OXYGEN SENSOR OUTPUT VOLTAGE ANALYSIS

by Scott Ulen (robert.s.ulen@boeing.com)

Reference Chapter 7, Section 7.4, Feedback Systems, pp 301~304, "Internal Combustion Engine Fundamentals" by John H. Heywood, copyright 1988 by McGraw-Hill, Inc.

According to the above reference, an oxygen (O_2) sensor puts out a voltage signal between zero and 1.0 volt when hot enough, and there is a difference in the partial pressure of O_2 between the exhaust gas and the outside atmosphere. The O_2 sensor is designed to produce an electrochemical reaction, in two separate "gas chambers" (one in the exhaust gas, and one in the outside atmosphere). The O_2 sensor is therefore an "oxygen concentration cell" which generates its own voltage between a positive electrode (center wire) and negative electrode (sensor body). The solid electrolyte is yttria (Y_2O_3) stabilized zirconia (ZrO_2) ceramic, and the electrodes are Platinum coated, non-corrosive metal. This particular electrochemical reaction produces four free electrons during equilibrium which carry the current between the two metal electrodes. The following formula represents the voltage output from an automotive O_2 sensor:

V_{output} = (R*)(T) / (n)(F) * ln[(Po, air)/(Po, exh)] (known as the Nernst Equation)

where,
V_{output} = O_2 sensor's output voltage (0 to 1.0 volt is normal range)
R* = Universal Gas Constant = 8.3143 [Joule/gram-mole * K]
T = Temperature of the exhaust gas [Deg K]
n = number of electrons involved in the reaction = 4 in this case
F = Faraday constant = 96,480 [Coulomb/gram-mole]
Po, air = Partial pressure of O_2 in the atmosphere [Pascals]
Po, exh = Partial pressure of O_2 in the exhaust gas at temp [Pascals]
Note: Volt = [J/Coulomb] or Coulomb = J/V

1.0 psi = 6894.8 Pascals = 6.8948 kPa
Per Heywood, atmospheric O_2 partial pressure is ~ 20 kN/m^2 (kPa) = 20,000 Pa

Assume that dry air at 1.0 Atm (sea-level), and 70 deg F is the reference point for the O_2 sensor output. Calculate the partial pressure of O_2 of this reference air to see if it agrees with Heywood.

d = (1.3254 * inHg) / T
d = (1.3254 * 29.92) / (459.7 + 70) = 0.07486 lbm/ft^3

O_2 mass % = 23.142%, Therefore,
density of O_2 = (0.23142)(0.07486) = 0.01732 lbm/ft^3

Po, air = (d)(R)(T)
In this case, R = (R*)/(M of O_2) = (0.7302)/(32) = 0.02282 [(atm-ft^3) / (lbm-mole * R)]
(Po, air) will be in [atm] units

Po, air = (0.01732)(0.02282)(529.7) = 0.20936 atm = 3.078 psi = 21219.4 Pa = 21.22 kPa
Therefore, Heywood's statement for (Po, air) and this calculation is very close.
Based on this, assume that Heywood's numbers in Figure 7-17 (p. 302) are based on dry air at sea-level, and 70 deg F.

According to Heywood, the partial pressure of O_2 in exhaust gas changes very quickly at the point of Stoichiometric combustion, and is also a function of the A/F ratio and the temperature of the exhaust gas when the A/F ratio is greater than Stoichiometric (14.7 to 1), per Figure 7-17.

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The O_2 partial pressure in the exhaust is a function of exhaust temperature in the richer than Stoichiometric region. Therefore, the O_2 sensor output will be more dependent on the exhaust gas temperature when the A/F ratio is less than Stoichiometric (rich burn) vs the lean burn region.

Exhaust Gas Temperature Conversion

Deg C	500	750	900
Deg K	773.15	1023.15	1173.15

Deg K = Deg C + 273.15

The following numbers are taken off Figure 7-17 (a) in Heywood. Numbers are approximate readings off the graph (not calculated), and have been "tweaked" slightly to agree with the O_2 sensor output voltages shown in Heywood's corresponding graph in Figure 7-17 (b).

O_2 Partial Pressure in Exhaust Gas, (Po, exh) [Pascals]

	Exhaust Gas Temp [Deg K]		
A/F	773.15	1023.15	1173.15
10.3	2.00E-22	1.00E-14	2.00E-11
11.8	8.00E-22	3.00E-14	6.00E-11
13.2	6.00E-21	2.00E-13	6.00E-10
14.7	5.00E-18	5.00E-11	1.00E-07
14.7	50	50	50
16.2	1500	1500	1500
17.6	4000	4000	4000
19.0	7000	7000	7000

(Po, exh) increases to ~50 Pa on the lean end of Stoichiometric before increasing above an A/F = 14.7. In the leaner than Stoichiometric region, (Po, exh) does not change with exhaust temperature.

