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UNMANNED TEST AND EVALUATION OF THE TELEDYNE ANALYTICAL INSTRUMENTS R-10DN OXYGEN SENSOR FOR USE IN THE MK 16 MOD 1 UNDERWATER BREATHING APPARATUS

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The Teledyne Analytical Instruments, Inc., oxygen sensor model R-10DN has been tested to determine its suitability for use in the MK 16 MOD 1. Tests included linearity with nitrogen and helium as inert gases, temperature sensitivity, stability during a dive lasting several hours, and response time. These tests were repeated throughout the sensors' lifetimes until all sensors tested had failed. These sensors performed within the manufacturer's specifications with two exceptions: non-linearity, when sensors were tested with helium during the first month of their lives, and temperature extremes, when performances of two sensors were sometimes just outside specifications. Tests such as material compatibility, flammability, size and off-gassing were beyond the scope of this project.

Between tests the sensors were exposed to accelerated aging by being stored in a high oxygen pressure environment.

The sensors failed in one of two ways: slow response to combined changes in ambient and oxygen pressure, and sudden large increases in signal output during decompression.

Statistical analysis showed that, with 95% certainty, sensor life expectancy is at least 27 months.

From these test results, we recommend that the R-10DN sensor be approved for use in the MK16 MOD 0 and MOD 1.

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ACKNOWLEDGMENT

Statistical analysis of the sensors lifetime was performed by Dr. W. Gerth, Navy Experimental Diving Unit.

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INTRODUCTION

Sensors control the level of oxygen (O_2) in some underwater breathing apparatus (UBA), such as the MK 16. It is of great importance that these sensors be reliable, that their limited life spans be predictable, and that sensors approaching the end of their useable lives be identifiable in the field.

Teledyne Analytical Instruments, Inc. (Industry, CA), has developed the R-10DN, a new model of oxygen sensor that is claimed to be a drop-in replacement with promise of an extended life and an improved response time at a lower cost. Table 1 shows the specifications for this sensor. The specifications for output voltage for the R-10DN are the same as for the previously used R-10DV.

The purpose of this set of tests, which were based on the proposal sent to PMS-EOD on 30 July 2001 and resulting in the tasking letter (task 01-24) dated 18 October 2001, was to determine what the life span of R-10DN sensors is and how the sensors behave as they fail. These questions were answered by testing the sensors' linearity, response times, temperature sensitivity and stability throughout their lifetimes. Experience with Teledyne R-10DV sensors previously approved for use in the MK16 had fostered an anticipated mode of failure: a slowed response to either an increase or a decrease in pressure.

These tests were designed to judge performance, and not suitability in terms of material off-gassing, material compatibility, flammability, physical dimensions.

METHODS

GENERAL

Sensors were evaluated through the following tests:

- Linearity, with either nitrogen (N_2) or helium (He) as the inert gas;
- Response time when switching from one level of O_2 to another;
- Stability during a 4-hour exposure;
- Sensitivity to changes in temperature;
- Longevity, by adding electrical loads that might determine their lifetime.

Between the tests, the sensors were exposed to accelerated aging by being stored in a high O_2 atmosphere (atm), the highest was 4 ATA. This way, the expected life span of 36 months was compressed to about 4 months. The manufacturer's stated expected life time is derived form on calculations (Mr. J. Lauer, personal communication) based on the known mass of electrode and the known rate of consumption proportional to the O_2 pressure and an empirically known efficiency factor. The age stated in this report is the equivalent time of air exposure.

EXPERIMENTAL DESIGN AND ANALYSIS

The breathing apparatus in which the sensors will be used may be exposed to water temperatures ranging from near freezing to tropical levels. Therefore, the temperature range chosen for testing included the full range of the manufacturer's specification, 10 to 40 °C (50 to 104 °F).

The linearity tests were performed at O_2 pressures both within normal operating levels [up to 1.45 atmospheres absolute (ATA)] for the MK 16 and at levels greater than these (up to 2.1 ATA). The normal operating levels were exceeded for two reasons: to determine how reliably the MK 16 could measure any overshoot in oxygen pressure, and to correlate any changes in non-linearity with sensor age.

