

# Flammability Measurement in Inerted VOC Waste-Gas Streams: Challenges and Monitoring Strategies

Debra Hall  
Elementale Enterprises, Inc  
15584 Summit Park Dr, Ste 301  
Montgomery, TX 77356

Chris Grieshaber  
Control Instruments Corporation  
25 Law Drive, Ste 1  
Fairfield, NJ 07004

## KEYWORDS

Flammability measurement; inerted gas streams; VOC waste-gas monitoring; lower flammable limit (LFL); flame temperature analysis (FTA); Thermal oxidizers

## ABSTRACT

Industrial waste-gas streams often contain complex mixtures of volatile organic compounds (VOCs) creating combustible and potentially explosive conditions that are difficult to measure reliably.

Many industrial processes intentionally operate with low-oxygen gas streams through inerting using nitrogen or carbon dioxide to reduce corrosion, improve product quality, and support environmental compliance; however, these inerted conditions can introduce unpredictable ignition behavior and complicate conventional flammability assessment.

Lower Explosive Limit (LEL) sensors, commonly used for combustible gas monitoring, may produce misleading readings in inerted environments if analyzer selection, sampling methods, and gas properties are not carefully managed.

Regenerative thermal oxidizers (RTOs), commonly used for VOC destruction, further elevate safety concerns because they handle flammable mixtures at high temperature. Ensuring safe operation requires robust gas-concentration monitoring, automated alarm systems, and interlocks that maintain operation well below explosive limits.

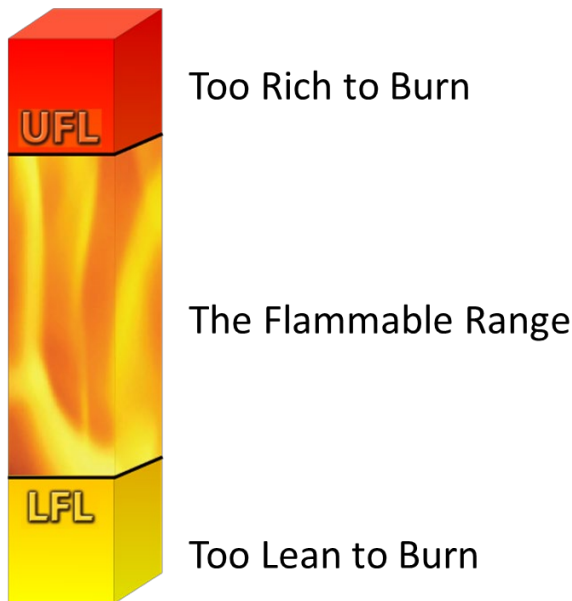
This paper reviews the key technical issues associated with measuring flammability in inerted process gas streams and presents strategies to improve detection reliability and

reduce process-safety risks, with particular emphasis on high-temperature applications such as regenerative thermal oxidizers.

## FUNDAMENTALS OF FLAMMABILITY IN INERT GAS MIXTURES

Flammability is commonly characterized by the lower and upper flammable limits (LFL and UFL), which respectively define the lowest and highest concentration of gas, vapor or combustibles in air that can lead to flame propagation or explosion in presence of an ignition source. These limits are typically determined under standardized conditions in air, assuming a nominal oxygen concentration of approximately 21 percent by volume. While LFL values are widely used in industrial safety systems, they represent simplified reference points rather than fixed physical constants and can shift significantly as gas composition and operating conditions change.

Figure 1 shows the behavior of a flammable concentration and how it passes through the LFL, Flammable Range and UFL ranges under normal oxygen conditions.

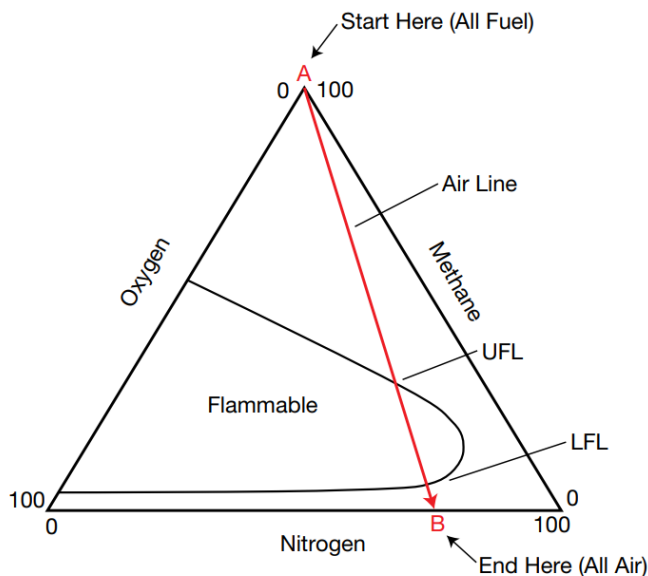


**Figure 1** Represents the flammability diagrams of gases in air (O<sub>2</sub> is approx. 21% vol). Where, the UFL (Upper Flammable Limit) has flammable concentrations that are too rich to burn and the LFL (Lower Flammable Limit) has concentration too lean to burn.

Oxygen concentration also plays a critical role in combustion behavior. As oxygen levels are reduced, the minimum fuel concentration required to support ignition generally increases, and flame propagation becomes less stable. Below a certain oxygen threshold, combustion may not be sustained at all. However, near this threshold, gas mixtures can exhibit non-linear and sometimes unpredictable ignition behavior, particularly when multiple combustible components are present. These effects complicate the direct application of air-based flammability limits to low-oxygen or inerted environments.

