2026 International Conference of Doble Clients

Understanding Combustible Gas in Transformers, LTCs and OCBs

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March 29 – April 3, 2026

Boston, Massachusetts USA

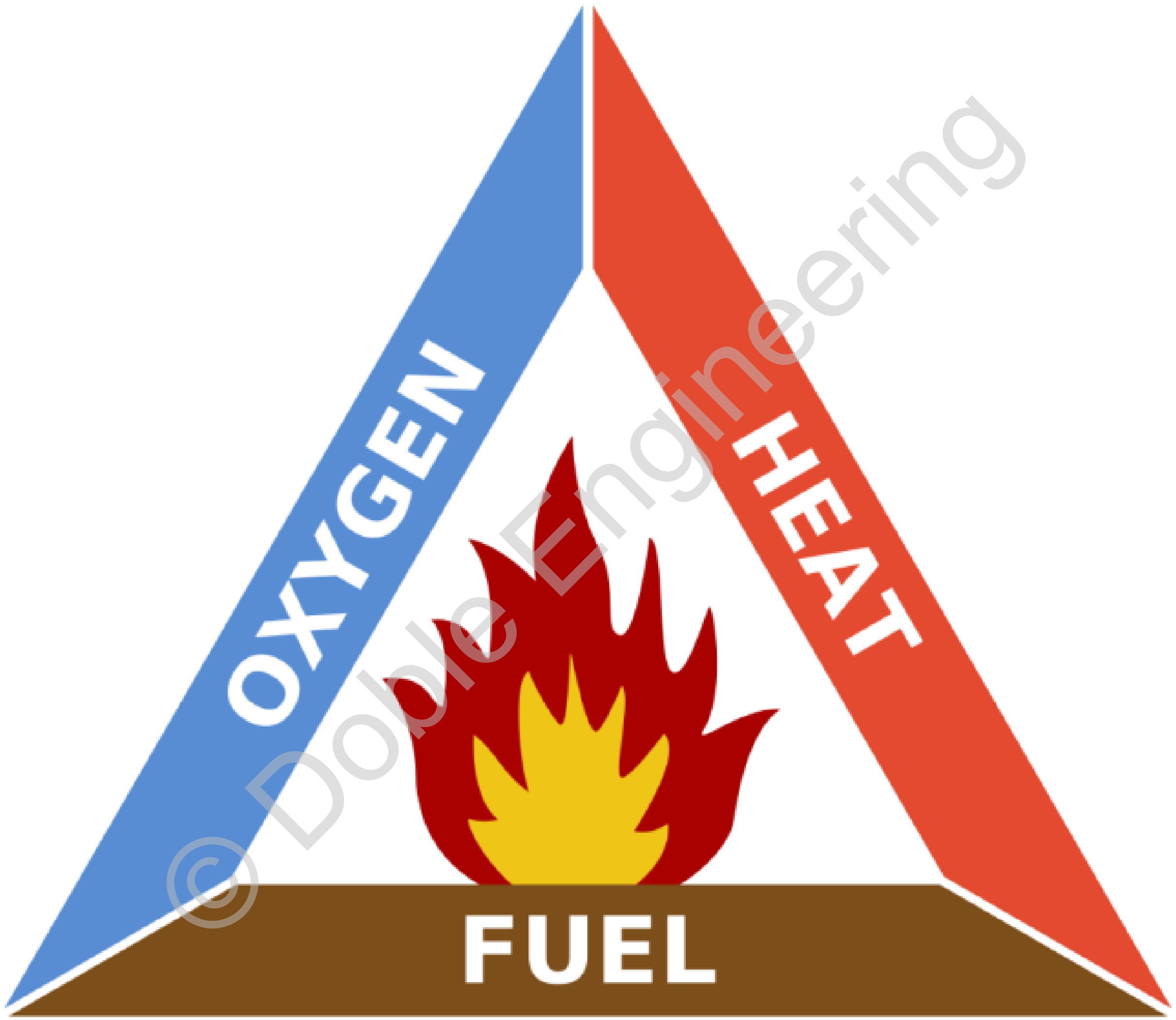
Introduction

- Thermal and electrical incipient faults or faults will create combustible gases
- So will stray gassing
- Paper degradation
- Gases created that are combustible
  - Hydrogen
  - Carbon monoxide
  - Methane
  - Ethane
  - Acetylene
  - Propane and Propene
  - Butane and Butene

Accumulation of Gases

- 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.
- 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.

Fire Triangle



Combustion and Explosion 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

More Listed in the Paper

Explosion

Part 1 of the Fire Triangle

FUEL

Lower and Upper Explosive Limits

- **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.

LEL and UEL Examples

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

Gas Partitioning – Ostwald Solubility Coefficients

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

Provided information at 70°C, can calculate at any temperature

Conversion Process

- Convert LEL percentage to µL/L in gas space: Direct percentage conversion based on 1,000,000 µL/L
- 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

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**

LELs in 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

LELs 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

DGA Example – 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

Factors to Consider

- **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 TCG Calculator

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.

Go To Spreadsheet

Part 2 of the Fire Triangle

OXYGEN

Limiting Oxygen Concentration (LOC)

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.

Hydrogen as an 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.

Part 3 of the Fire Triangle

INGNITION OR HEAT SOURCE

Ignition Possibilities

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

Example During Electrical Testing

Start at 1:15

Additional Information

- 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 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.

- 2006 Reference provides valuable information on safe pumping practices, splash-filling hazards, and methods to avoid static discharge.

- Comprehensive tutorial on this subject was presented in 2016, which is available on the Doble Resource Center for additional information.

Autoignition Temperatures for Gases

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

High Temperatures

- **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.

Conclusions

- **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.

Conclusions

- **Equipment-Specific Risks:**
  - Free-breathing equipment always has sufficient oxygen for combustion if fuel and ignition are present
  - Sealed equipment may lack sufficient oxygen, depending on seal integrity and liquid type
  - 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.

Risk Mitigation

- Regular DGA monitoring to track combustible gas accumulation
- Possible degassing operations when approaching flammability thresholds (case by case basis)
- Proper grounding and bonding during oil handling
- Elimination of ignition sources in areas with elevated combustible gas concentrations
- Use of inert gas blanketing for storage containers and during maintenance (Caution: Asphyxiation may occur)

Any Questions?