# UNDERSTANDING COMBUSTIBLE GASES IN TRANSFORMERS, LTCS, AND OCBS

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## ABSTRACT

Combustible gases generated from thermal and electrical incipient faults can accumulate in the headspace of liquid-filled electrical equipment, including transformers, on-load tap changers (OLTCs), and oil circuit breakers (OCBs). While gas accumulation is a common occurrence that has been managed for over a century, certain conditions can result in combustible gas concentrations exceeding the Lower Explosive Limit (LEL), creating potential hazards to both equipment and personnel. This paper examines the fundamental principles governing combustible gas behavior in electrical equipment, including gas partitioning, Ostwald solubility coefficients, and the fire triangle concept. Through detailed analysis of various operational scenarios and the interaction between fuel, oxygen, and ignition sources, this work provides practical guidance for assessing flammability risks and implementing appropriate safety measures. The paper includes comprehensive tables of LEL/UEL values, solubility coefficients for various insulating liquids, and oxygen requirements for combustion support, offering utility operators and maintenance personnel essential tools for risk assessment and decision-making.

## INTRODUCTION

Thermal and electrical incipient faults in liquid-filled electrical equipment produce combustible gases that can accumulate in the headspace of transformers, on-load tap changers (OLTCs), and oil circuit breakers (OCBs). Additionally, oil and paper degradation processes generate carbon monoxide, while stray gassing can produce hydrogen, carbon monoxide, and various hydrocarbon gases. These gases partition from the insulating liquid into the gas space based on temperature, pressure, and the Ostwald solubility coefficients at the prevailing temperature. Even in transformers equipped with conservators containing bladders, gases can accumulate beneath the bladder as a bubble.

Although the Ostwald solubility coefficients for certain insulating liquids may differ slightly, gases produced in these liquids will partition to a gas space when available, regardless of the liquid type.

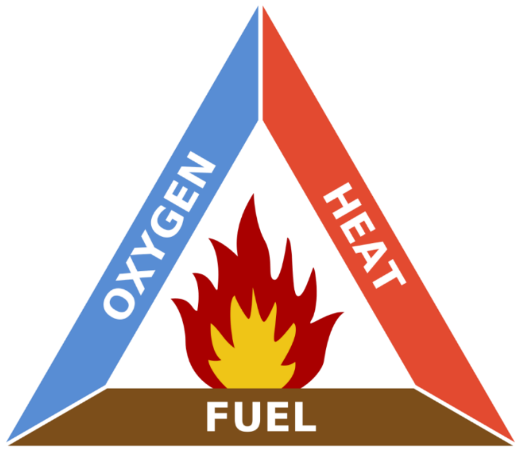
In most circumstances, the formation and migration of these gases to the headspace presents no significant concern, and transformer operators have successfully managed this phenomenon for more than 120 years. However, in rare cases, combustible gases can accumulate to concentrations exceeding the Lower Explosive Limit (LEL), resulting in potential hazards to both equipment and personnel. It is important to note that gas concentrations above the LEL do not automatically result in explosion or fire; other critical factors must be considered, which are discussed in detail throughout this paper.

### The Fire Triangle Concept

As stated in the introduction, circumstances where gas concentrations surpass the LEL do not automatically result in combustion. The accumulation of gases above the LEL represents only the fuel component. To create a combustible atmosphere, three elements must be present simultaneously:

1. **Fuel:** Combustible gases at concentrations above the LEL
2. **Oxidizer:** Oxygen (typically from air in our industry)
3. **Ignition Source:** Heat or spark of sufficient energy

This relationship is illustrated in Figure 1. It is critical to understand that this combustion scenario can only occur in the headspace, not beneath the oil surface.



From Smart Horizons Fire Training in UK

**Fire Triangle**
**Figure 1**

**Combustion and Explosion Scenarios**

Table 1 presents various scenarios in which explosion or combustion can occur (highlighted conditions). While not exhaustive, this table provides information on numerous situations commonly encountered in electrical equipment operation and maintenance.