Figure 2 shows the Lower Oxygen Concentration (LOC) diagram, where the Red Dilution path illustrates the “inerting process”. If this line passes through the Flammable Envelope, ignition is possible. In this diagram, the inerting component is nitrogen. If CO<sub>2</sub>, Argon or other inert compounds were represented, the flammable envelope curve would be slightly different.

Inert gases such as nitrogen and carbon dioxide suppress combustion through different mechanisms. Nitrogen primarily acts as a diluent, reducing the partial pressure of both fuel and oxygen, while carbon dioxide additionally absorbs heat and interferes with flame chemistry. As a result, inerted gas mixtures may appear less flammable based on calculated limits, yet still present ignition hazards under certain conditions, especially at elevated temperatures or during transient process events. The relative effectiveness of inerting depends not only on oxygen concentration but also on fuel type, mixture composition, and system dynamics.



**Figure 2:** A typical Flammability Triangle that represents how the flammability limits change with varying oxygen and inerting concentrations. Adding air to a fuel-rich concentration can pass through a flammable region before reaching a safe composition as seen in this red dilution path.

From a measurement perspective, flammability is therefore a system-level property rather than a simple function of fuel concentration alone. A reported “percent LFL” value assumes a specific reference atmosphere and combustion behavior that may not exist in an inerted process stream. Without accounting for oxygen content, inert gas effects, and real-world operating conditions, flammability measurements can be misinterpreted, leading to either an underestimation or overestimation of actual process-safety risk. Understanding these fundamentals is essential for selecting appropriate analyzer technologies and for interpreting flammability data in inerted industrial gas streams.

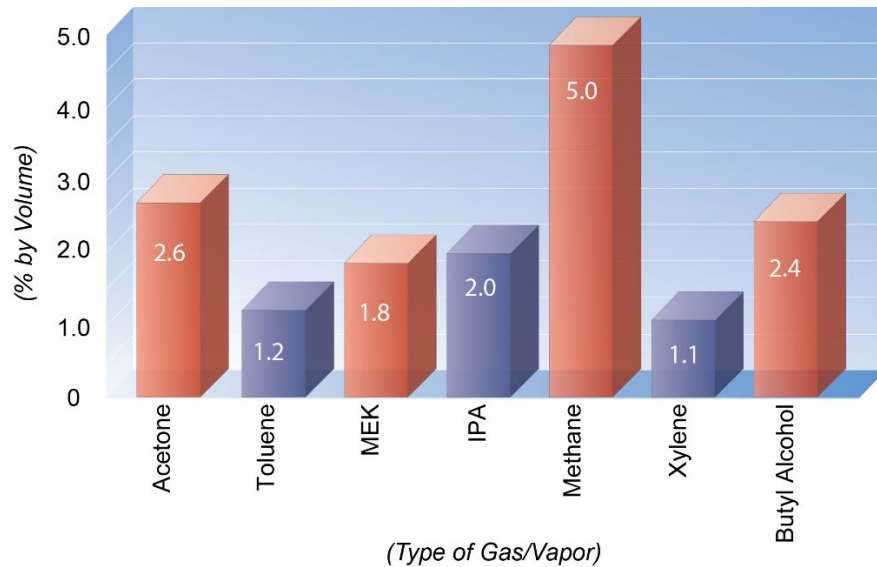
## CHARACTERISTICS OF INDUSTRIAL VOC WASTE-GAS STREAM

Industrial VOC waste-gas streams rarely consist of a single, well-defined combustible species. Instead, they typically contain complex and variable mixtures of hydrocarbons, oxygenated solvents, and inert components whose relative concentrations change over time. These streams may originate from coating operations, chemical processing, solvent recovery systems, or other production steps, and their composition is often influenced by raw materials, operating modes, and upstream process disturbances. As a result, the flammability characteristics of the gas stream cannot be assumed to be constant or easily predictable.

A key challenge in assessing flammability is the presence of multiple combustible species with different ignition properties. Individual VOCs may have significantly different LFLs, flame speeds, and heat release characteristics, and their combined behavior is not always linear or additive.

Figure 3 compares the LFLs of several common combustible gases and solvents, where the compounds are shown on the x-axis and the corresponding LFL (% by volume in air) is shown on the y-axis, illustrating the variability in the minimum concentration required for flame propagation.

Changes in the relative proportions of these components can shift the effective flammability envelope, particularly in inerted environments where combustion behavior is already highly sensitive to oxygen concentration. This variability complicates both analytical modeling and real-time measurement.



**Figure 3:** An example of different solvents & combustibles, and how their flammability levels vary. For Example, methane exhibits an LFL of approximately 5% by volume, while solvents such as toluene and xylene have LFL's near 1-1.2% by volume, highlighting the substantial variation between compounds.

Process conditions further influence waste-gas behavior. Elevated temperatures reduce ignition energy requirements and can expand the flammable region, while pressure variations alter partial pressures of fuel and oxygen. Moisture content may also affect both combustion behavior and analyzer response, especially in sampling systems where condensation or adsorption can occur. Transient events—such as batch releases, startup and shutdown sequences, or process upsets—can produce rapid changes in gas composition that challenge the response time and accuracy of flammability monitoring systems.