Stability tests were performed at an O_2 pressure of 1.45 ATA to determine whether sensors were stable during a long simulated dive. This pressure exceeds the range given by the sensor manufacturer but is in the upper range of the control band for the MK 16 MOD 1 and was therefore a worst-case test for the sensors.

The sensors, shipped directly from the manufacturer, were loaded with an additional resistor (an approach similar to a battery tester) provided by NEDU to determine whether this approach could work to determine the effective age of the sensors.

EQUIPMENT AND INSTRUMENTATION

A hyperbaric chamber (Bethlehem Foundry & Machine Co., South Bethlehem, PA; serial number H-224-BFM, design pressure 3,000 psig) was used for testing linearity, stability, and temperature as well as for storing sensors at pressures up to 4 ATA between tests. In addition, this chamber was equipped with a temperature control system that provided the desired range for temperature tests. Two temperature probes were used (YSI 400 series), they were within 15 mm of each other and suspended in the chamber atmosphere. One was connected to the temperature controller and the other to a separate thermometer, the displays agreed with other within 0.3 °C.

A fan that was inside the chamber (and that was turned off during data collection to avoid any electrical noise) circulated the air to even out any temperature fluctuations. Inside the chamber, sensors were plugged into cables that went through the chamber wall to a connection box outside, where the required 6 kΩ resistor was connected. Thus, each sensor was always loaded by this resistor (6.19 kΩ, 1% metal film). Chamber pressure was read on a digital pressure gauge (Mensor model 2101, serial number 531166, which was within its factory calibration period).

The gases used in the tests, air, O_2 and Heliox (79/21) were of breathing quality and delivered from the standard gas bank maintained by NEDU.

Another setup was used for the response time and load tests. During these tests, four sensors at a time were placed in separate rubber sleeves, each of which had a sensor at one end and a rubber stopper at the other. A tube entered the stopper and could flow either air or 100% O_2, as controlled by solenoids. The incoming gas was directed at each sensor's sensing surface, and the excess gas left through holes in the rubber stopper at the back end of the chamber. This alignment allowed rapid switching from air to O_2 and back. The flow of the gases was set so that an increase in flow did not change the response time measurements. These flows were not high enough to raise the pressure inside the sleeve to cause changes in readings: this was verified by flushing the sleeve with, for example, O_2 and then closing the solenoid and confirming the absence of any voltage changes from the sensors. The flows were balanced by being adjusting so that the voltage read from the sensors was the average of the reading in air and O_2 when both gases were flowing. The load tests were conducted by connecting an additional resistance in parallel to the 6 kΩ resistor already in place while the signal was monitored.

During all tests, the signals were recorded on a laptop computer (Dell Inspiron 8100) using Labview 6.1e (National Instruments; Austin, TX). The analog-to digital converter had 16 channels and used 16-bit conversion (DAS16/16-AO, Computerboards; Middleboro, MA) set for a full-scale input voltage of 1.25 V. This gave a maximum resolution of better than 0.02 mV, which should be compared to lowest measured voltage of about 25 mV. Typically, the readings of greatest interest (at O_2 pressure of 1 to 1.5 ATA) the voltages were about 120 to 180 mV. The data were logged in ASCII format on the hard disk. The sampling and logging frequencies were 50 Hz for the response and load tests, and 5 Hz for the other tests.

Calculations of response times (to 90%) and changes due to extra electrical loads were calculated with software written in-house.

Statistical analysis

Analysis of the survival statistics and resulting predictions of life expectancy was made with Kaplan-Meier survival statistics using in-house developed software.

PROCEDURES

Linearity test

General: The circulation fan was stopped during data acquisition, but was run otherwise. Travel rates did not exceed 30 feet of seawater (fsw) per minute. Data were recorded for at least one minute.