**Table 1**
**Combustible Gas and Explosion/Combustion Scenarios**

| Situation | Condition 1 | Condition 2 | Condition 3 | Result |
|---|---|---|---|---|
| Scenario 1 | Gas above LEL | Free breathing OLTC or oil breaker | Arcing under the oil | No explosion/combustion |
| Scenario 2 | Gas above LEL | Free breathing LTC or oil breaker | Arcing above the oil | Explosion/combustion will occur |
| Scenario 3 | Gases below LEL | LTC or oil breaker - No matter if there is oxygen present or not, or ignition is present or not, nothing will happen | | No explosion/combustion |
| Scenario 4 | Gas above LEL | Sealed Transformer, no O2 present | Arcing under the oil | No explosion/combustion |
| Scenario 5 | Gas above LEL | Sealed Transformer, no O2 present | Arcing in the gas space | No explosion/combustion |
| Scenario 6 | Gas above LEL | Leaking or free breathing Transformer, O2 present | Arcing in the gas space | Explosion/Combustion will occur |
| Scenario 7 | Gas above LEL | Leaking or free breathing Transformer, O2 present | Arcing under the oil | No explosion/combustion |
| Scenario 8 | Gas below LEL | Transformer - No matter if there is oxygen present or not, or ignition is present or not, nothing will happen | | No explosion/combustion |
| Scenario 9 | Gases above LEL | Drum, pail, tote or tank – if not blanketed with inert gas than 02 will be present | No heat source | No explosion/combustion |
| Scenario 10 | Gases above LEL | Drum, pail, tote or tank – if not blanketed with inert gas | No heat source | No explosion/combustion |
| Scenario 11 | Gases above LEL | Drum, pail, tote or tank – if not blanketed with inert gas | Heat sources present | Explosion/Combustion will occur |
| Scenario 12 | Gases below LEL | Transformer - No matter if there is oxygen present or not, or ignition is present or not, nothing will happen | | No explosion/combustion |

Scenarios 2, 6, and 11 represent conditions where all three elements of the fire triangle are present, creating genuine combustion/explosion hazards.

### Lower and Upper Explosive Limits

Explosive limits were established decades ago for the mining, gas, and oil industries to protect personnel and equipment. Two critical thresholds define the flammable range:

- **LEL (Lower Explosive Limit):** The minimum concentration of a specific gas that will combust, given the presence of sufficient oxygen and an ignition source.
- **UEL (Upper Explosive Limit):** The maximum concentration of a specific gas above which combustion will not occur, even if oxygen and an ignition source are present.

The electrical equipment industry is primarily concerned with the LEL, as combustible gases from incipient faults and stray gassing can accumulate to reach and surpass this threshold. A mixture with insufficient fuel (below the LEL) is described as "too lean," while a mixture with excessive fuel and insufficient oxygen (above the UEL) is considered "too rich" for combustion.

Table 2 provides comprehensive information on the LELs, UELs, and limiting oxygen concentration (LOC) for gases of interest generated in liquid-filled electrical devices. While minor variations exist in the literature regarding these values, all sources provide reasonably consistent data.

**Table 2**
**Combustible Gas LELs and UELs Values at 1 atm**

| Gas | LEL, % | UEL, % | Concentration of Oxygen Needed, %* |
|---|---|---|---|
| Carbon Monoxide | 12.0 | 75.0 | 5 |
| Hydrogen | 4.0 | 75.0 | 4 |
| Methane | 4.4 | 16.4 | 12 |
| Ethane | 3.0 | 12.4 | 11 |
| Ethylene | 2.75 | 28.6 | 8.5 |
| Acetylene | 2.5 | 100 | 7 |
| Propane | 2.1 | 10.1 | 11.5 |
| Propene (propylene) | 2.0 | 11.1 | 10 |
| Butane | 1.86 | 8.41 | 12 |
| Butene (Butylene) | 1.98 | 9.65 | 11.5 |

*in oxygen and nitrogen systems

Although the terms "combustion" and "explosion" are often used interchangeably in this paper, there is an important distinction:

- **Flammability/Combustion:** A chemical reaction (burning) with oxygen that produces heat and light (fire), typically occurring at a relatively slower rate.
- **Explosion:** A sudden and rapid release of energy causing a pressure wave or shock wave, characterized by extremely fast reaction rates.