Among these factors, temperature plays a particularly important role because it directly affects vapor generation and the margin to the lower flammability limit (LFL). As process temperature increases, vapor concentrations may rise even when the underlying liquid composition remains constant, potentially shifting a previously safe condition toward the flammable region. This relationship is illustrated in Figure 4.



**Figure 4.** Influence of temperature on flammability limits. Temperature (x-axis) increases from 75–400°F while the y-axis represents vapor concentration relative to the LFL. Increasing process heat can shift a previously safe condition into the flammable region.

In many installations, inerting is applied upstream to maintain low oxygen concentrations, adding another layer of complexity. The interaction between VOC concentration, inert gas dilution, and oxygen availability means that flammability risk cannot be evaluated based on any single parameter. Instead, industrial VOC waste-gas streams must be viewed as dynamic systems in which composition, operating conditions, and process transients collectively determine ignition potential.

Recognizing these characteristics is essential for understanding the limitations of conventional flammability measurements and for designing monitoring strategies that adequately protect high-risk equipment such as regenerative thermal oxidizers.

These dynamic conditions present significant challenges for conventional flammability measurement techniques, particularly when monitoring complex VOC mixtures in real time.

## MEASUREMENT CHALLENGES IN INERTED GAS STREAMS

As previously mentioned, conventional flammability monitoring in industrial applications is most often based on lower flammable limit (LFL) measurements, which are typically calibrated and interpreted assuming air-based gas mixtures. In inerted or oxygen-deficient environments, this assumption may not be valid. Reduced oxygen concentration alters both combustion behavior and sensor response, creating conditions in which measured LFL values do not directly correspond to actual ignition risk. As a result, LFL readings in inerted gas streams must be interpreted with caution.

One of the primary challenges is the oxygen dependence of many flammability sensors. Catalytic bead sensors, for example, rely on the oxidation of combustible gases at the sensor surface and therefore require sufficient oxygen to function as intended. In low-oxygen environments, these sensors may under-respond or fail to respond altogether, producing artificially low LEL indications even when combustible concentrations are elevated. Other sensor technologies may also exhibit oxygen-related biases or compensation limits that are not apparent under normal operating conditions.

Gas dilution effects introduced by inerting, further complicate measurement. The addition of nitrogen or carbon dioxide reduces the partial pressure of both fuel and oxygen, altering the sensor signal in ways that may not be proportional to actual flammability risk. In multi-component VOC mixtures, cross-sensitivity and equivalency assumptions used to convert sensor output into a “percent LFL” value may no longer be valid.

These effects are particularly problematic when gas composition varies over time, as previously discussed.

Sampling system design plays a critical role in measurement reliability and is a frequent source of error. Poorly located sample probes may not capture representative gas compositions, while long transport lines can introduce response delays that obscure transient events. Temperature gradients within the sampling system may lead to condensation or adsorption of VOCs, resulting in biased or lagging measurements. In inerted systems, even small sampling losses can significantly distort perceived flammability margins.

Finally, the presentation of flammability data as a single LFL percentage can obscure underlying uncertainties. A reported LFL value may imply a level of precision and safety margin that does not exist in practice, particularly in inerted environments operating near flammability boundaries. Without a clear understanding of sensor limitations, oxygen effects, and sampling behavior, operators and safety systems may either underestimate risk or impose overly conservative operating constraints.

These challenges highlight the need for careful analyzer selection, robust sampling design, and system-level interpretation of flammability measurements in inerted process gas streams.

## **ANALYZER TECHNOLOGIES**

A variety of analyzer technologies are used to assess flammability in industrial gas streams, each based on different sensing principles and each subject to distinct limitations in inerted environments. While many of these technologies perform adequately in air-based applications, their behavior can change significantly when oxygen concentration is reduced or when inert gases are present in high proportions.

Understanding these differences is essential for selecting appropriate instrumentation and for avoiding misinterpretation of flammability data.

### **CATALYTIC BEAD**

Catalytic bead sensors are among the most widely used devices for combustible gas detection and are commonly employed for lower explosive limit (LEL) of area monitoring. These sensors operate by oxidizing combustible gases on a heated catalytic surface and measuring the resulting resistance change. Because this oxidation reaction requires oxygen, sensor response is inherently dependent on oxygen concentration.

In inerted or low-oxygen gas streams, catalytic bead sensors may under-respond or fail to respond entirely, even in the presence of significant combustible concentrations. Although some designs incorporate oxygen compensation or minimum oxygen requirements, these features are typically limited in range and may not account for rapid or uneven oxygen depletion. As a result, catalytic bead sensors can produce deceptively low LEL readings in inerted environments, creating a potential false sense of safety if used without careful validation. Additionally, these sensors tend to get coated or wear-out quickly in process environments, requiring regular replacement and high downtime.

### **INFRARED**

Infrared gas analyzers detect combustible gases by measuring absorption of infrared energy at wavelengths characteristic of hydrocarbon bonds. Because IR absorption does not rely on oxidation, these analyzers are often viewed as better suited for low-oxygen or inerted applications. In practice, however, IR analyzers introduce their own challenges.

IR sensors are generally calibrated for specific target gases or gas families and rely on equivalency assumptions to report a generalized LFL value for mixed VOC streams.

In complex or changing mixtures, these assumptions may not hold, leading to measurement uncertainty.