1. The chamber was readied for diving according to a separate checklist. Either air or heliox (79/21) was used. The temperature control was set at 25 °C.

2. Signals from the sensors were recorded at depths from the surface to 297 fsw in steps of 33 fsw. Temperatures were allowed to stabilize before recordings were begun.
3. The chamber was decompressed to 165 fsw and signals were recorded.
4. The chamber was decompressed to the surface and signals were recorded.
5. A separate checklist was followed for post-dive procedures.

<u>Temperature test</u>

1. The temperature control system and the circulation fan were turned on.
2. Signals from the sensors were recorded at 10, 20, 30, and 40 °C. Temperatures were allowed to stabilize before recordings were begun. Data were recorded for at least one minute.
3. The temperature control system was turned off.

<u>Stability test</u>

General: The circulation fan was stopped during data acquisition, but was run otherwise. Travel rates did not exceed 30 fsw/min.

1. The chamber was readied for diving per its checklist: it was compressed with air. The temperature control was set at 25 °C.
2. The chamber was compressed to 195 fsw, a partial pressure of O_2 (PO_2) of 1.45 atm. The temperature was allowed to stabilize before recordings were started.
3. Signals from the sensors were recorded for at least one minute every 30 minutes, for a total of 4 hours.
4. Post-dive procedures followed the chamber's checklist.

<u>Response time test</u>

1. Air and O_2 supplies were turned on.
2. Four sensors were placed in the sleeves. If fewer than four sensors were tested, remaining holes were blocked with other sensors.
3. A flow of 100% O_2 was applied to the sensors.
4. After the sensor signal had stabilized, the solenoid was closed and a lack of changes in the sensor signal was verified.
5. Both solenoids were turned on, and the flow was adjusted to make the sensor readings about the average of the readings in air and the readings with 100% O_2.
6. The O_2 solenoid was closed, and the air flow was left on.

7. When the signals stabilized, the recording of data began.
8. The solenoid for air was turned off at the same time that the solenoid for O_2 was turned on.
9. When the signals stabilized, the O_2 flow was turned off at the same time that the air was turned on.
10. When the signals stabilized, the data recording was stopped and the air flow turned off.
11. The same measurements were repeated for the remaining sensors.

<u>Load test</u>

Four sensors were placed in the sleeves. If fewer than four sensors were tested, remaining holes were blocked with other sensors.

1. A flow of 100% O_2 was applied to the sensors.
2. The recording began.
3. A desired resistance was added.
4. The recording was stopped.
5. Steps 3, 4, and 5 were repeated until all resistances had been added.
6. Steps 1 through 6 were repeated, until all sensors had been recorded.
7. The O_2 was secured.

RESULTS

A first batch of 20 sensors was started with all the tests performed on them. Towards the end of their expected lifetimes, some the sensors behaved the same as the previously approved R-10DV O_2 sensors had: they were slow in providing the expected voltage after a change in the chamber pressure (Figure 1). This became evident both during compression and decompression but was noted earlier in the testing during decompression. However, the voltage did reach the expected value after a few minutes. Even after such changes were noted, response times did not change.

Some sensors behaved in unexpected ways when, during decompression, they produced a sudden large voltage increase to levels that were two to three times greater than the other sensors (Figures 1 and 2). The voltage later returned to expected levels. This recovery took from a few minutes to several hours. Some weeks of (accelerated) life later, such a sensor would typically start to leak a clear liquid that felt slippery. The manufacturer explained that this liquid was potassium hydroxide (KOH), a high-pH liquid that is the electrolyte in the sensor. After such a leak, a sensor produced no signal at all. A few days after a leak had started, a crusty coating could be found on the sensor, typically around the holes where the wires came out.

A few of the sensors started to display these failures at 28 to 30 months of their lifetimes, well before their rated 36 months. Since these signs were not looked for, but still noticed, the exact timing was not recorded. Tests of a second batch of sensors began, to better determine when this unexpected behavior actually started. To accelerate the determination, this batch received initial testing but then underwent limited testing until about 18 months of its lifetime. After that, it received the same tests as batch 1 and was closely monitored for signs of such failure.