### Gas Partitioning and Ostwald Solubility Coefficients

To understand how the percentage values in Table 2 correlate to dissolved gas-in-oil analysis (DGA) results, the concepts of gas partitioning and Ostwald solubility coefficients require explanation. In equipment with a two-phase system—liquid and gas—such as most transformers (except those with bladders or completely filled with expandable tanks), most OLTCs, OCBs, and various storage containers, gases will equilibrate or partition between the liquid phase and the gas space above it based on temperature and pressure.

Not all gases partition to the same degree; each gas has a specific partitioning percentage known as the Ostwald solubility coefficient, which is highly repeatable under consistent conditions. These values are presented in Tables 3 and 4 for various insulating liquids at different temperatures.

**Important Note:** Modern dissolved gas-in-oil analysis, as performed in ASTM Method D3612C [1], utilizes the headspace method. This technique does not involve direct extraction of gases. Instead, the insulating liquid is injected into a sealed vial that has been purged with inert gas. The vial is then heated and agitated to expedite the partitioning of gases from the liquid phase to the headspace. A sample from the headspace is subsequently injected into a gas chromatograph for analysis.

**Table 3**
**Ostwald Solubility Coefficients at Standard Operating Temperature and Pressure (STP)**
**760 mm Mercury, 0°C**

| Gas | Mineral Oil [1] | Soybean Natural Ester [2] | Synthetic Ester [2] | Silicone [2] |
|---|---|---|---|---|
| Carbon Monoxide | 0.133 | 0.111 | 0.127 | 0.204 |
| Hydrogen | 0.0558 | 0.047 | 0.051 | 0.092 |
| Methane | 0.438 | 0.341 | 0.381 | 0.569 |
| Ethane | 2.59 | 2.16 | 2.18 | 3.1 |
| Ethylene | 1.76 | 1.69 | 1.87 | 2.18 |
| Acetylene | 1.22 | 2.68 | 4.38 | 2.04 |
| Propane | 11.0 | | | |
| Carbon dioxide | 1.17 | 1.54 | | |
| Nitrogen | 0.0968 | 0.0728 | 0.0872 | 0.157 |
| Oxygen | 0.179 | 0.134 | 0.152 | 0.266 |

**Interpretation:** Larger Ostwald solubility coefficients indicate higher solubility in oil and lower likelihood of partitioning to the gas space (e.g., ethane). Conversely, lower coefficients indicate greater likelihood of partitioning to the headspace (e.g., hydrogen).

**Table 4**
**Ostwald Solubility Coefficients at Standard Operating Temperature and Pressure (STP)**
**760 mm Mercury, 70°C**

| Gas | Mineral Oil [3] | Soybean Natural Ester [3] | Sunflower Natural Ester [3] | Synthetic Ester [3] | Silicone [3] |
|---|---|---|---|---|---|
| Carbon Monoxide | 0.140 | 0.148 | 0.097 | 0.143 | 0.199 |
| Hydrogen | 0.090 | 0.097 | 0.069 | 0.103 | 0.114 |
| Methane | 0.423 | 0.387 | 0.324 | 0.355 | 0.519 |
| Ethane | 1.979 | 1.677 | 1.550 | 1.504 | 1.997 |
| Ethylene | 1.401 | 1.389 | 1.261 | 1.310 | 1.518 |
| Acetylene | 0.998 | 1.763 | 1.495 | 2.459 | 1.448 |
| Propane | 7.008 | 4.041 | 4.278 | 4.087 | 8.539 |
| Propene (propylene) | 5.417 | 4.078 | 4.189 | 4.281 | 6.440 |
| Carbon dioxide | 0.892 | 1.187 | 1.055 | 1.365 | 1.078 |
| Nitrogen | 0.128 | 0.141 | 0.129 | 0.137 | 0.165 |
| Oxygen | 0.206 | 0.255 | 0.061 | 0.193 | 0.264 |

The Ostwald solubility coefficients, combined with the LEL values for each gas, can be used to determine the concentration of gas in oil that would partition to the gas space to create sufficient fuel for combustion. Based on the LEL levels in Table 2, the equivalent amount in µL/L (ppm) in the oil phase can be calculated.

