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How 5-Wire Sensors Work

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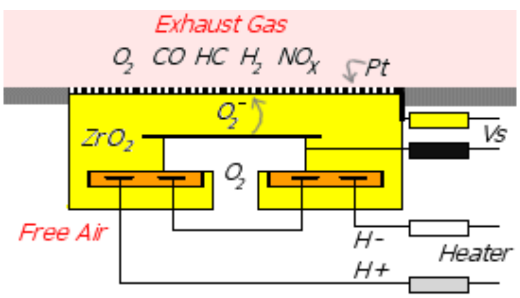
When using a 5-wire (wideband) sensor we make certain assumptions about the environment the sensor is used in, for example we assume the sensor is used to measure the exhaust byproducts of fairly complete combustion. The combustion can be internal, as in a conventional vehicle or external combustion, as in a furnace or other device consuming fuel and oxygen. If these conditions are altered then inappropriate readings may result. For example, if a miss-fire occurs and unburnt droplets of fuel go through the motor, then the sensor will read lean as it will not detect the liquid fuel. When tuning a vehicle, you should not rely solely on the reading from a sensor. Let your common sense, and a little knowledge of how the sensor works, guide you.

Wideband sensors require a controller because they are more complex than a standard narrowband sensor. They are more accurate because of this complexity, but this means they require a technically complex controller for them to work at all. The sensor itself can be thought of as two closely connected parts that are electrically heated to a dull read heat:

- A narrow-band sensor to detect the oxygen concentration within a small chamber.
- A pump cell that transports oxygen ions to or from the surface of this small chamber.

As we will see, the wideband sensor is operated by current that is pumped into or out of the pump cell by the wideband controller electronics. This is fundamentally different to a narrowband sensor that produces its narrowband voltage, without any external electronics, when heated to operating temperature. To understand wideband, we must first understand **narrowband** sensors:



Narrow Band Sensors

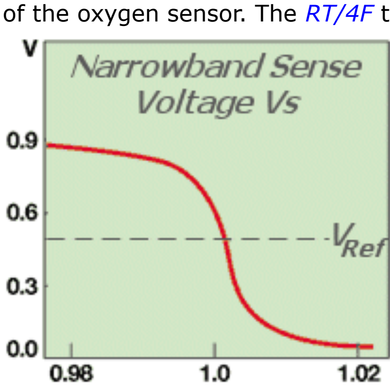
Narrowband sensors have between one and four wires. One of the wires will always be the signal voltage. A second wire can be used to isolate the ground end of the signal to reduce signal noise. Three and four wire sensors add a heating element so the sensor starts operating faster and more reliably.

The image at left shows a representation of a 4-wire version - in practical narrowband designs the sensor is often shaped as a thimble to maximise surface area exposed to the exhaust gas. The electrical heater is used to raise the temperature of the Zirconium Dioxide (ZrO_2) material that the sensor element is made from.

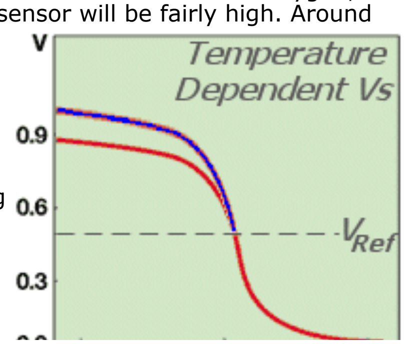
Zirconium Dioxide (often doped with Yttrium oxide) is an important substance that maintains mechanical rigidity while capable of conducting an electric current when in a molten (red hot) state. The sensor current is carried by oxygen ions that become available only when the sensor is hot enough. The Platinum covering is both conductive and promotes a catalytic reaction between oxygen ions and partially burned fuel. The Nernst equation describes the voltage produced as a result of this catalytic reaction involving Oxygen ions, Platinum catalyst and exhaust gas.

- $V_s = (RT/4F)*ln(pO_2^{air}/pO_2^{exh})$ pO_2 = *partial pressure across gas boundary*

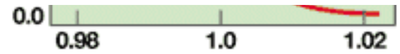
The pO_2^{xxx} is the partial pressure of oxygen, and is a convenient representation of the oxygen concentration on each side of the oxygen sensor. The *RT/4F* term can be thought of as a constant multiplied by temperature *T*.



What this equation says is that with rich mixtures, where there's almost no oxygen, but lots of free fuel, the voltage V_s produced by the sensor will be fairly high. Around stoich some free oxygen becomes available and the voltage produced by the sensor rapidly drops. The graph at left shows how V_s rapidly *switches* from a voltage around 0.9 Volts to around 0.1 Volt over a very small Lambda (or AFR) range. This rapid switching is one reason narrowband sensors are not accurate in the rich region, where most power tuning takes place.

