



AEROSPACE INFORMATION REPORT

AIR5933™

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Oxygen Sensor Technologies

RATIONALE

This SAE Aerospace Information Report is intended to provide reference and background information pertaining to oxygen sensor equipment as part of an overall document set to address oxygen equipment for aircraft.

AIR5933 has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

AIR5933 provides an overview of contemporary technologies (i.e., sensors) that measure the proportion of oxygen in a gas. The use of these sensors in the aerospace environment, with its special constraints, is discussed and papers/reports with detailed information are summarized and referenced.

The sensors are divided into expendable and non-expendable sensors. Expendable sensors are based on electrochemical properties, whereas non-expendable sensors rely on paramagnetic, photo-acoustic, electromagnetic, and laser spectroscopy properties.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR825/6A On-Board Oxygen Generating Systems (Molecular Sieve)

2.1.2 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA/DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

2.2 Abbreviations and Acronyms

PTFE	Polytetrafluoroethylene
MEMS	Microelectronic Mechanical System
OBIGGS	On-Board Inert Gas Generating System
OBOGS	On-Board Oxygen Generation System
PPB	Parts Per Billion
QTF	Quartz Micro Tuning Fork
QUEPAS	Quartz Enhanced Photo Acoustic Spectroscopy

2.3 Terminology

Terms used in the technical definitions throughout this document:

ABSORPTION: In physics, absorption of electromagnetic radiation is how matter (e.g., electrons bound in atoms) takes up a photon's energy.

AMPLITUDE: The amplitude of a periodic variable is a measure of its change over a single period (such as time or spatial period).

ANION: An anion (–) is an ion with more electrons than protons, giving it a net negative charge.

ANODE: An electrode through which the conventional current enters into a polarized electrical device.

AROMATIC: In organic chemistry, aromaticity is a property of cyclic (ring-shaped), planar (flat) structures with a ring of resonance bonds.

ATOM: Smallest constituent unit of ordinary matter that constitutes a chemical element.

CALIBRATION: The comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy.

CATHODE: Electrode from which a conventional electrical current leaves a polarized electrical device.

CATION: A cation (+) is an ion with fewer electrons than protons, giving it a positive charge.

DIAMAGNETISM: Materials which are repelled by a magnetic field and is a quantum mechanical effect that occurs in all materials.

DIFFUSION: Net movement of a substance (e.g., gas, liquid, etc.) from an area of high concentration to an area of low concentration driven by a concentration gradient.

DIODE: Two-terminal electronic component that conducts current primarily in one direction with low resistance in one direction and high resistance in the other.

DYE: Colored substance that chemically bonds to the substrate to which it is applied.

ELECTROCHEMICAL CELL: A device capable of generating electrical energy from chemical reactions or using electrical energy to cause chemical reactions.

ELECTRODE: An electrical conductor used to make contact with a nonmetallic part of a circuit.

ELECTROLYTE: A substance that produces an electrically conducting solution when dissolved in a polar solvent, such as water.

EMISSION: Release of wave or particle radiation by atoms, molecules, ions, liquids, or solids.

EVACUATED: Containing a vacuum.

EXCITATION: An excited state of an atom, molecule, or nucleus in any quantum state that has a higher energy than the ground state.

FLUORESCENCE: The emission of light by a substance that has absorbed light or other electromagnetic radiation.

FUEL CELL: An electrochemical cell that converts the chemical energy of a fuel and an oxidizing agent into electricity through redox reactions.

HERMETIC SEAL: Any type of sealing that makes a given object airtight (preventing the passage of air, oxygen, or other gases).

ION: An atom or molecule with a net electrical charge.

INTERFERENCE: An effect caused by gases which are also paramagnetic; their presence in the gas stream can cause a false reading.

LAMBDA PROBE: Zirconium dioxide, lambda sensor is based on a solid-state electrochemical fuel cell (Nernst cell) with two electrodes providing an output voltage corresponding to the quantity of oxygen in the measured gas relative to that in the atmosphere.