**Conversion Process:**

1 Convert LEL percentage to μL/L in gas space: Direct percentage conversion based on 1,000,000 μL/L
2 Calculate equivalent concentration in oil: Multiply the gas space concentration by the Ostwald coefficient

**Formula:**

μL/L in oil = (μL/L in gas space) × Ostwald coefficient

**Calculation Examples**

**Example 1: Hydrogen**

- LEL in gas space: 4.0% = 40,000 μL/L
- Ostwald coefficient (mineral oil at 0°C): 0.0558
- **μL/L in oil = 40,000 × 0.0558 = 2,232 μL/L**

**Example 2: Acetylene**

- LEL in gas space: 2.5% = 25,000 μL/L
- Ostwald coefficient (mineral oil at 0°C): 1.22
- **μL/L in oil = 25,000 × 1.22 = 30,500 μL/L**

As demonstrated in Table 5, the concentration required in oil to reach the LEL varies significantly among gases. Hydrogen requires relatively low concentrations (2,232 μL/L), whereas gases with higher solubility, such as ethane, require much higher concentrations (77,700 μL/L). Even acetylene, considered the most critical combustible gas for fault diagnosis, requires substantial concentrations (30,500 μL/L) to reach the LEL.

**Table 5**
**Combustible Gas LELs and Conversion to μL/L at 20°C and 1 atm For Mineral Oil**

| Gas | LEL, % | Minimum amount needed in oil, uL/L |
|---|---|---|
| Carbon Monoxide | 12.0 | **15,960** |
| Hydrogen | 4.0 | **2,232** |
| Methane | 4.4 | **19,272** |
| Ethane | 3.0 | **77,700** |
| Ethylene | 2.75 | **48,400** |
| Acetylene | 2.5 | **30,500** |
| Propane | 2.1 | **231,000** |

The same calculations can be performed for alternative insulating liquids, as shown in Table 6.

**Table 6**
**Flammable Gas LELs and Conversion to μL/L at 20°C and 1 atm For Alternative Liquids**

| Gas | LEL, % | Minimum amount needed in Soybean NE, μL/L | Minimum amount needed in Synthetic Ester, μL/L | Minimum amount needed in Silicone, μL/L |
|---|---|---|---|---|
| Carbon Monoxide | 12.0 | 13,320 | 15,240 | 24,480 |
| Hydrogen | 4.0 | 1,880 | 2,040 | 3,680 |
| Methane | 4.4 | 15,004 | 16,764 | 25,036 |
| Ethane | 3.0 | 64,800 | 65,400 | 93,000 |
| Ethylene | 2.75 | 46,475 | 51,425 | 59,950 |
| Acetylene | 2.5 | 67,000 | 109,500 | 51,000 |

When determining whether sufficient fuel exists to exceed the LEL, either a single gas above its individual limit or multiple gases with additive effects can create a flammable condition [4]. Table 7 illustrates this calculation method. **If the cumulative percentage equals or exceeds 100%, sufficient fuel exists for potential combustion.**

**Table 7**
**Example: DGA and the Relationship to Flammability in Mineral Oil**

| Gas | LEL in μL/L | DGA Example, μL/L | Calculated % of Flammability |
|---|---|---|---|
| Carbon Monoxide | **15,960** | 400 | **2.5** |
| Hydrogen | **2,232** | 1,500 | **67.2** |
| Methane | **19,272** | 250 | **1.3** |
| Ethane | **77,700** | 124 | **0.2** |
| Ethylene | **48,400** | 8,200 | **16.9** |
| Acetylene | **30,500** | 3,800 | **12.5** |
| **Total Flammability/Combustion Percentage:** | | | **100.6** |

Several factors must be considered when interpreting flammability calculations:

- **Unmeasured Gases:** Routine DGA does not measure all combustible gases, including propane, propene, butane, butene, and others, which can contribute to the total flammability percentage.
- **Literature Variability:** Some variability exists in published LEL values for gases listed in Table 2 across various literature sources.
- **Temperature Effects:** Calculations assume 20°C; actual operating temperatures may differ significantly.
- **Pressure Effects:** Pressure variations can influence LEL values and gas partitioning behavior.