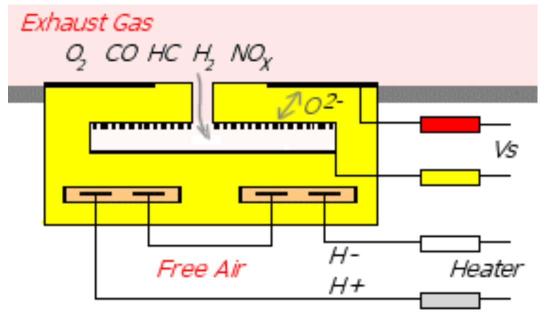


The equation also says that at higher temperatures V_s will also be higher. This is shown in the image at right. It is the other major reason why narrowband



sensors are not very accurate away from stoich. As the load on the motor varies, the temperature of the sensor will change, and it will read a different value, although the actual Lambda (or AFR) has not changed. It is possible to *temperature compensate* by measuring the impedance of the sensor and calculating its average temperature, and this is what most better quality Lambda meters, that use a narrow band sensor (such as the LSM-11), do in order to improve their accuracy.

Pump Cell



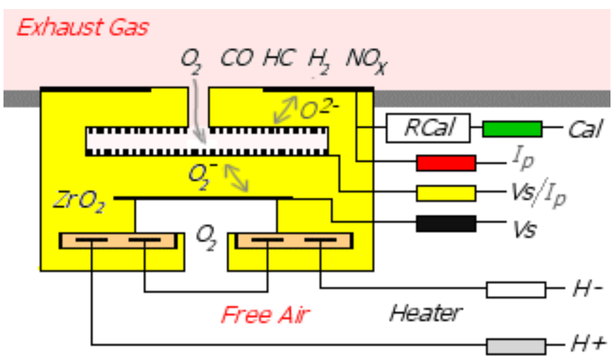
The narrowband sensor, described above, detects the voltage V_s produced by the Nernst Cell. It is possible to force a current through the molten electrolyte and to drive the chemical reaction such that oxygen is pumped (in the form of o^{2-} ions) from one side of the cell to the other.

- $O_2 + 4e^- \rightarrow 2\ O^{2-}$

In a **rich** mixture the oxygen ions will combine, on the pump cell's catalytic surface, with fuel to produce water and carbon dioxide. When all the fuel is consumed there will be no free oxygen and the resulting mixture will be at stoich. In a **lean** mixture (or even in free air) the pump current is reversed and the free oxygen is pumped out until none remains, and the resulting mixture will also be at stoich.

The image at right shows a **pump cell** and a small **chamber** that exhaust gas can enter. The rich, or lean, gas inside the chamber can be reduced, or oxidised, to produce a stoich mixture. An important part of the pump cell is the size of the pump cells entry hole and width of the diffusion chamber. As these are all subject to manufacturing variations, spreads in operating parameters are expected, and a scheme to allow for this variation is required.

Combining Narrow Band and Pump Cells —> 5-wire Sensor



Combining the narrow band and the pump cells allows the narrowband sensor to sense the mixture resulting from pumping oxygen into or out of the diffusion chamber. The resulting sensor is shown at left. To save wires, the *Vs* (sense) and the *Ip* (pump) cells are connected together - they share a common reaction surface anyway, so this isn't a problem.

The manufacturing variation problem, which results in sensors of varying sensitivities (differing pump currents for the same Lambda), is solved by adding a calibration component. A resistor (Rcal) is laser trimmed after the sensor is constructed and tested. The laser burns away material and increases the value of the resistor until a standard *Ip* current is produced at a known Lambda value. If this circuit is reproduced in the controller itself then each sensor will be automatically calibrated without further calibration. Obviously, as each sensor is factory calibrated, and the calibration component is usually in the sensor connector itself, if someone removes the connector, then the sensor has become uncalibrated!

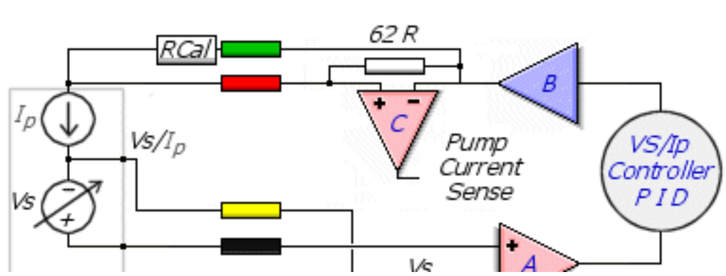
Many controllers do not have this circuit and they must go through a free-air calibration phase to work accurately. Note also that all pump-cell wideband sensors will have at least 5 wires from the sensor. Six or 7 wires will come from the connector (some sensors use a calibration resistor in the connector that has both ends free).

