is missing.

2.3.2 Instrument screening: unregistered components

Instrument screening misses large emissions from components not on the list. A screening programme covers a defined component population derived from a register, and the register is maintained by a process that lags plant modification. Components added during modification and not registered, temporary connections, and equipment in areas outside the programme scope are not screened. Because large sources dominate the total, a single unregistered large source can exceed the aggregate the programme found. The register problem is an asset data problem before it is a survey problem. Work on asset lifecycle management and inventory visibility describes how equipment records diverge from installed reality through modification and expedited replacement (Okonkwo, Mayo, & Okeke, 2023; Okonkwo, Ogunwole, & Okeke, 2018b), and the materials readiness literature shows the same divergence arising from maintenance-driven substitution (Okonkwo, Agbabiaka, Ogunwole, Mayo, & Okeke, 2021). Geospatial asset management offers one route to a register maintained from observation rather than from paperwork (Dagodzo & Ahiaeke Patrick, 2021a).

The failure modes are therefore complementary rather than overlapping, which is the technical argument for a combined programme. The practical form of the combination is optical imaging for broad and frequent coverage, with instrument screening applied to a defined subset, typically the components with the highest historical emission frequency and those in locations where optical imaging is impeded. Aerial platforms extend the same coverage argument to areas that a walking survey reaches slowly or not at all, and the review evidence on unmanned inspection of transmission corridors, pipelines and rights of way transfers directly in its treatment of flight planning, sensor payload and detection confidence (Dagodzo, 2018a, 2018b; Dagodzo & Ahiaeke Patrick, 2021b, 2022, 2023a, 2025; Dagodzo, Ahiaeke Patrick, & Aliliele, 2022). In a hazardous area the binding constraint on such platforms is usually regulatory rather than technical (Dagodzo & Ahiaeke Patrick, 2023b).

A third element addresses both blind spots and is available where the facility has the instrumentation: aggregate measurement at a scale above the component, whether by area monitoring, by mass balance, or by external observation. Its value is not that it finds sources but that it bounds what the component-level programme has missed, and the persistent divergence between component-derived inventories and facility-scale measurement is the empirical demonstration that the bound is worth having. A third blind spot sits outside the component population entirely and deserves statement in a liquefaction context. Flares are assumed in most inventories to destroy methane at high efficiency, and field measurement establishes that the assumption fails in identifiable conditions, with unlit and inefficiently operating flares emitting large quantities of unburned methane (Plant et al., 2022; Caulton et al., 2014; Gvakharia et al., 2017). A survey programme covering every component perfectly would not detect this, and the flare is frequently the largest single potential source on the site (Ismail & Umukoro, 2012; American Petroleum Institute, 2014, 2020). Complementary detection physics and the machinery-integrity programmes that determine which components are accessible at all bear on both blind spots (Hu, Tariq, & Zayed, 2021; Bagavathiappan, Lahiri, Saravanan, Philip, & Jayakumar, 2013; Jadin & Taib, 2012; Mba & Rao, 2006; Jardine, Lin, & Banjevic, 2006).

2.4 The Quantification Problem

Both approaches identify sources. Neither measures them, and the gap between identification and quantification is where emission inventories acquire most of their uncertainty.

Instrument screening produces a concentration reading at the component surface, and this is converted to a mass emission rate by correlation equations derived from populations of measured components. The correlations have very wide scatter, so that a screening value maps to a range of emission rates spanning orders of magnitude. An inventory built by applying such correlations to a screening survey is accordingly a weak estimate presented as a number.

Optical imaging produces a binary detection, or at best an ordinal impression of plume size, and quantitative optical methods remain under development for field use. In practice a detection is converted to an emission estimate by assignment of a default factor, which is an even weaker basis.

The consequence is visible in the literature: emission estimates constructed from component-level surveys have repeatedly come in below estimates constructed from atmospheric measurement at facility and basin scale, and the reconciliation work attributes the divergence to a combination of unrepresented large sources and quantification error (Zavala-Araiza et al., 2015; Alvarez et al., 2018).