**Safety Recommendation:** As a precautionary measure, Doble Engineering Company recommends exercising caution once the cumulative flammability percentage reaches or exceeds **85%**, providing a safety margin for the factors listed above.

Doble Engineering Company has developed a comprehensive combustible gas calculator to assist users in determining whether a combustible gas fuel source exists based on DGA results. This tool is freely available to all interested parties. Currently, the calculator determines the total combustible gas concentration but does not calculate oxygen availability or assess ignition source presence (see Figure 2).

**Determination of a Combustible Gas Atmosphere**

*This determination is made at 25 degrees C and 760 mm Mercury (1 atmosphere)*

| | LEL in Oil, ppm (if oil is saturated with air) | Enter the Concentration of Each Gas from DGA Analysis in PPM | Flammability in Air, %[1] | Flammability in Headspace, %[2] |
|---|---|---|---|---|
| Hydrogen | 2232 | 32 | 1.4 | 1.8 |
| Methane | 23,214 | 11 | 0.0 | 0.1 |
| Carbon Monoxide | 16,625 | 43 | 0.3 | 0.3 |
| Ethane | 77,700 | 2.8 | 0.0 | 0.0 |
| Ethylene | 54,560 | 27 | 0.0 | 0.1 |
| Acetylene | 30,500 | 49 | 0.2 | 0.2 |
| Oxygen | | 283 | | |
| Nitrogen | | 77,600 | | |
| Carbon Dioxide | | 926 | | |
| | | | 2.0 | 2.4 |

*IMPORTANT: If total value is greater than 100% an explosive atmosphere may exist!! For safety purposes leave a margin of at least 15%.*

[1]The flammabilty in air is used if the oil is saturated with air, in a closed chamber, for example oil in a drum from a free-breathing LTC.

[2]The flammabilty in the headspace would be used to estimate the flammability of gas in the gas blanket of a transformer. If there is insuffient oxygen then it would not be a flammable mixture.

**These calculations are used for estimating the flammability and does not consider effects of changing temperature and pressure or the presence of other combustible gases that have not been measured. To meet government regulations or industrial safety practices direct measurements should be made on the gas space.**

**Example of Combustible Gas Calculator**
**Figure 2**

### The Role of Oxygen Concentration in the Fire Triangle

As shown in Table 2, most combustible gases require relatively modest oxygen concentrations to support flammability and combustion. Similar to combustible gases, the Ostwald solubility coefficients can be applied to oxygen to calculate the required concentration in the oil phase.

Using the limiting oxygen concentration (LOC) values from Table 2 and the oxygen solubility coefficients from Table 3, the minimum oxygen concentration in oil required to support flammability/combustion can be calculated, as presented in Table 8.

**Table 8**
**Minimum Amount of Oxygen in the Insulating Liquid to Support Flammability/Combustion at STP**

| Gas | Concentration of Oxygen Needed in gas space, % | µL/L in gas space, minimum | Minimum µL/L in Mineral oil | Minimum µL/L in Natural Ester | Minimum µL/L in Synthetic Ester | Minimum µL/L in Silicone |
|---|---|---|---|---|---|---|
| Carbon Monoxide | 5 | 50,000 | 8,950 | 6,700 | 7,600 | 13,300 |
| Hydrogen | 4 | 40,000 | 7,160 | 5,360 | 6,080 | 10,640 |
| Methane | 12 | 120,000 | 21,480 | 16,080 | 18,240 | 31,920 |
| Ethane | 11 | 110,000 | 19,690 | 14,740 | 16,720 | 29,260 |
| Ethylene | 8.5 | 85,000 | 15,215 | 11,390 | 12,920 | 22,610 |
| Acetylene | 7 | 70,000 | 12,530 | 9,380 | 10,640 | 18,620 |
| Propane | 11.5 | 115,000 | 20,585 | 15,410 | 17,480 | 30,590 |
| Propene (propylene) | 10 | 100,000 | 17,900 | 13,400 | 15,200 | 26,600 |
| Butane | 12 | 120,000 | 21,480 | 16,080 | 18,240 | 31,920 |
| Butene (Butylene) | 11.5 | 115,000 | 20,585 | 15,410 | 17,480 | 30,590 |

Any free-breathing transformer, LTC, or OCB will have sufficient oxygen to support combustion, as these systems have direct contact with atmospheric air containing approximately 21% oxygen.