Calculate the O_2 sensor output voltage to see if it agrees with Heywood's chart in Figure 7-17 (b), using the Nernst Equation.

V_{output} = (R*)(T) / (n)(F) * ln[(Po, air)/(Po, exh)]

Use reference O_2 of dry air at sea-level and 70 deg F, then (Po, air) = 21,219 Pa
R = Universal Gas Constant = 8.3143 [(Joule/gram-mole * K)]
n = number of electrons involved in the reaction = 4 in this case
F = the Faraday constant = 96,480 Coulomb/gram-mole

O_2 Sensor Output [Volts]

	Exhaust Gas Temp [Deg K]		
	773.15	1023.15	1173.15
A/F	500 C	750 C	900 C
10.3	0.998	0.930	0.874
11.8	0.975	0.906	0.847
13.2	0.942	0.864	0.788
14.7	0.830	0.742	0.659
14.7	0.101	0.133	0.153
16.2	0.044	0.058	0.067
17.6	0.028	0.037	0.042
19.0	0.018	0.024	0.028

Rich end of Stoichiometric
Lean end of Stoichiometric

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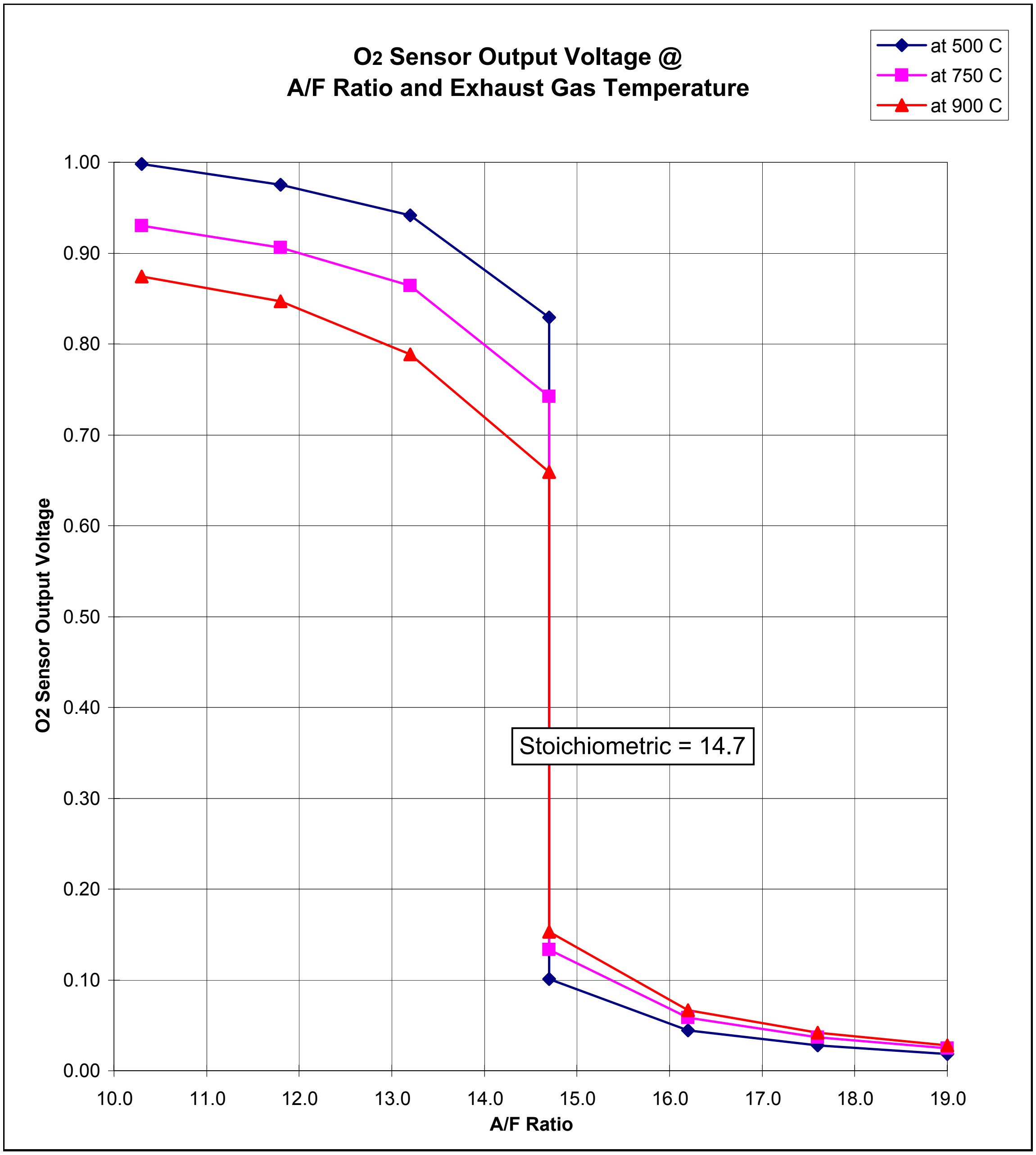
Graph of Calculated O_2 Sensor Output Voltage