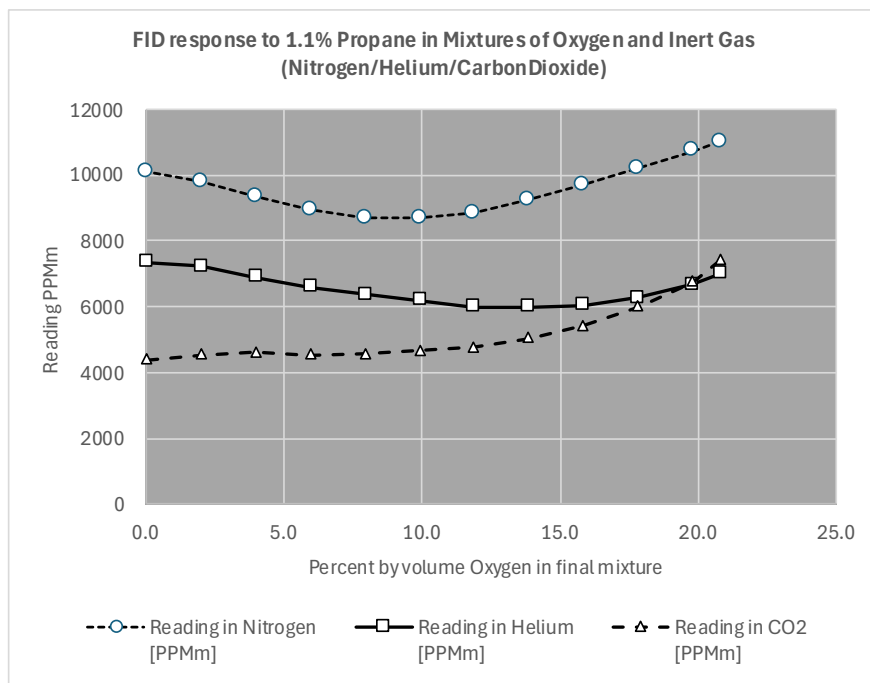
Additionally, high concentrations of inert gases such as carbon dioxide can interfere with infrared measurements, either through spectral overlap or by affecting optical path conditions. While IR analyzers can provide stable readings in inert environments, their output still requires careful interpretation in terms of actual flammability risk.

### **FLAME IONIZATION DETECTION**

Flame ionization detectors (FIDs) are widely used for measuring total hydrocarbon concentration in industrial gas streams, particularly in environmental monitoring and emissions control applications. FIDs operate by combusting hydrocarbons in a hydrogen flame and measuring the resulting ionization current, which is proportional to the number of carbon atoms present. Because the flame is supplied with its own fuel and oxidant, the FID response is largely independent of the oxygen concentration in the sample gas.

However, small oxygen-related effects can occur due to the way the sample gas is introduced into the detector. The sample enters the FID through a narrow capillary that meters the gas flow into the combustion chamber. As the gas passes through this capillary, its flow rate is influenced by physical properties such as density, viscosity, and diffusion. Changes in oxygen concentration or the type of inert gas present can therefore slightly alter the amount of sample reaching the flame.

This effect is illustrated in Figure 5, which shows the FID response to a constant concentration of propane in mixtures containing varying levels of oxygen and inert gases (nitrogen, helium, and carbon dioxide). Differences in the curves arise from the physical properties of the inert gases, which influence sample transport through the capillary and mixing within the flame.



**Figure 5:** FID “Oxygen effect” on readings when different inert gases are applied. For example, helium’s low density and high diffusivity tend to increase sample transport to the flame, while heavier gases such as carbon dioxide can slightly restrict flow, producing a lower detector response

Additionally, Flame Ionization Detectors (FIDs) do not directly measure flammability. The signal produced by an FID represents total hydrocarbon concentration rather than ignition potential and does not account for differences in flammability among individual VOC species. Two gas mixtures with identical FID readings may exhibit substantially different flammability behavior depending on molecular structure, dilution by inert gases, and

oxygen availability. Consequently, converting an FID output to an equivalent LFL value requires assumptions that may not be valid for complex or changing VOC mixtures.

For example, different isomers of butyl alcohol contain the same number of carbon atoms but exhibit different flammability characteristics:

- n-Butyl alcohol: LFL = 1.4% vol, Flash point = 37°C
- sec-Butyl alcohol: LFL = 1.7% vol, Flash point = 24°C
- tert-Butyl alcohol: LFL = 1.9% vol, Flash point = 11°C

Although the molecular formula is identical, their flammability behavior varies significantly due to differences in molecular structure.

In addition, some flammable substances commonly present in process environments are not hydrocarbon-based (e.g., carbon monoxide, ammonia, or sulfur-containing compounds) and may not be detected by an FID. Furthermore, FID response does not reflect proximity to the limiting oxygen concentration or other combustion-inhibiting effects introduced by inerting.

In practice, FIDs can provide valuable information about total VOC loading and trends in hydrocarbon concentration, particularly in inerted systems where oxygen-dependent sensors are unreliable. However, FID measurements should be interpreted as concentration indicators rather than direct measures of flammability.

These limitations highlight the need for measurement approaches that more directly reflect combustion behavior rather than relying solely on hydrocarbon concentration. Technologies that assess the thermal response of a mixture during combustion, such as Flame Temperature Analysis, provide an alternative approach to evaluating flammability risk in complex VOC streams.