LASER: A device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation ("light amplification by stimulated emission of radiation").

LAYER: A single thickness of some material covering a surface.

LIFETIME: A product's expected time in use between point of sale and point of discard.

LUMINESCENCE: A photometric spontaneous emission of visible light by a substance not resulting from heat; measured in candela per square meter (cd/m^2).

MEMBRANE: A selective barrier allowing molecules, ions, or other small particles to pass through but stops others.

MAGNETO-ACOUSTIC WAVE: A longitudinal wave of ions and electrons in a magnetized plasma propagating perpendicular to the stationary magnetic field.

MOLAR MASS: The mass of a sample of that compound divided by the amount of substance in that sample, measured in moles.

MEDIUM: The nature of the surrounding environment (e.g., solid, liquid, gas, vacuum, or a specific substance).

NUCLEUS: The very dense central region of elementary particles and atomic nuclei, e.g., an atom.

OPTICAL: Using the behavior and properties of light, including its interactions with matter, and the construction of instruments that use or detect light.

OXYGEN PUMP: An ion oxygen pump based on a planar zirconia element and/or an electrochemical gas pump.

PARAMAGNETIC: Paramagnetic materials are weakly attracted by an externally applied magnetic field, and form internal, induced magnetic fields in the direction of the applied magnetic field.

PERMEABLE: Ability of a gas or vapor to pass through a solid substance.

PHOSPHORESCENCE: Type of photoluminescence related to fluorescence, but does not immediately re-emit the radiation it absorbs.

PHOTODIODE: A semiconductor device that converts light into an electrical current.

PIEZO: Piezoelectricity is the electric charge that accumulates in certain solid materials in response to applied mechanical stress.

PORPHYRIN: A group of heterocyclic macrocycle aromatic organic compounds.

PH-VALUE: The negative of the base 10 logarithm of the molar of hydrogen ions in a solution; a scale used to measure the acidity (acid) or alkalinity (basic) of a water-based solution.

PROBE: A physical device used to connect electronic test equipment to a device under test.

PYREX GLASS: A brand introduced by Corning Inc. in 1915 for a line of clear, low-thermal-expansion borosilicate glass used for laboratory glassware.

QUENCHER: Refers to any process that decreases the fluorescence intensity of a given substance.

SPECTROSCOPY: The interaction between matter and electromagnetic radiation (via electron spectroscopy, atomic spectroscopy, photo-acoustic spectroscopy, etc.).

SUBSTRATE: The material on which a process is conducted.

SPIN: A fundamental property of elementary particles in quantum mechanics and particle physics; spin is an intrinsic form of angular momentum carried by elementary particles, composite particles, and atomic nuclei.

SPECIES: A substance or ensemble composed of chemically identical molecular entities that can explore the same set of molecular energy levels on a characteristic or delineated time scale.

SPECTRUM: A condition that is not limited to a specific set of values but can vary, without steps, across a continuum; a pattern of absorption or emission of physical properties produced by a substance when subjected to energy (e.g., spectroscopy, etc.).

TRANSDUCER: A device that converts energy from one form to another. A transducer typically converts a signal in one form of energy to a signal in another.

TUNABLE LASER: A laser whose wavelength can be altered in a controlled manner.

ULTRASONIC: Sound waves with frequencies higher than the upper audible limit of human hearing.

VIBRATION: A mechanical phenomenon whereby oscillations occur about an equilibrium point.

WAVE LENGTH: The spatial period of a periodic wave-the distance over which the wave's shape repeats.

WAFER: A thin slice of semiconductor, such as a crystalline silicon, used for fabricating integrated circuits and serves as the substrate for microelectronic devices built in and upon the wafer.

3. INTRODUCTION

Oxygen sensors gain more and more importance as the technology continues to diversify and grow. Since oxygen sensors often serve life critical functions, they must be extremely reliable.