Now, verify what effect there is on the O_2 sensor voltage output if there is a large change in atmosphere oxygen level due to altitude and/or humidity. This will change the (Po, air) value in the Nernst Equation for the O_2 sensor voltage output. The actual A/F ratio will remain constant because the FD maintains a constant absolute manifold pressure (and therefore charge density) by increasing boost pressure with altitude. Assume that the car is at an elevation of 7000 feet, and the air is dry (no humidity) at 70 deg F. The humidity ratio at this temperature is small and will be neglected to simplify this analysis. Any humidity would only slightly reduce the atmospheric oxygen level, and hence the partial pressure of O_2 (Po, air).

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Find the partial pressure of O_2 in this air due to decreased atmospheric pressure.

Po, air = 11.34 psia = 23.09 inHg at 7000 ft (From another spreadsheet)

d = (1.3254 * inHg) / T
d = (1.3254 * 23.09) / (459.7 + 70) = 0.05778 lbm/ft^3

O_2 mass % = 23.142%, Therefore,
density of O_2 = (0.23142)0(0.05778) = 0.01337 lbm/ft^3

Po, air = (d)(R)(T)
In this case, R = (R*)/(M of O_2) = (0.7302)/(32) = 0.02282 [(atm-ft^3) / (lbm-mole * R)]
(Po, air) will be in [atm] units

Po, air = (0.01337)(0.02282)(529.7) = 0.16162 atm = 2.376 psi = 16,380 Pa = 16.38 kPa

Again, use the Nernst Equation, but use 16,380 Pa for the atmosphere O_2 partial pressure.

V_{output} = (R*)(T) / (n)(F) * ln[(Po, air)/(Po, exh)]
Use reference O_2 of dry air at sea-level and 70 deg F, then (Po, air) = 16,380 Pa
R* = Universal Gas Constant = 8.3143 [(Joule/gram-mole * K)]
n = number of electrons involved in the reaction = 4 in this case
F = the Faraday constant = 96,480 Coulomb/gram-mole

O_2 Sensor Output [Volts] @ 7000 ft

	Exhaust Gas Temp [Deg K]			
	773.15	1023.15	1173.15	
A/F	500 C	750 C	900 C	
10.3	0.994	0.924	0.868	
11.8	0.971	0.900	0.840	
13.2	0.937	0.858	0.782	
14.7	0.825	0.737	0.653	Rich end of Stoich
14.7	0.096	0.128	0.146	Lean end of Stoich
16.2	0.040	0.053	0.060	
17.6	0.023	0.031	0.036	
19.0	0.014	0.019	0.021	

O_2 Sensor Volts @ Sea-Level for Comparison to 7000 ft

A/F	500 C	% Change
10.3	0.998	0.43
11.8	0.975	0.44
13.2	0.942	0.46
14.7	0.830	0.52
14.7	0.101	4.28
16.2	0.044	9.77
17.6	0.028	15.51
19.0	0.018	23.34

As can be seen between the two tables above (at T_{exh} = 500 C), that the O_2 sensor output voltage has not changed much on the rich side of Stoichiometric when the car is at 7000 ft elevation, even though the amount of oxygen mass in the air has decreased by approximately 23%.
Therefore, if you are at a high elevation, and in a WOT escapade watching the A/F meter, you can feel confident that its output has not shifted due to the high elevation causing a lack of O_2 in the air.
A correctly functioning O_2 sensor and A/F meter should give accurate A/F readings in the rich region of Stoichiometric regardless of elevation or humidity.

A larger concern is the O_2 sensor voltage shift in the rich A/F region due to increasing exhaust gas temperatures. It is unknown at this time if the stock FD O_2 sensor exhibits this phenomena. If it does, you could see as much as ~0.15 volt difference (3 LEDs out of 20 on A/F meter) between 500 C and 750 C exhaust gas temperature, at an A/F of ~13 to 1.

