AUTOMOTIVE OXYGEN SENSOR DEVELOPMENT
STAGES

There are thousands of Internet web pages that deal with oxygen sensors each trying to explain the total functionality of the oxygen sensor as it applies to the automobile industry. Each of these web pages take a ‘snapshot’ of the development of the sensor at a particular point in time. When the reader views just that web page, the information may have been current at the time of publication, but newer developments and more sophisticated oxygen sensors are designed rendering most web pages inaccurate or at best obsolete. The basics may be true, but the application and technology have changed tremendously since the initial introduction of the automotive oxygen sensor. This technical paper is written to summarize historical oxygen sensor developmental stages as well as explain CURRENT design functionality of the automotive exhaust gas oxygen sensor.

Background

In 1973 the oxygen sensor was developed mainly due to the 1970's EPA clean air regulations. In 1976 Volvo placed their first oxygen sensor in a production vehicle (believed to be a Volvo 240). United States federal law created the broad oxygen sensor demand in 1982. The USA IM-240 federal regulation came into being. That IM-240 federal regulation has been enhanced upward from the original OBD (on-board diagnostics) to the current OBD-II federal regulation (applicable for 2003 USA vehicles as well as vehicles around the world). Development and subsequent enhancements of oxygen sensors have seen a drastic change over this same time period. These changes have taken place as the automotive electronic circuitry that controls the overall fuel delivery system was enhanced.
Names Given to Oxygen Sensors

Oxygen sensors have been given various names over the years. Exhaust gas oxygen sensor (EGO); O2 (oxygen) Sensor; Lambda Sensor; Titania Oxygen Sensor; Zirconia Oxygen Sensor; Narrow-Band Oxygen Sensor; Heated Exhaust Gas Oxygen Sensor (HEGO) (heated planar-type introduced by Bosch in 1997); Universal Exhaust Gas Oxygen Sensor (UEGO) and Air/fuel Ratio or Wide-Band Oxygen Sensor (introduced by Bosch November 2001 and now available from NTK) are the more common names in the automotive industry.

EGO's were introduced with only one wire attached. The grounding was fully dependent upon the threaded portion of the oxygen sensor contacting the exhaust pipe in close proximity to the exhaust source. The physically placement was due to the fact that for the oxygen sensor to function properly, the temperature of the oxide (ceramic portion) had to be at least 600 degrees Fahrenheit. As the oxygen sensors were improved and the electronic control modules (ECM's) where able to read more circuitry, more wires were added to the oxygen sensor.

Next came the two-wire oxygen sensor. The second wire was the direct ground instead of depending upon the threaded sensor portion for a reliable ground. (We all know how much corrosion can occur in the area of the exhaust pipe!) Since it was known that the oxygen sensor did not become fully functional until the exhaust gases heated up the oxide (ceramic portion) to 600 degrees Fahrenheit, a ‘pre-heater’ was added. This allowed the oxygen sensor to perform quicker after the engine was started, thereby reducing the initial cold-start emissions. This also allowed the timing of functionality to be reduced from minutes to the 30-60 second time frame. This heater created a demand for the three-wire oxygen sensor. The first wire was the signal wire and the remaining two were the negative and positive battery voltage for the ‘pre-heater’. Today, most vehicles have four-wire oxygen sensors. One wire is the ‘signal wire’ (NTK black wire); the second wire is the dedicated ground for the signal (so as not to rely on the threaded portion contacting the exhaust pipe) (NTK gray wire). The third and fourth wires (usually the same color, NTK are white) are the ‘pre-heater’ negative and positive battery voltage. Five-wire oxygen sensors are available on a special order basis from most oxygen sensor manufacturers (NTK part number LZA03-E1). Some distributors of specific components that have a need for a five-wire oxygen sensor do have the five-wire oxygen sensors readily available. There are 02 sensors up to eight wires available for specific purposes. Each individual manufacturer of sensors should be contacted directly for the specifics of these sensors, as they are usually not readily available in the open automotive aftermarket. The development of ‘pre-heated’ oxygen sensors allowed them to be placed in the exhaust system further downstream. The most
common is before and after the catalytic converter to assist in measuring the effectiveness (and possible failure) of the converter itself.