Oxygen sensors have important applications in medical and aerospace fields, e.g., for OBOGS and OBIGGS.

Much of the effort in developing of oxygen sensing technologies has been focused on medical applications, but this activity has also proven beneficial to aviation interests. In the aviation environment, it is important to have a measurement of oxygen concentration partial pressure reliable and safe enough for the intended application. Therefore, special attention should be given to: useful life, reliability and safety, accuracy, cross sensitivity, weight, and to basic environmental conditions such as temperature, altitude, humidity, vibration, and operational shocks (RTCA/DO-160).

In general, the output signal of such a sensor is proportional to the oxygen concentration respective to partial pressure. AIR5933 provides an overview of different measuring principles.

Different principles for measuring oxygen concentration can be employed in sensor technologies, and the sensors themselves can be divided into expendable and non-expendable sensors. For each of the sensor types, several examples are provided. The measuring principle and sensor layout are described, as well as advantages and disadvantages. Expendable sensors which use electrochemical principles, such as the lambda probe, are discussed first, followed by non-expendable sensors which use electrochemical, paramagnetic, ultrasonic, and laser absorption principles.

The different measuring principles are analyzed and evaluated, with the intent to find a suitable oxygen sensor for airborne systems. In aviation environment, several environmental conditions are of enormous importance such as operating and ambient temperature, ambient pressure, altitude, as well as vibration and shock. Sensor lifetime for aircraft application should be compatible with the intended aircraft operating scenario.

4. MEASURING PRINCIPLES

As mentioned previously, there are two broad categories of oxygen sensor technology: expendable and non-expendable sensors.

4.1 Expendable Sensors

Expendable sensors are based on electrochemical reactions and fall into three different categories as described in the following subsections.

4.1.1 Amperometry Oxygen Sensor

The amperometry oxygen sensor is based on Clark's principle.

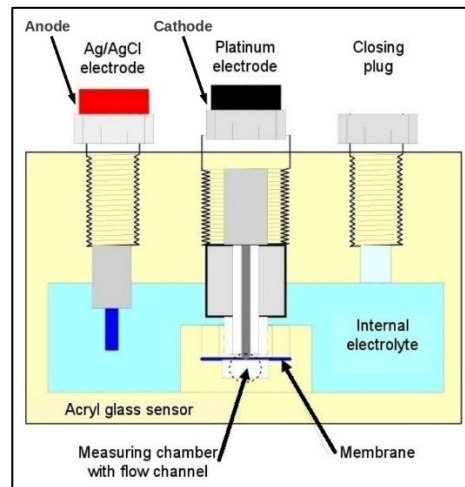
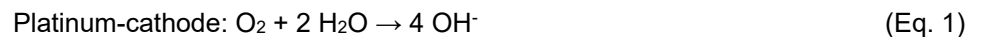


Figure 1 - Amperometric oxygen sensor [1]

After a negative voltage is applied to a system with two electrodes (Figure 1), oxygen is reduced at the cathode. In doing so, a threshold current flows between the cathode and anode proportional to the oxygen partial pressure in the gaseous medium in the measuring chamber. The medium is separated from the electrolyte within the measuring chamber by a PTFE-membrane (polytetrafluoroethylene). The diffusion of oxygen through the membrane controls the diffusion threshold current. At the anode, which is the Ag/AgCl-electrode, argentic (Ag) is oxidized. The reactions at the electrodes are summarized in the following equations:



This principle works well, but due to the consumptive behavior, its lifetime is limited to approximately 3 years. The PTFE-membrane is the lifetime limiting element. More specifications of this sensor are listed in Table 4.