When pressurized, the chamber was maintained within 0.5 fsw: i.e., the worst-case error (shallow depth) was less than 0.5%.

LINEARITY TESTS

Air testing

The average deviations from linear response during one test are illustrated in Figure 3. The average error within the manufacturer's specified range (0 to 1.3 ATA) was –0.01%, and the greatest error in any sensor was 1.4%. Even at O_2 pressures as high as 1.9 atm the mean errors were within the manufacturer's limit of ±2%.

Heliox testing

During the first month of heliox testing, the average linearity was within 2.7% but then improved and remained within the manufacturer's limit of ±2% for the rest of the testing period.

Effect of aging

Apart from the first month's testing with heliox, no effect of aging was apparent. The sensors failed for other reasons.

TEMPERATURE TEST

Temperature changes increased output voltages for some sensors, while for others those voltages decreased (Fig. 4). For each sensor, output voltages were averaged for all temperatures, and deviations from the average were then calculated. The average deviations due to temperature changes are well within specifications (Table 2). The greatest individual deviations were just outside specifications and occurred in the same two sensors at both ends of the temperature range. At these temperatures, the two sensors were sometimes outside, sometimes inside the specifications.

Effect of aging

No effect of aging was apparent.

STABILITY TEST

The average deviation from the mean during a test was 0.3%. Any changes were found in the first readings after reaching the desired pressure. One test was extended from 4 to 5 five hours with no noticeable effect on the readings.

Effect of aging

No effect of aging was apparent.

RESPONSE TIME TEST

The measured response times to 90% of change varied from 2.5 to 3.8 seconds when the O_2 both increased (Fig. 5) and decreased.

Effect of aging

No effect of aging was apparent.

LOAD TESTS

The voltage dropped, depending on the additional resistance used to load the sensor (Table 3). The voltage drop can be predicted from an equivalent electric circuit having a voltage source of about 133 mV with an internal resistance of 0.26 kΩ.

Effect of aging

No effect of aging was apparent.

SURVIVAL ANALYSIS

The survival rate is illustrated in Figure 6. All sensors survived at least 27 months. The Kaplan-Meyer survival analysis indicated a lower 95% confidence limit of 27 months.

DISCUSSION

LINEARITY

With air testing, the sensors' linearity was well within the manufacturer's limit of ±2%; the worst performance for any sensor was 1.4%. The sensors were within the manufacturer's limit even at oxygen pressures well beyond the normal operating range of the MK 16 MOD 1. The average non-linearity was not noted until oxygen pressures reached the highest values that the MK 16 display can show (1.99 atm). During the initial heliox testing, a few sensors showed linearity errors beyond the specifications. However, these errors disappeared after the first month, and the sensors were within specifications thereafter.

Comparing the linearity errors in the O_2 sensors to the calibration of the MK 16 MOD 0 and MOD 1 is worthwhile: when settings are changed by one click, the voltage presented to the electronic control circuits changes by 3.5% to 4.2% in the range normally used (E through 8). In other words, the calibration of the MK16 may give an error of over 4% even with the best possible procedures and sensors.

The sensors showed no signs of aging before they failed for other reasons.

TEMPERATURE

The majority of the sensors showed temperature changes that were within the manufacturer's specifications. Two sensors were marginal in their sensitivity to temperature changes, sometimes being just beyond and sometimes within specifications at the extreme temperatures.

STABILITY OVER A FOUR-HOUR PERIOD

The average deviation from the mean during a test was 0.3%. This deviation is small enough that it is not noticeable on the diver's display. No change with sensor age was apparent.

RESPONSE TIME

The response time to changes in O_2 levels were well within specifications, and no changes with age were apparent.

LOAD TEST

The load tests showed no changes with age; therefore, such tests are not useful in detecting sensor age (Table 3).