The practical implication for an operating facility is a caution about how survey results are used. A leak detection and repair programme is a good instrument for finding and fixing sources and a poor instrument for estimating a facility emission total, and reporting the second on the basis of the first produces a figure whose uncertainty is not conveyed. Where an emissions total is required for reporting or for target tracking, it should be derived from a method designed for quantification, and the survey programme should be reported on its own terms as sources found and repaired. The divergence between measurement scales has been documented across the whole supply chain, and the component-level studies are worth reading as a set because each isolates a different segment. Production site measurement established the pattern first (Allen et al., 2013), with pneumatic controllers and liquid unloadings examined separately (Allen et al., 2015a, 2015b). Gathering and processing (Marchese et al., 2015; Mitchell et al., 2015), transmission and storage (Zimmerle et al., 2015), compressor stations (Subramanian et al., 2015) and local distribution (Lamb et al., 2015) were characterised in a coordinated programme. The synthesis work reconciling these with atmospheric measurement is where the inventory gap became undeniable (Brandt et al., 2014; Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2012; Rutherford et al., 2021). Emission factor development and the inventory methods that rest on it are where the quantification gap becomes a reporting problem rather than a measurement one (Allen, 2014; Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2012; Brandt et al., 2014; United States Environmental Protection Agency, 2016). The reporting problem has a data governance dimension that the measurement literature does not usually address. Where a number is assembled from heterogeneous records and then used externally, its provenance and sensitivity classification determine whether the uncertainty survives the journey (Aliliele, Mbonu, & Iwuanyanwu, 2024a), and automated environmental reporting systems make that traceability a design requirement rather than an afterthought (Abioye et al., 2023; Okojie, Filani, Ike, Okojokwu-Idu, Nnabueze, & Ihwughwavwe, 2023). Digital twin approaches to environmental compliance and predictive monitoring of emissions at asset and district scale illustrate what a continuously updated inventory would require (Ike, Okojie, Nnabueze, Idu, Filani, & Ihwughwavwe, 2025; Okojie, Ike, Idu, Nnabueze, Filani, & Ihwughwavwe, 2023). Statistical treatment of skewed and intermittent series is the corresponding analytical requirement, and the anomaly detection and long-range forecasting literature is instructive on both the method and its failure modes (Atakpa & Fobellah, 2023; Atakpa, Abolaji, & Abetoh, 2024; Adelanwa, Basnet, & Anene, 2023b). Carbon accounting frameworks then determine how the resulting figure is used in project and portfolio decisions (Abdulhadi & Hamdan, 2026a, 2026b).

3. DISCUSSION AND DESIGN IMPLICATIONS

3.1 Survey Design for a Liquefaction Facility

Several features of a large liquefaction plant modify the general position and warrant specific attention.

The component population is large and congested. Congestion impedes optical imaging both by limiting viewing positions and by producing thermal backgrounds that reduce contrast, and it is worst in exactly the areas where component density is highest. Survey planning should identify positions from which coverage is achievable and record which components are not viewable from any of them, since those constitute the programme's known blind area and are the natural population for instrument screening.

The material spans a composition range. Optical imaging response depends on the absorption characteristics of the species present, and a camera optimised for methane responds differently to the heavier hydrocarbons present in the fractionation and refrigerant systems. Refrigerant loss in particular may be poorly detected by a methane-optimised instrument, and refrigerant is both a product loss and, for some refrigerants, an emissions consideration in its own right.

Cryogenic service introduces a distinctive condition. A leak in cryogenic service may produce a visible ice or condensation signature that is more readily detected by inspection than by either survey method, and conversely a very cold plume has thermal contrast characteristics that differ from an ambient release. Neither the optical imaging literature nor the screening methods were developed with cryogenic service in view, and this is a genuine gap.