Sealed transformers may or may not have sufficient oxygen, depending on: - The integrity of the seal - The type of insulating liquid present (which controls oxygen solubility, as shown in Table 8) - The initial oxygen content at the time of sealing - Any subsequent oxygen ingress through seal degradation

Using hydrogen as an illustrative example:

- **Fuel Requirement (from Table 5):** Minimum of 2,232 μL/L of hydrogen in mineral oil to meet the LEL in the gas space
- **Oxygen Requirement (from Table 8):** Approximately 7,160 μL/L of oxygen in mineral oil to support combustion
- **Ignition Source:** Heat or spark of sufficient energy to initiate the reaction

All three elements must be present simultaneously in the gas space for combustion to occur.

### The Role of an Ignition or Heat Source in the Fire Triangle

Ignition sources or heat in electrical equipment environments can include:

4. **Open Flames:** Maintenance activities, welding operations, or external fires
5. **Mechanical Sparks:** Generated by tools, equipment, or mechanical failures
6. **Electrical Arcs:** From equipment operation, particularly in OLTCs and OCBs during switching operations
7. **Static Electricity:** Electrostatic discharge (ESD) from unbonded or ungrounded systems
8. **Lit Cigarettes or Smoking Materials:** In maintenance areas
9. **Hot Surfaces:** Equipment surfaces that have reached a gas's autoignition temperature
10. **Electrical Test Equipment:** Devices that generate heat or arcing during diagnostic procedures

The ignition or heat source must be located above the oil surface. Arcs or discharges occurring beneath the oil will not cause combustion in the gas space.

Static discharges during oil processing [5] represent one of the most hazardous situations for combustion and explosion. Unbonded hoses, drums, tanks, and ungrounded systems can accumulate electrostatic charges that may suddenly discharge, potentially causing not only combustion but violent explosions.

Reference [5] provides valuable information on safe pumping practices, splash-filling hazards, and methods to avoid static discharge. Doble Engineering Company presented a comprehensive tutorial on this subject in 2016 [6], which is available on the MyDoble Resource Center for additional information.

Great care should be exercised when transferring oil. It is preferable to remove combustible gases from equipment before oil transfer operations using either: - Vacuum treatment - Sparging with an inert gas (nitrogen or argon)

Autoignition temperatures represent the minimum temperature at which a gas will spontaneously ignite without an external ignition source. These temperatures are critical considerations when assessing combustible environments. Table 9 provides autoignition temperatures for gases of interest in the electrical equipment industry [7].

**Table 9**
**Autoignition Temperatures for Gases [7]**

| Gas | Autoignition Temperature, °C |
|---|---|
| Hydrogen | 520 |
| Methane | 537 |
| Ethane | 472 |
| Ethylene | 450 |
| Acetylene | 305 |
| Propane | 450 |
| Propene (Propylene) | 455 |
| Butane | 288 |
| Butene (Butylene) | 385 |

The temperatures listed in Table 9 are rarely encountered in the gas space of electrical equipment, with the following exceptions:

- **Hot Spots in Transformers:** Localized areas of excessive heating due to faults
- **Contact Making and Breaking:** In OLTCs or OCBs during switching operations
- **Fault Locations:** At the point of incipient electrical or thermal faults

In most cases, heat dissipates rapidly before reaching the gas space, significantly reducing the temperature by the time it could interact with combustible gases. Consequently, autoignition rarely poses a threat under normal operating conditions. However, exceptions exist, and each situation must be evaluated individually.

### Temperature and Pressure Effects on Explosive Limits

Both temperature and pressure significantly impact explosive limits, and these effects must be considered in comprehensive safety assessments.