FAILURE MODES

Two failure modes were observed:

1. Responses to simultaneous changes in pressure and PO_2 (Fig 2.) slowed during compression and, at an earlier age, during decompression.
2. Sudden large increases in signal during a decompression (Fig. 1) preceded electrolyte leaks.

GENERAL

The linearity for air dives (i.e., with N_2 as inert gas) was within specifications at O_2 pressures even much higher than the MK 16's control range. With He as inert gas, initial linearity errors slightly outside the specifications disappeared within a month of sensor age.

The response time was even faster than the manufacturer's specifications and will improve the control of the O_2 levels in the MK 16.

The stability of the sensors was better than what a diver could read on the MK 16's secondary display.

The sensor lifetime of 27 months is set to be shorter than that at which any of the failures were noted. Some sensors failed by having a slowed response to changes in pressure, the same failure noted in some of the R-10DV sensors. Over a period of time (i.e., from minutes to hours), these slow responses would go away but recurred during the next dive. Other sensors failed by showing a drastic increase in signal during decompression. A MK 16 diver can notice these impending failures by watching the readings on the secondary display. If one sensor seems to respond to O_2 pressure changes more slowly than the others do, such sluggishness may signal an impending failure. Similarly, if one sensor shows unreasonably high values during decompression or after a dive, it may be about to fail or may be considered to have failed already.

Historically, oxygen sensors from any manufacturer have been stored in a gas tight bags or in an atmosphere low in O_2 in an effort to extend their life span. However, the manufacturer of the R-10DN sensors, Teledyne Analytical Instruments, states that such procedures are not necessary for these sensors, rather it is better to store them in a refrigerator if they are not going to be used for a while.

Except for the R-10DN's improved response times and expected lifetimes, specifications for it are the same as for the currently approved R-10DV sensors.

CONCLUSIONS

The R-10DN sensors are essentially within the manufacturer's specifications. Since these specifications are the same or better than those for the currently approved R-10DV sensor, we recommend that the R-10DN sensors be approved for use in the MK 16 MOD 0 and MOD 1 for a service life of 27 months.