#### **FLAME TEMPERATURE TECHNOLOGY (FTA)**

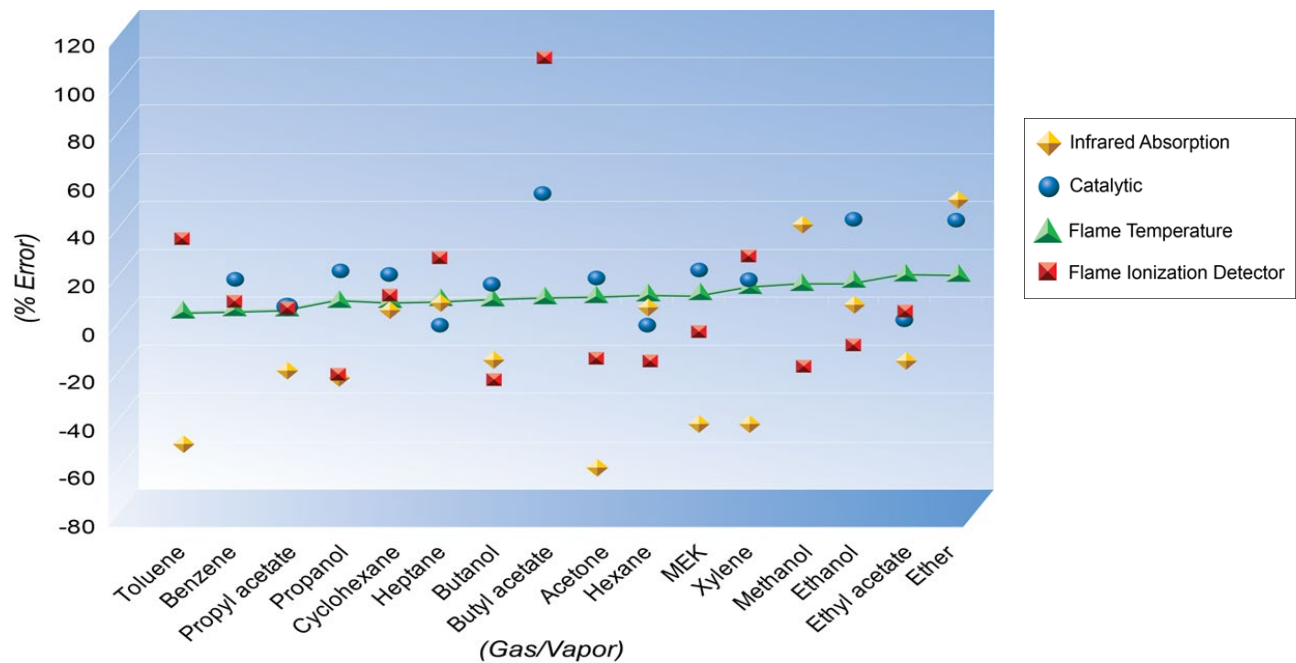
Flame temperature analysis (FTA) principle to measure flammability directly by observing the effect of combustible gases on a sensing flame. In this approach, a carefully metered pilot flame burns continuously within a small chamber, and sample gas drawn into the chamber is incinerated; the resulting change in flame temperature is directly proportional to the flammability, reported as a percentage of the lower flammable limit (% LFL).

Unlike indirect methods that rely on gas-specific absorption or oxidation properties, the flame temperature sensor *directly interacts* with combustible components across a broad range of species, yielding a uniform response even for complex or variable mixtures without frequent recalibration. This characteristic makes flame temperature technology particularly useful in industrial waste-gas streams where VOC composition changes over time, and where traditional “equivalency” assumptions used in infrared or catalytic measurements may introduce large uncertainties.

From a safety perspective, the FTA design includes built-in fail-safe diagnostics: loss of fuel, air, sample flow, or flame, all trigger alarms or fault relays, ensuring that instrument failure does not go undetected. The entire sampling train is heated to minimize condensation and sample loss, and the analyzer's direct mount installation reduces sampling lag by eliminating long heated lines. [https://www.controlinstruments.com/sites/default/files/product-brochure/PrevExBrochure\\_700Series.pdf?utm\\_source=chatgpt.com](https://www.controlinstruments.com/sites/default/files/product-brochure/PrevExBrochure_700Series.pdf?utm_source=chatgpt.com)

Despite these advantages, it is important to recognize that FTA remains a measure of flammability potential rather than a standalone predictor of ignition risk in all conditions. Interpretation of % LFL values still depends on understanding how inert gases, low oxygen concentrations, and transient process events affect flame behavior in the sampled stream. As with other analyzer technologies, integration with oxygen measurement and thoughtful safety logic are essential for robust risk management in inerted process environments.

Table I show a comparison of all Flammable Measurement technologies and their measurement error across a range of common combustible gases and vapors. The results illustrate that sensor accuracy can vary significantly depending on the chemical composition of the gas stream. Technologies that rely on gas-specific properties or equivalency assumptions exhibit larger variability and wider error margins across different compounds. In contrast, technologies based on direct combustion response show a more consistent relationship to flammability, resulting in narrower error ranges across the tested fuels. These differences highlight the importance of selecting analyzer technologies that remain robust under varying VOC compositions, particularly in industrial waste-gas streams where fuel mixtures may change over time.



**TABLE I:** Measurement error varies significantly across combustible compounds. Technologies relying on gas-specific calibration or equivalency assumptions show wider variability, while combustion-based measurements maintain a more consistent response across different fuels.