The original zirconia oxygen sensors (known as narrow-band oxygen sensors) could not correlate an exact air/fuel ratio to the voltage output. The nominal voltage of 0.45 volts is considered stoichiometric for the desired air/fuel mixture of 14.7:1. The output voltage spectrum of the zirconia oxygen sensor is 0.0V to 1.1V (depending upon the manufacturer). When the ECU reads an output voltage as a result of ‘cross count’, the lower than 0.45 voltage is considered lean and more fuel is allowed through the fuel injector. Whereas, when the ECU reads an output voltage as a result of ‘cross count’, the higher than 0.45 voltage is considered rich and less fuel is allowed through the fuel injector. This ‘transition time’ is expected to cycle in about 50 to 100 milliseconds from rich to lean mixture and about 75 to 150 milliseconds from a lean to rich mixture. Therefore, the more ‘cross counts’ the oxygen sensor generated, the oxygen sensor is considered more efficient. (This higher ‘cross count’ is the norm for NTK zirconia oxygen sensors.) If the oxygen sensor is taking significantly longer to reverse readings, this is an indication that the sensor is getting sluggish and replacement is recommended.

**Aluminum Oxide**

Those individuals who have been in the spark plug industry for quite awhile are well familiar with the terminology of ‘alumina’ (http://ngkaz.home.att.net). This is the compound made up of 80-99% of aluminum oxide (Al2O3) and technically is the most important oxide material used in the spark plug industry considered the ‘heart’ of the spark plug. This oxide was chosen for a spark plug environment due to its properties of high strength and hardness, high resistance to wear and corrosion, high thermal conductivity, excellent insulation properties, excellent toughness and high temperature strength. Used in the harsh environment of the engine cylinder (where temperatures of in excess of 4,000 degrees occur), this oxide has proven itself superior over the years of the internal combustion engine.
**Titania Oxygen Sensors**

The remaining family of oxide ceramics found in “mother earth” are: magnesium oxide, aluminum titanate, zirconium oxide (ZrO2) and piezo ceramic. Aluminum titanate (derived from earth/dirt/soil known as rutile and anatase) (also known as Titanium dioxide, TiO2) was originally used in the production of exhaust gas oxygen sensors (EGO). This oxide does NOT have the ability to produce a self-voltage. Instead, in automotive oxygen sensor applications, a resistance is measured ranging from a low resistance of 1000 ohms (when the engine air/fuel mixture is too rich) to a high resistance of over 20,000 ohms (when the air/fuel mixture is considered too lean). This rapid change is read by the electronic control unit (ECU) or sometimes referred as the electronic control module (ECM) and that unit, in turn, generates its own voltage. This sometimes may confuse the automotive technician in thinking that the **titania oxygen sensor** “does generate a voltage” making it a **zirconia oxygen sensor**, when in reality the **titania oxygen sensor** truly CANNOT generate any voltage. The engine ECU supplies a base reference voltage of approximately one volt to the **titania oxygen sensor**. The ECU then reads the resulting voltage flowing through the sensor to monitor the air/fuel ratio. When the air/fuel mixture is rich, the resistance in the **titania oxygen sensor** drops at a fast rate and the sensor’s voltage signal (as generated by the ECU) is high. When the fuel mixture is lean, resistance in the **titania oxygen sensor** increases at a fast rate and the voltage signal read by the ECU drops drastically. This is when ‘cross counts’ become a major important factor in the effectiveness of any oxygen sensor. A good oxygen sensor should offer ‘cross counts’ of about one per second or in the case of NTK even more. Should the ‘cross counts’ be less than one per second; the **titania oxygen sensor** most likely is getting sluggish and replacement is recommended. At this point, the person selecting the correct oxygen sensor replacement must be reminded that should a vehicle be using the circuitry in the ECU/ECM for a **titania oxygen sensor**, care must be taken that the other oxygen sensor, **zirconia oxygen sensor**, is NOT accidentally installed in the vehicle. Obviously, these two are definitely NOT interchangeable! Some vehicle manuals will make reference to a ‘voltage reading’ when dealing with the **titania oxygen sensor**. This voltage reading as discussed in this technical paper in detail does not necessarily mean that the vehicle has a **zirconia oxygen sensor** installed. In the heated version of the **titania oxygen sensor**, the heater resistance is 4 to 7 ohms.
The question has arisen as to “why do automotive manufacturers still install the titania oxygen sensors as OEM”? The best response that can be uncovered is that titania oxygen sensors do not depend upon outside air for reference when doing its job. Therefore, in vehicles that are regularly used in harsh environments and off-road circumstances, the reliability factor is more important than high technology. Zirconia oxygen sensors will not perform if the physical unit is covered in mud, dirt, grease, or oil blocking the ability of the sensor to compare outside air with the internal exhaust gases.