FIGURES

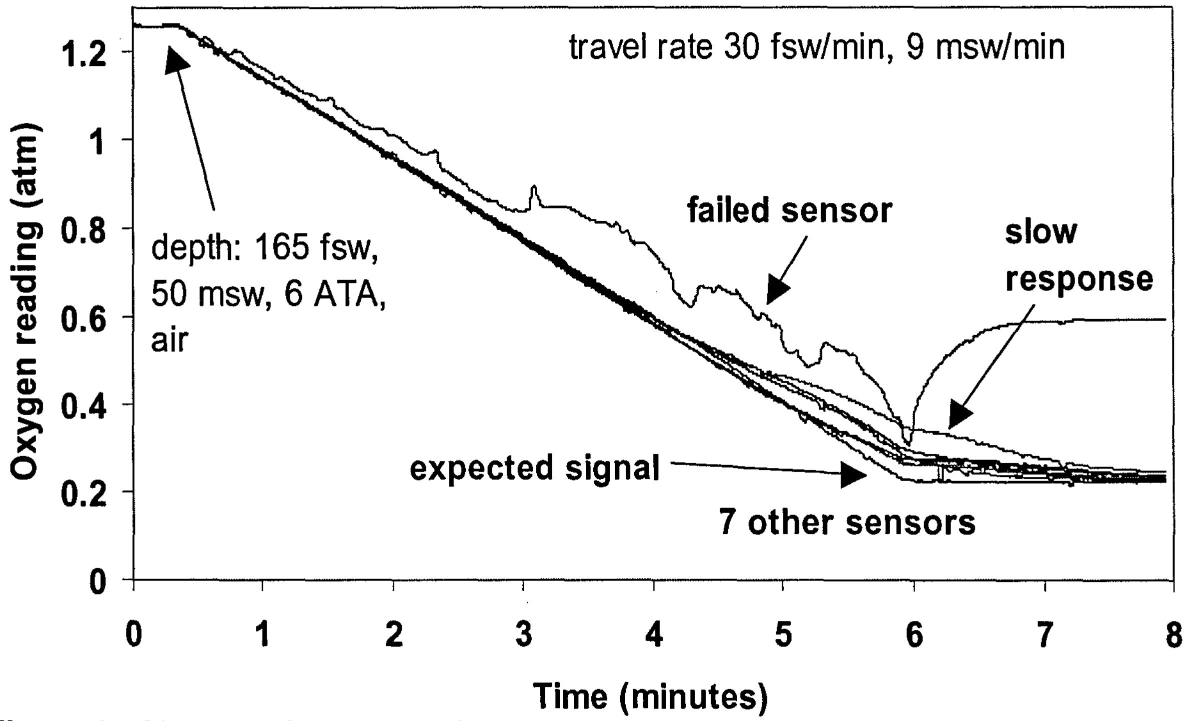

Figure 1. Observed failures of other sensors. The lowest line is a recording of a normally functioning sensor. The red line shows the erratic behavior of a failed sensor. The lines between, at about 6 minutes, show the slow response to changes in oxygen pressure caused by changes in absolute pressure.

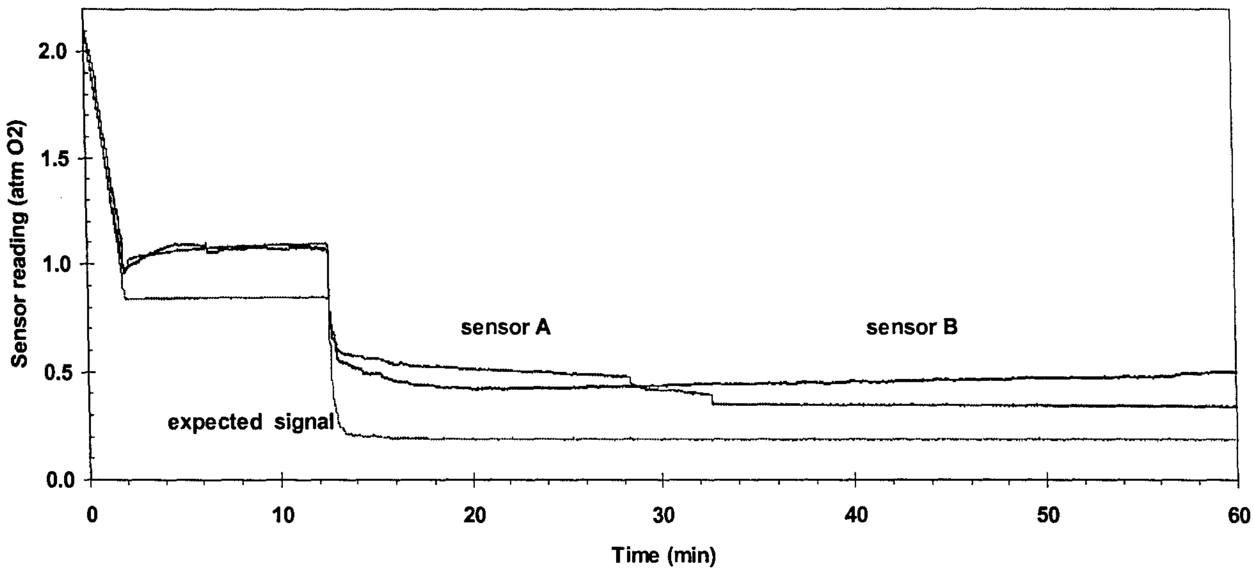

Figure 2. Observed failure of two sensors during a decompression from 300 fsw with air. The bottom line is a recording of a normally functioning sensor. See text for a discussion of the failure modes for sensors A and B.