## **OXYGEN MEASUREMENT & LIMITING OXYGEN CONCENTRATION (LOC): BENEFITS AND TRADEOFFS**

Oxygen analyzers are commonly used in inerted process systems to assess flammability risk by monitoring oxygen concentration relative to the limiting oxygen concentration (LOC). The LOC represents the minimum oxygen concentration below which combustion cannot be sustained for a given fuel mixture under defined conditions. When properly applied, oxygen measurement provides a powerful and intuitive means of confirming that a process remains non-flammable, independent of absolute fuel concentration.

One of the primary benefits of oxygen-based flammability control is its direct relationship to combustion. Unlike fuel-based measurements, which rely on assumptions about gas composition and sensor equivalency, oxygen concentration is a fundamental requirement for ignition. Maintaining oxygen below a conservative LOC provides a clear safety margin, particularly in inerted systems where fuel concentration may vary widely. Oxygen analyzers are also generally insensitive to VOC composition and can respond rapidly to changes in inerting effectiveness, making them well suited for detecting loss of purge gas or air ingress.

Oxygen measurement is especially valuable under highly variable or poorly characterized fuel conditions, where calculating or measuring percent LEL becomes uncertain. In such cases, LOC-based control can simplify safety logic by focusing on a single parameter that is easier to define conservatively. This approach is widely supported by standards such as NFPA 69, which recognize oxygen concentration as a valid and robust basis for explosion prevention when properly designed.

However, the LOC is not a fixed value and represents a key tradeoff in oxygen-based flammability assessment. LOC depends on fuel type, mixture composition, inert gas used, temperature, pressure, and turbulence. In real industrial waste-gas streams containing multiple VOCs, the true LOC may be difficult to determine precisely. To compensate, systems often adopt conservative LOC values, which can reduce operational flexibility and increase inert gas consumption.

Another important limitation is that oxygen measurement alone provides no information about fuel loading. A system operating safely below the LOC may still contain high concentrations of combustible material, which can present risks during transient conditions such as startup, shutdown, maintenance, or loss of inerting. If oxygen concentration increases rapidly due to air ingress, a previously safe mixture can quickly become flammable before corrective action occurs. For this reason, oxygen analyzers

are most effective when combined with fast response times, reliable interlocks, and complementary fuel or flammability measurements.

In practice, oxygen analyzers provide a strong but incomplete picture of flammability risk. LOC-based control is highly effective for confirming inerting integrity and preventing sustained combustion, but it does not eliminate the need to understand fuel behavior or transient hazards.

The following Table II shows a comparison of all technologies, and their benefits/tradeoffs:

The most robust approach is to integrate oxygen measurement with conservative LOC setpoints, along with complementary flammability or fuel concentration monitoring, and system-level safety logic that accounts for upset conditions.

Analyzer placement and reliability is also an important strategy for mitigating flammability issues. Analyzers must be located where they accurately measure the best representative sample of the gas entering critical equipment, such as regenerative thermal oxidizers. Sampling delays, condensation, or analyzer drift can undermine the assumed safety margin. Redundancy, validation, and regular functional testing are therefore essential elements of any oxygen-based safety system.

Technology	Measurement Principle	O <sub>2</sub> Sensitivity	VOC Composition Sensitivity	Key Strengths	Key Limitations / Tradeoffs	Typical Use in Inerted Systems
Catalytic Bead (LEL)	Oxidation of combustibles on heated catalyst; temperature rise proportional to fuel	High – requires O <sub>2</sub>	Moderate; relies on equivalency	Simple, fast response in air; widely used	Under-responds in low O <sub>2</sub> ; catalyst poisoning; misleading low LEL readings	Generally unsuitable unless O <sub>2</sub> is verified
Infrared (IR)	IR absorption by hydrocarbon bonds	Low–Moderate	High; gas-specific calibration	Independent of oxidation; stable in low O <sub>2</sub>	Equivalency errors in mixed VOCs; possible CO <sub>2</sub> interference	Fuel concentration trending
Flame Ionization Detector (FID)	Ionization of hydrocarbons in H <sub>2</sub> flame; signal ∝ total carbon	Low (independent of sample O <sub>2</sub> )	High; measures total hydrocarbons	Very sensitive; robust in inerted streams	Not a flammability measure; requires H <sub>2</sub> ; no LOC awareness	VOC loading and trend analysis
PrexEx Flame Temperature (FTA)	Change in flame temperature from combusting sample gas	Low (self-contained flame)	Low; uniform response to mixtures	Direct flammability indication; effective for variable VOCs; fail-safe diagnostics	Requires fuel and flame management; interpretation needed near LOC	Direct %LFL indication
Oxygen Analyzer	Direct O <sub>2</sub> concentration measurement	N/A	None	Direct link to combustion physics; fuel-independent	LOC varies with fuel, temperature, pressure; no fuel loading info	LOC-based inerting control

**Table II:** Compares common analyzer technologies used in inerted gas applications and highlights the tradeoffs between fuel concentration, flammability indication, and oxygen-based control.