**Zirconia Oxygen Sensors**

Now, we go to another ceramic that is known as zirconium oxide (ZrO2). Once again this oxide is selected for use in the automotive industry for its outstanding properties being: high flexura and tensile strength, high fracture toughness, high resistance to wear and corrosion, low thermal conductivity, oxygen ion conductivity (most important for automotive use), and E-module like steel. Zirconium dioxide (known as zirconia) along with platinum electrodes and a heater make up the major current internal components of the zirconia oxygen sensor. The majority of today’s automotive oxygen sensors have zirconium dioxide as the basis of the sensor due to its ability of oxygen ion conductivity (generating a self voltage). However, the vehicles considered for use in harsh off-road outdoor environments still use the titania oxygen sensors. The main reason is zirconia oxygen sensors need a clear atmospheric (outside) pathway to compare the inside exhaust to the outside air to function properly whereas titania oxygen sensors do not. This is why the zirconia oxygen sensors must be kept free of oil, vehicle undercoating, dirt, and anti-freeze coolant to allow this clear pathway to the outside air.

Tests have proven that the lowest amount of nitrous oxide (NOx), carbon monoxide (CO) and hydrocarbons (HC) are created when the air/fuel mixture is a perfectly balanced aka ‘stoichiometric” fuel mixture of 14.7 parts of air to 1 part of fuel. The zirconia oxygen sensor at this 14.7:1 mixture generates a nominal voltage of 0.45 volts (450 millivolts). The zirconia oxygen sensor’s output voltage does not remain constant. However, the universal benefit of the UEGO is that it is not limited to controlling an engine at stoich. This means that if you want to control your engine to a 16:1 A/F ratio for lean burn to improve emissions or fuel economy, you can do so (whereas you cannot with a typical switching sensor).

The zirconia dioxide oxygen sensors are further divided into three types based upon the internal element being used. The ‘thimble’ type (three and four-wire sensors only) has heater resistance of 2 to 6.5 ohms. The output signal ranges from 0.1 to 0.9 volts (100 to 900 millivolts).
The second zirconia dioxide oxygen sensor is the ‘thick film, planar’ type (four-wire only). This sensor has a heater resistance of 12 to 15 ohms. The output signal also ranges from 0.1 to 0.9 volts (100 to 900 millivolts). Some manufacturers have data sheets showing a range of 0.0 to 1.1 volts output. At the time of writing this paper, this ‘thick film, planar’ type of zirconia oxygen sensor is the most popular. One of the reasons for the popularity is that the ‘thick film’ does not need reference (outside) oxygen; it produces its own reference, thus eliminating the need of ambient (outside) air reference. Of the 272 part numbers produced by NTK, 37 (or 14 percent) are titania oxygen sensors and the remaining 235 (or 86 percent) are zirconia oxygen sensors.

Wide-Band Oxygen Sensors

The third and most recent zirconia dioxide oxygen sensor is the ‘wide band’ ‘lean burn’ type (or Air Fuel Sensor) and available at NTK only in five-wire. NTK has been around since the early 1990’s. The heater resistance ranges from 12 to 15 ohms. The 5-wire sensor utilizes a (separate) electronic controller that monitors and maintains the heater temperature and also has a signal conditioner to manipulate the output of the sensor into a useful voltage. The output signal is considered discrete voltage levels between 0 and 5 volts to offer exact air/fuel mixtures. Bosch officially announced via a press release the development of this ‘wide-band’ heated oxygen sensor in November 2001. NTK has developed a “wide-band” originally for Honda under the number “H1L1”. Today, the five-wire ‘wide-band’ is available under special order from NTK with the part number LZA03-E1. This newest design expands upon the original ‘planar’ design and adds the ability to actually measure the air/fuel ratio directly for the first time. Instead of switching back and forth like all previous sensor designs, the new ‘wide-band’ oxygen sensor produces a (voltage) signal that is directly proportional to the air/fuel ratio. To accomplish this, the wide-band sensor’s construction uses a dual sensing element that combines the Nernst effect cell (yttrium stabilized zirconia) (http://www.nernst.de) in the ‘planar’ design with an additional oxygen
pump layer and diffusion gap on the same strip of ceramic. The result is a sensor element that can precisely measure air/fuel ratios from a very rich condition (10:1 air/fuel ratio) to extremely lean (considered straight air). This allows the future engine computer to use an entirely different operating strategy to control the air/fuel ratio. Instead of switching the air/fuel ratio back and forth from rich to lean (as in previous oxygen sensor designs) to create and average balanced stoichiometric mixture, it can simply add or subtract fuel as needed to maintain a desirable steady ratio of 14.7:1. Recapping: Under current OBD-II designs, some ECM’s (a few Honda and VW vehicles with a second HEGO sensor after the catalytic converter) detect the change and strength of current flow and emits a voltage signal relatively proportional to exhaust oxygen content. Therefore, an ‘exact’ air/fuel mixture can be determined with the current OBD-II exhaust gas oxygen sensor instead of a ‘high’ or ‘low’ mixture above the stoich 14.7:1 air/fuel mixture. This range can start at 10.0:1 upwards to 18.0:1 air/fuel mixture ratio. To accomplish this more accurate measurement, the “wide band” air/fuel ratio sensor operates at about 1200 degrees Fahrenheit instead of the previously mentioned operation temperature of about 600 degrees Fahrenheit for the standard sensors. The heater circuit also has been enhanced. This circuit is pulse-width modulated to maintain a consistent operating temperature of 1292 to 1472 degrees Fahrenheit. The sensor now takes about 20 seconds to reach operating temperature.