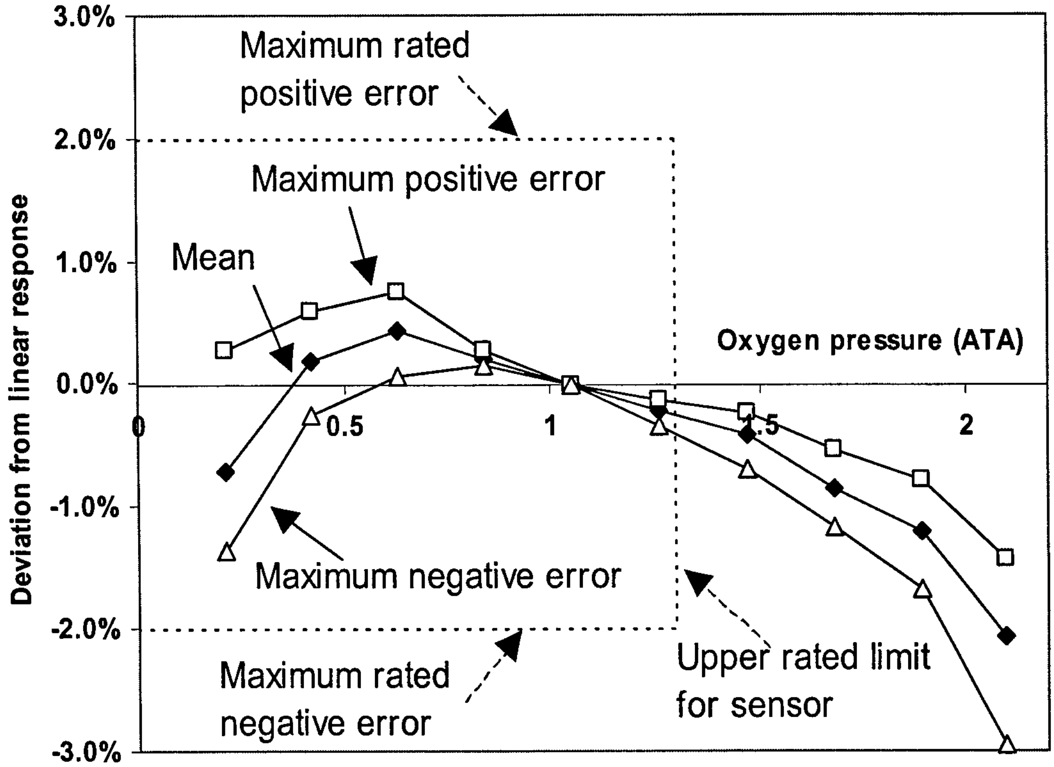

Figure 3. Average and maximum deviations from a linear response for 20 sensors (about 10 months old) tested with air. The reading at 1.05 ATA was set to be the calibration point for each sensor. This was as close as possible to the calibration procedure for the MK 16. The dotted line shows the range specified by the manufacturer (±2% error, max 1.3 ATA O_2).