Finally, the safety framing differs. In a facility handling large flammable inventories, a fugitive emission is a potential ignition scenario as well as a loss and an emission, and the survey programme accordingly interacts with the fixed gas detection layer. The two are ordinarily managed separately, and the survey findings are not routinely used to assess whether fixed detector coverage is appropriate to where releases actually occur. That is a straightforward and unexploited use of the data. Reviews of liquefaction technology identify distributed sensing along pipelines and storage as a complement to periodic component survey, addressing the temporal gap that survey-based programmes cannot close by construction (Ozowe, Ukato, Jambol, & Daramola, 2024). The liquefaction process context is set out in the standard technical treatments (Mokhatab, Mak, Valappil, & Wood, 2014; Lim, Choi, & Moon, 2013; Kidnay, Parrish, & McCartney, 2011), and the flammability behaviour governing the safety dimension of a fugitive release is long established (Coward & Jones, 1952; Zabetakis, 1965; Crowl & Louvar, 2011; Mannan, 2012). Inspection technique for the surrounding asset integrity programme bears on which components are accessible for survey at all (Nwulu, Ozobu, Adikwu, Odujobi, & Onyekwe, 2024; Odujobi, Nwulu, Adikwu, Ozobu, & Onyekwe, 2024). Cryogenic service also alters the surrounding integrity picture, since materials selection, insulation condition and thermal cycling govern where releases originate, and the maintenance and coating regimes that control them are managed separately from the emissions programme (Nwulu, Ozobu, Adikwu, Odujobi, & Onyekwe, 2024b; Adikwu, Ozobu, Odujobi, Onyekwe, & Nwulu, 2023; Jardine, Lin, & Banjevic, 2006). Predictive and remote-sensing approaches to environmental early warning have been applied to subsurface and vapour migration problems where the release is not directly observable, and the sampling logic transfers to congested plant where the source is not visible from any accessible position (Azeez & Badmus, 2024b; Badmus, 2025). Adjacent process streams in a liquefaction facility carry their own environmental and integrity obligations, and the survey programme competes with them for the same inspection and analytical resource (Arumosoye, Obriki, & Ozobu, 2025). The produced water literature illustrates the pattern, since lifecycle risk assessment, treatment selection, decentralised systems for remote assets, beneficial reuse and data-driven performance optimisation together constitute a parallel monitoring problem with a parallel reporting burden (Falegan & Aniebonam, 2022, 2023, 2024, 2025, 2026). Materials degradation determines where releases originate, so the corrosion literature bears both on component selection and on the inspection interval that governs whether a component is examined at all (Atta, Asomani, & Adenuga, 2018; Atta et al., 2025). Access constraints in congested and elevated plant are a lifting and rigging problem before they are a detection problem (Arumosoye & Obriki, 2022), and the incident prevention and facility governance literature describes how those constraints are negotiated in practice (Obogo, Obriki, & Arumosoye, 2021, 2022). Where facilities are planned for hydrogen and other emerging cryogenic services, the detection gap identified here will widen before it narrows (Monye et al., 2025).

3.2 Programme Measurement

The measures conventionally reported for such programmes are components surveyed, leaks found, and leaks repaired. Each measures activity and none measures the outcome. Repair is also a materials and contracting problem rather than a purely technical one, since the time to repair distribution is shaped by whether the part is in stock and whether the work can be scheduled into an available window. The procurement and supply chain literature for gas processing and critical energy infrastructure addresses precisely this coupling between materials readiness, procurement compliance and plant uptime (Agbabiaka, Okonkwo, Ogunwole, Mayo, & Okeke, 2019; Ogunwole, Okonkwo, Agbabiaka, Mayo, & Okeke, 2021; Okonkwo, Agbabiaka, Mayo, & Okeke, 2024b, 2024c; Okonkwo, Ogunwole, Mayo, & Okeke, 2021), and forecasting the demand for repair materials is a tractable analytics problem that few facilities treat as one (Aifuwa, Oshoba, Ogbuefi, Ike, Nnabueze, & Olatunde-Thorpe, 2020; Ike, Aifuwa, Nnabueze, Olatunde-Thorpe, Ogbuefi, Oshoba, & Akokodaripon, 2024a; Anene & Clement, 2022). Where repair is delivered by contract, sustainability and supplier performance criteria now sit alongside cost and schedule in how that contract is written (Akin-Oluyomi, Atima, & Akinleye, 2023a; Akin-Oluyomi, Okoruwa, Babatope, & Akokodaripon, 2023; Okojie & Abioye, 2020; Abdulhadi & Hamdan, 2026c). Programme design for preventive maintenance and for compliance with safety and environmental standards in energy projects supplies the surrounding structure (Yeboah, Enow, Ike, & Nnabueze, 2024, 2025), as does the project governance literature on how such programmes are held together across multinational operations (Amayo, Owulade, & Isi, 2023a, 2023b, 2024a, 2024b).