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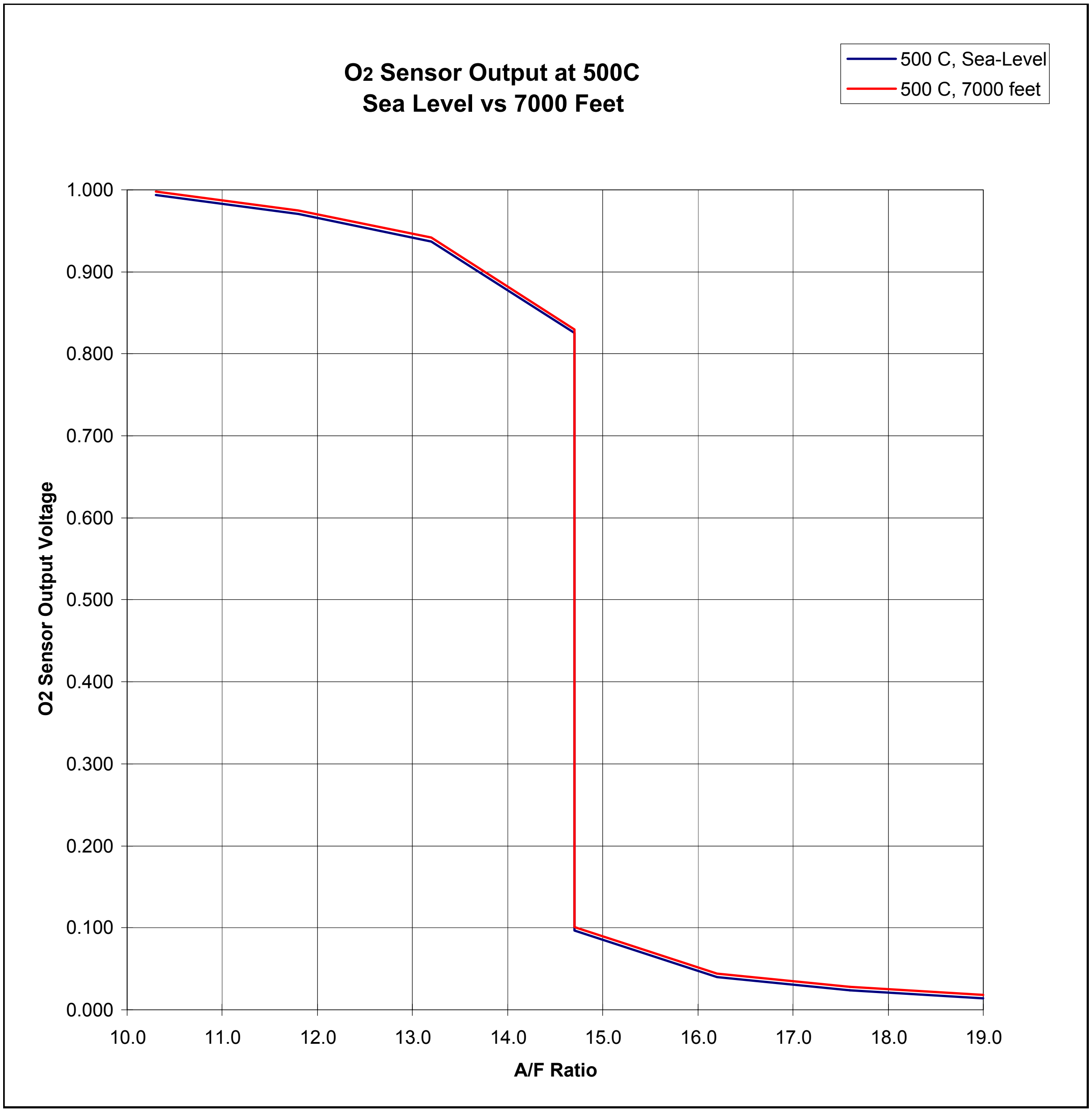
Plot showing the negligible shift in an O_2 sensor due to oxygen reduction from elevation and/or humidity.



Disclaimer

This information is for the purpose of showing that the output signal from an ideal O_2 sensor is not effected by the reduction of oxygen in the atmosphere due to altitude and/or humidity. The information was made as accurate as possible, and can be used as a general guideline for the expected O_2 sensor output as a function of the A/F ratio and exhaust gas temperature. This information is for O_2 sensors in general, and is not specific to the Mazda 3rd Generation RX-7.

Updated on 12/8/99 by Scott Ulen (robert.s.ulen@boeing.com)