Generally, an increase in temperature widens the flammable range:

- **LEL Effect:** Temperature increases tend to lower the LEL (less gas is needed to form a flammable mixture)
- **UEL Effect:** Temperature increases tend to raise the UEL (higher concentrations remain flammable)
- **Mechanism:** Higher temperatures increase molecular energy, making gases easier to ignite and sustaining combustion over a broader concentration range

An increase in pressure typically widens the flammable range:

- **LEL Effect:** Pressure increases have minimal effect on LEL for most gases
- **UEL Effect:** The UEL increases significantly with pressure for many gases

The values presented in this paper are based on standard temperature and pressure (STP) conditions. Actual operating conditions may differ significantly, and appropriate adjustments should be made when conducting risk assessments.

## CONCLUSIONS

The accumulation of combustible gases in liquid-filled electrical equipment represents a manageable risk when understood within the framework of the fire triangle. Key conclusions include:

- **Three Elements Required:** Flammability/combustion or explosion requires the simultaneous presence of fuel (combustible gases above LEL), oxygen, and an ignition source. The absence of any single element prevents combustion.

- **Gas Partitioning Behavior:** Gases partition predictably between liquid and gas phases according to their Ostwald solubility coefficients, which vary with temperature, pressure, and insulating liquid type.

- **Flammability Assessment:** The cumulative flammability/combustibility percentage, calculated from DGA results and LEL values, provides a quantitative method for assessing fuel availability. A safety threshold of 85% is recommended to account for unmeasured gases and environmental variables.

- **Equipment-Specific Risks:**

    1. Free-breathing equipment always has sufficient oxygen for combustion if fuel and ignition are present
    2. Sealed equipment may lack sufficient oxygen, depending on seal integrity and liquid type
    3. Ignition sources must be above the oil surface to initiate combustion in the gas space

- **Static Discharge Hazards:** Oil transfer operations present significant risks due to static electricity generation. Proper grounding, bonding, and degassing procedures are essential safety measures.

- **Temperature and Pressure Considerations:** Operating conditions significantly affect explosive limits, and standard values should be adjusted accordingly for accurate risk assessment.

- **Practical Risk Mitigation:** The most effective strategies include:
    1. Regular DGA monitoring to track combustible gas accumulation
    2. Possible degassing operations when approaching flammability thresholds (case by case basis)
    3. Proper grounding and bonding during oil handling
    4. Elimination of ignition sources in areas with elevated combustible gas concentrations
    5. Use of inert gas blanketing for storage containers and during maintenance (Caution: Asphyxiation may occur)

The electrical equipment industry has successfully managed combustible gas risks for over 120 years. With proper understanding of the fire triangle principles and appropriate precautions, this risk remains controllable.

Equipment operators and maintenance personnel should utilize available tools, such as the Doble Engineering combustible gas calculator, combined with the principles outlined in this paper, to make informed decisions regarding equipment safety and operational procedures. When flammability thresholds approach critical levels, consultation with experienced diagnostics specialists is strongly recommended.

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## BIOGRAPHY

Lance Lewand has been in the utility industry for 40 years. First with a transformer service company and then with Doble Engineering for the past 33 years. He is the R&D and Technical Director for the Insulating Doble Insulating Materials Laboratories. Since joining Doble in 1992, Mr. Lewand has published over 85 technical papers pertaining to testing and sampling of electrical insulating materials and laboratory diagnostics.

Mr. Lewand received his Bachelor of Science degree from St. Mary's College of Maryland. He is actively involved in professional organizations including the American Chemical Society, a representative of the U.S. National Committee for TC10 of the International Electrotechnical Commission (IEC) and ISO TC28, ASTM D-27 since 1989, is the sub-committee chair 06 on Chemical Tests, former chair and vice-chair of D-27 on insulating liquids, and the recipient of the ASTM Award of Merit for Committee D-27, and is current Chair of ASTM D-27 committee on insulating liquids. He is also vice-chair of IEEE C57.146 and 155, and the chair for the new IEEE committees on cellulose degradation and corrosive sulfur. He is also involved in several CIGRE technical committees.