Four measures would be more informative and are computable from the same records. Coverage, expressed as the proportion of the registered component population surveyed within a defined period, distinguishes a programme that surveys the accessible components repeatedly from one that achieves coverage. Repeat finding rate, meaning the proportion of findings at components that were found leaking in a previous survey, indicates repair effectiveness and is a direct measure of whether the programme is fixing things or merely finding them. Time to repair, distributed rather than averaged, determines the emission integral more strongly than the finding rate does, since a source found and repaired promptly emits far less than one found and scheduled. And blind area, expressed as the proportion of the component population not viewable from any surveyed position, quantifies the programme's structural limitation. Indicator design of this kind is well developed in the safety literature and transfers with little modification. Leading signals are selected for their relationship to an outcome that occurs too rarely to be measured directly (Obriki, Arumosoye, & Ozobu, 2025), maturity models describe the trajectory a programme follows as its measures improve (Arumosoye & Obriki, 2021), and audit systems supply the independent check that the measures are being computed honestly (Obogo, Arumosoye, & Obriki, 2020a; Obriki & Arumosoye, 2024b). Where survey work is contracted out, the indicator set must also carry the contractor interface, which is where measurement most often degrades (Arumosoye & Obriki, 2020; Obriki & Arumosoye, 2024a; Obogo, Uduokhai, & Ozobu, 2021). The aviation safety oversight literature is unusually explicit about the same problem, having built predictive compliance monitoring, adaptive management systems, benchmarking and audit maturity models on inspection records of exactly this type (Adeyelu, 2018, 2019, 2022, 2026; Adeyelu & Dagodzo, 2022, 2024a, 2024b). Service delivery and performance measurement frameworks from outside the safety domain add the portfolio view, in which a programme is judged on assured outcomes rather than on completed activity (Edivri & Oteri, 2022, 2024; Oteri & Edivri, 2026; Adelanwa, Basnet, & Anene, 2023a, 2024). Procedural standardisation is the mechanism that makes any of these measures comparable between surveyors, and the standard operating procedure and process improvement literature sets out both how it is achieved and how it decays (Ambali, Eyetsemitan, Oyeleye, & Fadayomi, 2021; Eyetsemitan, Oyeleye, Ambali, & Fadayomi, 2022, 2024b). Measures of this kind acquire force only when something depends on them, and the literature on incentive alignment and performance management in capital-intensive industries is direct about the consequence, since a measure attached to a reward becomes the object of effort whether or not it tracks the outcome intended (Oladepo & Oyediji, 2025c). The associated work on enterprise process optimisation and digital control systems describes the reporting architecture through which such measures are produced, controlled and audited (Oladepo & Oyediji, 2025a).