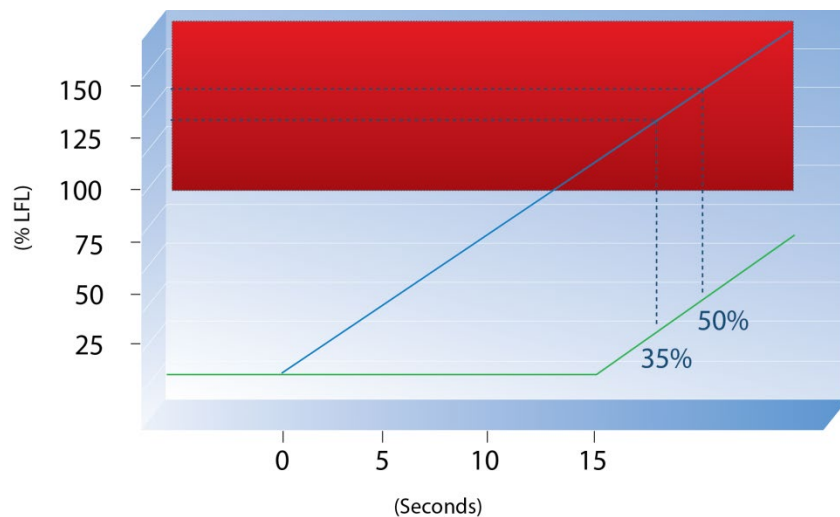
## ALARM MANAGEMENT AND SAFETY INTERLOCKS

Alarm management and safety interlocks form the critical link between flammability measurement and protective action in inerted process systems. Since flammability

measurements in low-oxygen, complex gas environments can involve uncertainty, alarm and interlock design must account for both sensor limitations and transient process behavior. Effective systems prioritize timely risk mitigation over precise quantification of flammability (speed of response vs. accuracy is critical in explosion prevention).

In addition to an analyzer response time, it is important to consider the sample line going to the analyzer to provide the complete sample transport time. The sample tubing must be as short as possible.

The following figure shows the importance of response time in avoiding critical events.



**Figure 6:** The sample delivery line and the response time of some analyzer produce a 15 second delay. By the time the analyzer activated its warning alarm set at 35% LFL, the true concentration in the process is already above 130% LFL.

Alarm setpoints should therefore be established conservatively and based on credible worst-case assumptions rather than nominal explosive limits. In inerted systems, reliance on air-based lower flammable limit (LFL) values or calculated thresholds without appropriate margin can create a false sense of security. Setpoints are commonly selected well below flammable conditions to provide adequate time for corrective action, particularly in high-temperature applications such as regenerative thermal oxidizers. Where oxygen-based control is used, limiting oxygen concentration (LOC) values should incorporate conservative safety factors to account for variability in fuel composition, temperature, and pressure.

Safety interlocks should be designed to respond automatically to conditions that indicate increasing flammability risk or loss of protective barriers. Typical interlock actions include initiating inert gas purge, reducing or isolating process flow, or executing controlled shutdown sequences. Interlocks should be independent of routine control functions where possible and designed to fail to a safe state in the event of power loss, signal failure, or

analyzer fault. Clear definition of interlock logic and reset conditions is essential to avoid unintended or unsafe operation.

The interaction between alarms and operator response must also be carefully managed. Excessive or poorly configured alarms can lead to nuisance conditions that desensitize operators and reduce overall effectiveness. Alarm rationalization practices should be applied to ensure that each alarm represents a meaningful deviation requiring operator awareness or action. Distinct separation between advisory alarms and shutdown-level interlocks helps maintain clarity during abnormal or upset conditions.

Reliability of alarm and interlock systems depends on the integrity of the underlying measurements. Analyzer health diagnostics, fault detection, and validation routines should be incorporated into the safety logic to prevent reliance on failed or degraded sensors. Redundant or diverse measurements can further enhance reliability, particularly where the consequences of failure are severe. Periodic testing of alarms, interlocks, and purge functions is necessary to confirm that protective actions occur as intended under realistic conditions.

Ultimately, alarm management and safety interlocks must be viewed as part of a broader flammability risk management strategy rather than as standalone safeguards. When conservative setpoints, appropriate interlock actions, reliable measurements, and trained operators are combined, these systems provide an effective defense against ignition hazards in inerted industrial gas streams. This layered approach is especially important in dynamic applications such as regenerative thermal oxidizers, where operating conditions and risk profiles can change rapidly.

## **CASE CONSIDERATIONS: REGENERATIVE THERMAL OXIDIZERS**

Regenerative Thermal Oxidizers (RTOs) are widely used for the destruction of VOCs in industrial waste-gas streams and represent a class of equipment where flammability measurement is particularly critical. RTOs routinely handle combustible mixtures at elevated temperatures and often operate with variable flow and composition. While these systems are designed to safely oxidize VOCs, their thermal environment and internal geometry can amplify the consequences of inaccurate flammability assessment.

Flammability risk in RTO systems is not uniform across all operating conditions. Steady-state operation may present relatively stable and predictable gas composition, while transient conditions—such as startup, shutdown, bed switching, or process upsets—can produce rapid changes in VOC concentration and oxygen content. During these periods, waste-gas streams may temporarily approach or exceed flammability thresholds before corrective action can occur. Reliable and timely measurement is therefore essential to ensure that interlocks and alarms respond appropriately.

Inerting is frequently applied upstream of RTOs to maintain oxygen concentrations below flammable levels and to provide an additional layer of protection. However, the interaction between inert gas dilution, variable VOC loading, and elevated temperature complicates both flammability behavior and measurement interpretation. Oxygen concentration alone may confirm inerting integrity, but it does not provide visibility into fuel loading, while fuel-based measurements may not accurately reflect ignition risk in low-oxygen environments. These limitations underscore the importance of understanding how measurement technologies behave under RTO operating conditions.