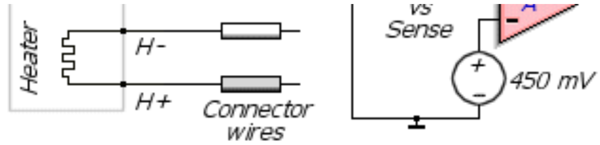
Some things to note are that when the sensor is being actively controlled, the mixture in the diffusion chamber is at stoich and the *Vs* voltage is close to 450 mVolts. There is a small self-pumping effect of atmospheric oxygen into the diffusion chamber by the *Vs* sensor part, but this is much smaller than the pump cell's action. As atmospheric oxygen concentration (ie. free-air) is used as the reference on one side of the *Vs* cell, then the flow of air to the back of the sensor must be maintained - this is usually via the sheath covering the wires to/from the sensor. The wire sheath should not be constricted!

How does a Wideband Controller Work?

The job of the controller is to maintain the diffusion chamber's temperature within close limits and to control the mixture there at stoich by pumping more or less *Ip* current, and by changing the direction of *Ip* when the mixture changes between lean and rich. A precise measurement of *Ip* is made to calculate the Lambda of the mixture by using a look-up table.

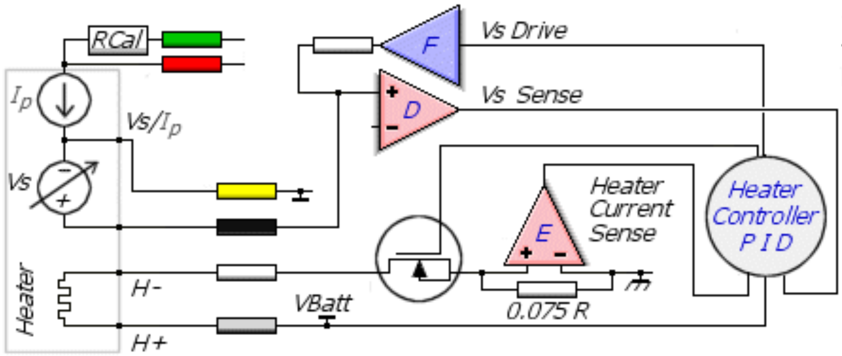
The image at right represents this in action. Op-Amp **A** produces a voltage representing the difference between *Vs* and a reference Voltage of 450 mV - the idea being to maintain *Vs* at the stoich value of 450 mV. A microcontroller implementing a [PID controller](#) uses *Vs* as its input and the PID output drives op-amp **B** configured as a current source which produces the *Ip* current used by the sensor. Op-amp **C** directly measures the pump current and produces a voltage that is measured by the microcontroller. The microcontroller effectively converts *Ip*





into an internal Lambda representation that is used to produce output voltages, stored as data etc.

For the controller to work at all, the sensor element must be heated to the correct operational temperature where oxygen ions can sustain the necessary catalytic reactions. The sensor temperature is maintained at the optimal operating temperature by measuring the impedance (electrical resistance) of either the pump cell or the *Vs* sense cell. More accurate results usually result from *Vs* cell temperature sensing (as is done in *Tech Edge* units) but this can be a little more complex than *Ip* cell impedance measurements. The heater of most 5-wire sensors is designed to produce maximum heating power at a lower voltage than the vehicle's battery voltage. This is to allow for voltage losses in the controller circuitry and for more rapid heat up from cold, but it also means that for a long sensor life, the controller should be careful not to stress the sensor during warmup when large enough currents to destroy the heater can flow.



The image at left shows the major parts of the heater control circuitry. It is in fact more complex than the Lambda measuring circuitry. Op-amp **E**, with the aid of a very low ohms resistor, can directly measure the current through the heater and this is used during warm-up to control the average heater power to within close limits (as specified in sensor manufacturers' documentation). The heater current and battery voltage (*Vbatt*) can also be used (via Ohm's Law) to calculate a rough heater temperature. When the sensor is warm enough for it's *Vs* sense cell impedance to be measured directly a more accurate temperature measurement can be made. Small voltage pulses are applied to *Vs* using driver **F** and again Ohm's law is used to calculate the sense cell impedance by measuring various voltages with op-amp **D**. The heater is switched, at around 30 hz, using a low-side FET driver and the heater PID control algorithm.

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