**Oxygen Sensor Testing Equipment**

More sophisticated exhaust gas oxygen sensors create the demand for more sophisticated diagnostic equipment. Therefore, the newer oxygen sensors demand use of the high-impedance digital volt/ohm meter to assure accuracy in reading output measurements. The wide-band A/F sensor is currently designed so that at stoichiometry, there is no current flow and the voltage output of the detection circuit of the ECU is now 3.3 volts (aiming at the 14.7:1 air/fuel mixture exactly). A rich mixture, which leaves very little oxygen in the exhaust stream, produces a negative current flow. At this point the detection circuit of the ECU will produce a voltage below 3.3 volts (once again aiming at the 14.7:1 air/fuel mixture exactly). When there is a lean mixture, which has more oxygen in the exhaust stream, a positive current will flow. The detection circuit will now produce a voltage signal that is above 3.3 volts (still aiming at the exact air/fuel mixture of 14.7:1). As you can see, this is totally inconsistent from the aforementioned zirconia oxygen sensor voltage production range of 0.0 to 1.1 volts. Where the tests are made and what diagnostic equipment is used yields a different method of testing and reading of results. The main point to remember with the newer wide-band air/fuel sensors is that the voltage output is the opposite of what happens.
in the older narrow-band oxygen sensors. Now, the voltage output through the detection circuit increases, as the mixture gets leaner. The voltage, too, is exactly proportional to the change in the air/fuel mixture. This change allows the ECU/ECM to more accurately judge the exact air/fuel ratio under a wide variety of conditions and quickly adjust the amount of fuel to the nominal or 'stoichiometric' point. This type of rapid correction is not possible with the older narrow-band oxygen sensors.

**Oxygen Sensor Outside Influences**

Due to today's high replacement costs of certain newer oxygen sensors, the idea of simply replacing the oxygen sensor as a 'maintenance' item (as was the single-wire sensor) becomes most undesirable. To assure that the oxygen sensor is actually the cause of an engine OBD-II USA Federally mandated testing failure requires sophisticated equipment and proper reading of the appropriate output resistance and voltages. The failure of some other component(s) in the engine system can create a domino effect of failures. The past habit of the consumer taking out the oxygen sensor and making a determination of replacement based on visual inspection is no longer the norm. The following should be considered when 'dash lights' or 'codes' show a potential oxygen sensor failure:

1.) A simple cracked ceramic in a spark plug will result in misfire. This constant misfire will result in unburned fuel reaching the oxygen sensor. This unburned fuel will coat the oxygen sensor creating a failed sensor. This failed sensor will give incorrect information to the ECU that may result in further unburned fuel reaching the catalytic converter, which eventually will create the failure of that unit. Costly repairs will be required simply due to a single spark plug failure. The misfiring plug allows unburned oxygen to pass through into the exhaust, causing the sensor to give a false lean indication.

2.) Engine air leaks in the intake or exhaust manifold can have an affect on the sensor's accuracy.

3.) Excessive hydrocarbon (HC) and carbon monoxide (CO) emissions, poor fuel mileage, rough idle and loss of power are prime indications of a sluggish or static oxygen sensor. Drivability problems such as engine surging or hesitation can be attributed to a failing oxygen sensor.

4.) If the average voltage from the sensor remains high (more than 0.50v), the prime indication is a rich condition possibly due to a bad MAP, MAF or airflow sensor or leaky injector. If the average voltage reading is a steady low (less than 0.45v) the air/fuel mixture is running lean possibly due to a vacuum leak or just the oxygen sensor itself has failed completely.