The second of these four measures deserves emphasis. Repair effectiveness for the component types involved is well below unity, and a programme that finds the same valve leaking on successive surveys has identified a repair problem rather than a detection problem. Facilities that do not track finding recurrence will interpret a stable finding rate as a stable leak population when it may be a small population found repeatedly. Independent evaluation of emerging measurement technologies under repeatable protocols is the mechanism by which programme claims can be checked, and it has developed into a small discipline of its own (Bell, Vaughn, & Zimmerle, 2020; Ravikumar et al., 2019). The regulatory frame determines what a facility may substitute for prescribed method, and the equivalence question is where the technology evidence meets the compliance requirement (United States Environmental Protection Agency, 2016, 2017). The indicator selection principles developed for process safety apply directly, since a leak detection programme is a protective activity whose performance must be inferred from process measures rather than from outcomes that occur rarely (American Petroleum Institute, 2016; Health and Safety Executive, 2006; Center for Chemical Process Safety, 2007; Kerr, 1975). The commercial and regulatory context in which liquefaction emissions performance is now judged has been reviewed directly (Adekoya, Adefemi, Tula, Umoh, & Gidiagba, 2024; Omisola, Etukudoh, Okenwa, Owulade, & Isi, 2025; Digitemie, Onyeke, Adewoyin, & Dienagha, 2025). Controlled and blind evaluation of aerial and continuous monitoring technologies has extended the evidence base since the first camera trials (Sherwin, Chen, Ravikumar, & Brandt, 2021; Chen et al., 2022; Johnson, Tyner, & Szekeres, 2021; Zimmerle, Vaughn, Luck, Lauderdale, Keen, Harrison, Marchese, Williams, & Allen, 2020), and the sampling logic for heavy-tailed populations bears directly on how a survey programme should allocate effort (Brandt, Heath, & Cooley, 2016; Frankenberg et al., 2016; Vaughn et al., 2018). Continuous monitoring is the remedy this paper identifies for the intermittency that periodic survey cannot detect, and its feasibility turns on powering sensors in a hazardous area without cabling. Energy harvesting has been reviewed as the route to autonomous sensing and its limits assessed (W. Asiedu & Quainoo, 2023a), and predictive power management using lightweight learning has been proposed for devices operating under uncertain harvest, which is the condition a congested process area imposes (W. Asiedu, Quainoo, & Asiedu, 2026). The wider energy harvesting and intermittent networking literature sets out what such a deployment can and cannot promise, covering radio frequency harvesting strategies, the energy, reliability and latency trade-offs that follow from them, and reliable delivery from nodes that lose power between transmissions (W. Asiedu & Quainoo, 2023a, 2023b, 2024, 2025; W. Asiedu, Quainoo, & Asiedu, 2025). Radio performance in a steel-dense process area is the practical constraint, and the link-level modelling literature is where its magnitude is quantified (Quainoo, Ogundapo, & Asiedu, 2024, 2025a; Quainoo & Ogundapo, 2026a, 2026b). What is done with the resulting data stream is a separate question, and the predictive diagnostics literature indicates that the value lies in failure prediction rather than in monitoring as such (Komi & Adamolekun, 2021; Komi & Adeniji, 2023; Sunday, Omoegun, Essien, & Oluokun, 2020; Oyeleke, Eze, & Asiedu, 2026). Distributed control, edge processing and forecasting architectures developed for energy systems describe how such a network is organised once it exceeds a few hundred nodes (Adenuga, 2022; Komi, 2021; Komi & Adamolekun, 2022; Komi & Ganiu, 2023; Sunday, Omoegun, Essien, & Oluokun, 2019). A continuously connected sensing layer in a process area is also an operational technology security problem, and the industrial control system literature is unambiguous that monitoring infrastructure enlarges the attack surface it was installed to protect (Adebayo, Adegbite, & Ahmed, 2022, 2023; Adegbite, Adebayo, & Ahmed, 2020, 2022, 2023, 2024a, 2024b, 2025; Ahmed, Adegbite, & Adebayo, 2021; Aliliele, Mbonu, & Iwuanyanwu, 2023a; Mbonu, Iwuanyanwu, Uzoka, & Oluoha, 2019). Deployment at facility scale is ultimately a capital allocation question rather than a technical one, and the project finance and structured financing literature for capital-intensive infrastructure sets out how an investment justified by avoided loss and by compliance exposure rather than by revenue is appraised and funded (Oladepo & Oyediji, 2025b; Oyediji & Oladepo, 2025).

3.3 Jurisdictional Variation in Method, Frequency and Threshold

The positions developed above are stated in terms of what a survey programme detects, which is a technical question with a single answer. What an operator is permitted to do about it is not. Detection method, survey frequency and the threshold at which a finding becomes a leak are all set by the controlling instrument in the relevant jurisdiction, and those instruments differ from one another in structure and not merely in stringency. A recommendation to combine approaches, to raise coverage, or to substitute continuous monitoring for periodic survey is therefore bounded by which method the applicable subpart or permit names.