4.1.2 Lambda Probe

The Lambda probe is based on an electrochemical cell with a solid matter electrolyte from zirconium oxide (ZrO_2) doped with 5% yttrium oxide. In this electrolyte, oxygen mobility reaches temperatures above 650°C (1202°F), high enough to conduct a current. Compared with non-doped ZrO_2 sensors, yttrium oxide doping increases the conductivity of oxygen molecules by introducing vacancies into the crystal lattice.

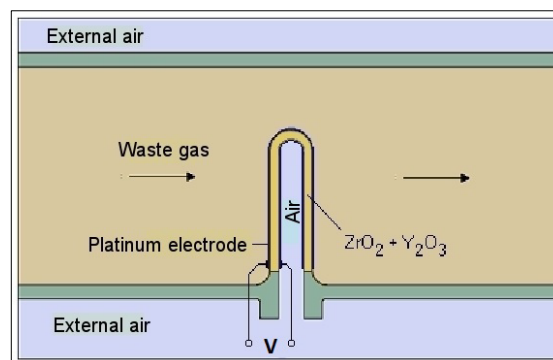


Figure 2 - Lambda probe [2]

The hollow lambda probe extends into the gas flow (Figure 2). The oxygen concentration in the hollow probe is constant (ambient air).

A platinum electrode surrounds the inner and outer walls of the probe and measures the voltage of the electrochemical cell. The voltage that is produced by the lambda probe is proportional to the oxygen partial pressure in the gas flow (Nernst):

$$V = \frac{RT}{4F} \ln \frac{p_{O_2}^{\text{reference gas}}}{p_{O_2}^{\text{measuring gas}}} \quad (\text{Eq.3})$$

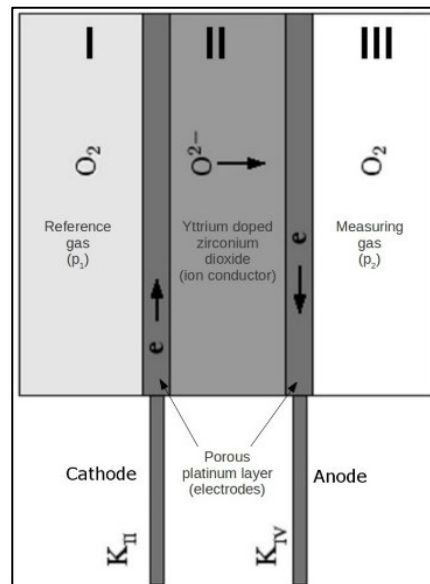


Figure 3 - Flow in the lambda probe [3]

Figure 3 shows a schematic of a lambda probe, separated into its three basic sections. The following reaction applies:



Due to the difference in partial pressure of the reference gas (section I) and the sample gas (section III), resulting from different gas concentrations, a diffusion of oxygen ions (O²⁻) through the ion conductor takes place. As molecular oxygen is electrically neutral in the gaseous state, it becomes negatively charged at the reference electrode (i.e., cathode).

The reference electrode (i.e., cathode) is between section I and section II; the platinum electrode (i.e., anode) is between section II and section III.

The molecular oxygen (O₂) from section I forms a boundary layer with the thin, porous platinum layer and an edge layer of section II. The oxygen then reacts as shown in Equation 4. The platinum electrode transfers electrons to the molecular oxygen (O₂), ionizing it. The formed 2 O²⁻ ions are embedded into the solid matter within section II. The 2 O²⁻ ions diffuse through the electrolyte and transfer their electrons to the platinum electrode (i.e., anode) between sections II and III, becoming neutralized as summarized in Equation 4.

This electrochemical process generates a voltage, which is dependent on ion diffusion through the electrolyte. The amount of ion diffusion is dependent on the difference in partial pressure between section I and section III.

The primary advantage of the lambda probe is the relatively low cost; the primary disadvantage is the limited lifetime. Typical automotive applications are approximately 20000 hours of operation. Additional disadvantages include toxicities and the operating temperatures are very high (400 °C to 650 °C). More specifications of this sensor are listed in Table 4.