Analyzer placement and sampling design are also critical in RTO applications. Measurement points must be selected to represent the gas entering the combustion chamber rather than localized or diluted regions. Sampling systems must be designed to withstand high temperatures, prevent condensation of heavier hydrocarbons, and minimize transport delay, particularly during transient events. Inadequate sampling can lead to delayed or misleading measurements that compromise protective logic.

The following table summarizes common RTO operating conditions and illustrates how transient behavior can influence both flammability risk and the implication of different measurement philosophies.

**Table 2. Flammability Measurement Considerations During Typical RTO Operating Conditions**

RTO Operating Condition	Typical Process Characteristics	Primary Flammability Concerns	Measurement Implications
Startup	Rapid temperature increase; unstable flow; variable VOC loading	Transient approach to flammable conditions before steady-state control is achieved	Fast response and conservative interlocks required; sampling lag can mask short-duration excursions
Steady-State Operation	Relatively stable temperature, flow, and composition	Sustained operation near design limits if process loading increases	Continuous monitoring required; reliance on single-parameter measurement may mask gradual risk escalation
Bed Switching / Valve Sequencing	Short-duration flow and pressure disturbances	Localized composition changes; potential dilution or enrichment effects	Measurement location and response time become critical to avoid misleading readings
Process Upset / Batch Release	Sudden increase in VOC concentration or air ingress	Rapid transition toward flammable conditions	Redundant or complementary measurements improve detection reliability
Shutdown	Declining temperature; changing flow paths; possible air intrusion	Loss of inerting margin as oxygen increases	Oxygen measurement <u>critical</u> ; fuel measurements alone may be insufficient

**TABLE II:** Flammability Measurement Considerations During Typical RTO Operating Cycle

Effective RTO safety strategies typically rely on a combination of measurement approaches rather than a single parameter. Oxygen analyzers are commonly used to verify that operation remains below a conservative limiting oxygen concentration, while flammability or fuel concentration analyzers provide additional assurance during abnormal or transitional conditions. Integrating these measurements with well-defined alarm setpoints, automated shutdowns, and purge sequences allows RTO systems to maintain operation well below explosive limits. This layered approach reflects the reality that flammability risk in RTOs is a dynamic, system-level concern that cannot be addressed by any single measurement in isolation.

## **STRATEGIES FOR IMPROVING DETECTION RELIABILITY**

Improving the reliability of flammability detection in inerted process gas streams requires a system-level approach that accounts for sensor limitations, process variability, and transient operating conditions. No single analyzer technology can fully characterize flammability risk under all conditions, particularly in applications involving complex VOC mixtures, low oxygen concentrations, and elevated temperatures. Effective strategies therefore focus on combining complementary measurements, conservative design assumptions, and robust safety logic.

A key element of reliable detection is matching analyzer technology to the specific process conditions. Oxygen-dependent sensors should not be relied upon in environments where oxygen concentration is intentionally reduced or subject to rapid change. Additionally, fuel-based or flammability-based measurements must be selected with an understanding of how gas composition, inert dilution, and temperature influence sensor response. Validation of analyzer performance under representative operating conditions, including transient scenarios, is essential before relying on measurement data for safety decisions.

Multi-parameter measurement strategies significantly improve reliability by reducing dependence on any single assumption. Combining oxygen analyzers with flammability or fuel concentration measurements provides both confirmation of inerting effectiveness and visibility into combustible loading. For example, maintaining oxygen below a conservative limiting oxygen concentration (LOC) establishes a fundamental barrier to ignition, while independent monitoring of flammability or VOC concentration provides additional protection during upsets or loss of inerting. Such layered approaches are particularly effective in high-risk equipment such as regenerative thermal oxidizers.

Sampling system design is equally critical to detection reliability. Sample probes must be located where they accurately represent the gas entering critical equipment, and sampling lines should be designed to minimize lag, condensation, and adsorption losses. Heated sampling systems, short transport distances, and well-controlled flow rates help ensure that measured values reflect real-time process conditions. Inadequate sampling design can negate the benefits of even the most advanced analyzer technologies.

Alarm management and safety interlocks must be designed to reflect the inherent uncertainty in flammability measurements. Alarm setpoints should incorporate conservative margins rather than relying on nominal explosive limits or calculated thresholds. Automated shutdowns, purge sequences, and interlocks should be triggered by credible indicators of increasing risk, and nuisance alarms should be minimized to preserve operator confidence. Where applicable, functional safety principles can be applied to define performance requirements and verification practices.

Finally, improving detection reliability depends on operator understanding and procedural discipline. Operators and engineers must understand what a given measurement does—and does not—represent, particularly in inerted systems where conventional interpretations of percent LFL may not apply. Clear documentation, training, and periodic system reviews help ensure that flammability monitoring remains effective as process conditions evolve. When flammability detection is treated as an integrated element of process safety rather than a standalone measurement point, safety, product throughput and energy optimization are achieved.

## REFERENCES

- *Minimize the Risk of Flammable Materials*, AIChE.org/CEP, Daniel Crow, April 2012, [20120428.pdf](#)
- *Understanding NFPA-86, Safety Ventilation and Continuous Monitoring*, Control Instruments Corporation, NFPA-86-2023
- The limiting oxygen concentration and flammability limits of gases and gas mixtures, NIOSH, Isaac A. Zlochower; [cdc-2017](#)
- NFPA-69 2024 Edition