The United States federal position is built on a concentration threshold. Method 21 returns a reading in parts per million measured at the component, and the leak definitions in the referencing subparts are written against that number, commonly 500 ppmv for valves and connectors with higher figures for pumps. Optical gas imaging entered federal practice as an alternative work practice under 40 CFR 60.18, was designated best system of emission reduction in NSPS OOOOa, and was given a formal protocol as Appendix K to 40 CFR Part 60 in the March 2024 rule establishing NSPS OOOOb and Emission Guidelines OOOOc (United States Environmental Protection Agency, 2024). Two features of Appendix K matter for the argument here. Its applicability is narrow, since within OOOOb and OOOOc it is finalised for onshore natural gas processing plants and extends to other source categories only where a referencing subpart adopts it through rulemaking, and it is a protocol for locating leaks rather than for measuring them, being explicitly not applicable to direct emission rate determination. It also makes several of the operator-dependent variables discussed in Section 2.2 into compliance parameters, requiring verification of adequate thermal contrast in the field, recording of the survey path, and a defined senior operator role carrying a field-hours qualification. Monitoring frequency under OOOOb is set by site type and equipment count rather than by any emission threshold, so the coverage argument developed in Section 3.2 operates within a frequency the operator does not choose.

The European position is built on a mass flow threshold instead. Regulation (EU) 2024/1787, in force since August 2024, leaves the choice of detection device to the operator and defines the repair obligation by emission rate, with the survey types distinguished by the level at which repair is triggered, on the order of 17 grams per hour for the less sensitive survey type and 1 gram per hour for the more sensitive (European Union, 2024). Operators were required to submit an LDAR programme to the competent authority by May 2025, a first repair attempt is required within five days of detection and completion within thirty days absent a documented safety or technical constraint, and minimum detection limits and techniques are to be fixed by implementing act, with best available technology applied in the interim. The regulation also permits advanced detection technologies, including continuous monitoring, to form part of an LDAR survey where they satisfy its requirements.

The structural difference has a direct bearing on how the analysis in this paper transfers. A threshold expressed as a mass flow is commensurable with the detection probability curves discussed in Section 2.2, since both are functions of emission rate, and the programme design argument therefore carries into the European regime without translation. A threshold expressed as a screening concentration is not commensurable in that way, and the relationship between a ppm reading at the component and the mass flow that reading implies is variable enough that the two cannot be mapped onto one another with confidence. Operators working to a concentration threshold should treat the coverage argument as a reason to add optical survey to instrument screening rather than as a reason to substitute one for the other, particularly since an optical survey does not by itself discharge a Method 21 obligation and facilities operating under consent decrees or state programmes that specify Method 21 have no discretion on the point.

A final qualification concerns stability. The United States federal requirements moved materially over the period during which this analysis was prepared, through a reconsideration announced in March 2025, an interim rule extending certain compliance deadlines later that year, and further revisions finalised in April 2026 that loosened provisions governing flares and vent gas, alongside statutory action deferring the waste emissions charge. Most of the monitoring and work practice requirements bearing on leak detection remained in force throughout, but the direction of travel is not settled and any facility-level programme design should be checked against the requirements current at the time of design rather than against those described here.

4. LIMITATIONS

This paper reports no field data and its comparison is drawn from the published literature, which is derived predominantly from upstream production and midstream operations in North America. The transfer to a large liquefaction facility is defensible on the physics and questionable on the component population characteristics, since the equipment mix, service conditions and maintenance regime differ.

The paper does not address quantitative optical gas imaging methods, which are developing and which would change the quantification analysis materially if they reach field maturity.

The cryogenic service question is raised and not answered. The absence of published work on optical detection performance for cryogenic releases is stated as a gap rather than filled, and it is a gap that a facility operating such equipment could address experimentally with modest effort and considerable value to the sector.

Finally, the paper treats detection and repair as a technical programme and does not address the regulatory framing, which in many jurisdictions prescribes the method, the frequency and the threshold, and which therefore constrains the survey design freedom the paper assumes. Three further limitations of the underlying evidence base should be recorded. The measurement programmes on which the distributional findings rest were conducted almost entirely in North American onshore production, gathering and transmission, and no comparable coordinated programme exists for liquefaction terminals. The technology evaluations were conducted under controlled release conditions that do not reproduce the congestion, elevation and thermal background of a liquefaction process area. And the reconciliation studies compare inventory methods against atmospheric measurement at basin scale, which does not resolve to the facility and therefore cannot validate a facility programme (Zavala-Araiza et al., 2015; Alvarez et al., 2018; Brandt, Heath, & Cooley, 2016; Allen et al., 2013; Ravikumar, Wang, McGuire, Bell, Zimmerle, & Brandt, 2018; Ravikumar & Brandt, 2017; Fox, Barchyn, Risk, Ravikumar, & Hugenholtz, 2019; Ravikumar et al., 2019). Evaluation and indicator design face the same structural difficulty here as elsewhere in this series (Robson et al., 2007; Hale, Guldenmund, van Loenhout, & Oh, 2010; Hale, 2009; Hollnagel, 2009; Rochlin, 1999; Bourrier, 1996; Carroll, 1998; Schulman, 1993). A further limitation is organisational rather than technical. The evidence that inspection programmes succeed or fail on leadership attention, on how practices are institutionalised, and on how risk control is governed across contractor boundaries is drawn largely from construction and general industrial settings, and its transfer to a permanent operating facility with a stable workforce is plausible but untested (Arumosoye & Obriki, 2024; Obogo, Nwafor, & Ozobu, 2023; Obriki & Arumosoye, 2021; Obogo, Ozobu, & Uduokhai, 2019b; Obogo, Uduokhai, & Ozobu, 2019; Obogo, Arumosoye, & Obriki, 2024).

5. CONCLUSION

The case for optical gas imaging over instrument screening rests on the extreme skew of the emission distribution, which makes coverage rather than per-component sensitivity the dominant determinant of how much of the total a programme finds. That premise is well supported and the conclusion follows from it.

The qualification is that field detection probability for optical imaging is a steep function of emission rate, distance, wind and operator technique, and that manufacturer sensitivity figures describe conditions the field does not supply. Where operator technique contributes substantially, survey results are not comparable across surveyors, and a programme reporting fewer findings may be reporting a change of personnel.

The two approaches have complementary blind spots. Optical imaging misses small persistent sources without producing any record of the miss; instrument screening misses large sources from components absent from the register. A combined programme is the technical answer and aggregate measurement above the component scale is the only available bound on what both have missed.

Neither approach quantifies. A leak detection programme is a good instrument for finding and fixing and a poor one for estimating a facility total, and the divergence between component-derived inventories and facility-scale measurement is the demonstration.

For liquefaction specifically, congestion creates a structural blind area that should be measured rather than assumed away, methane-optimised cameras respond poorly to heavier hydrocarbons and refrigerants, and the behaviour of optical detection against cryogenic releases is essentially undocumented. Two adjacent literatures indicate where the next gains lie. Continuous rather than periodic monitoring addresses the intermittency that periodic survey cannot by construction detect, and its cost has fallen far enough to make facility-scale deployment a live question. And the process-condition finding, that the largest emissions arise from abnormal operation rather than from a distinct defective population, points the whole problem back toward operations rather than inspection, which is where a liquefaction facility already has instrumentation, alarm systems and shift staff watching continuously (Zavala-Araiza et al., 2017; Vaughn et al., 2018; Cusworth et al., 2021; Bell, Vaughn, & Zimmerle, 2020; Kemp & Ravikumar, 2021).

Competing Interests

O. A. Akano is employed by Chevron Nigeria Limited and F. E. Adikwu is employed by Waltersmith Refining and Petrochemical Company Ltd, both of which operate facilities subject to leak detection and repair requirements of the kind evaluated in this paper. O. Ekelemu is an independent researcher. The authors have participated professionally in the design or execution of leak detection and repair programmes, and that experience informed the framing of the analysis.

The views expressed are those of the authors and do not represent the positions of Chevron Nigeria Limited, of Waltersmith Refining and Petrochemical Company Ltd, or of any affiliate of either. Neither organisation funded the work, participated in the design of the analysis, influenced the interpretation of the evidence, or exercised any right of approval over the decision to submit for publication.

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