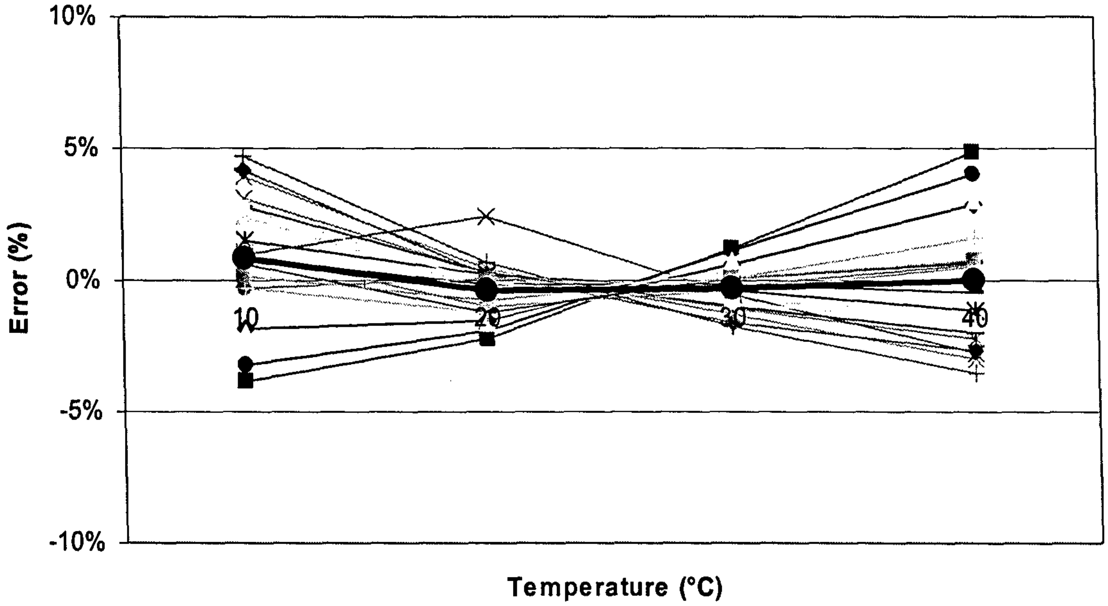

Figure 4. Changes in sensor outputs based on ambient temperature changes. Each thin line represent a sensor, while the thick black line shows the mean for all 20 sensors.

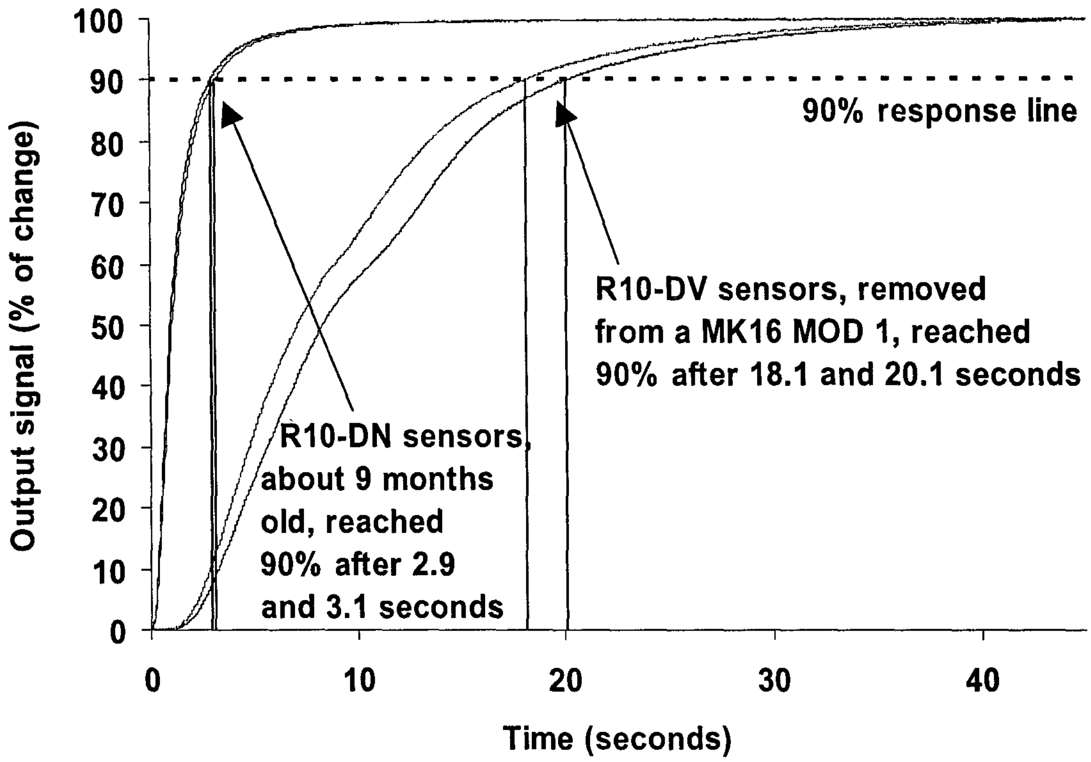

Figure 5. Change in output signal when the sensor was exposed to a change from air to 100% O_2. The responses of two R-10DN and two currently approved R-10DV sensors are shown.

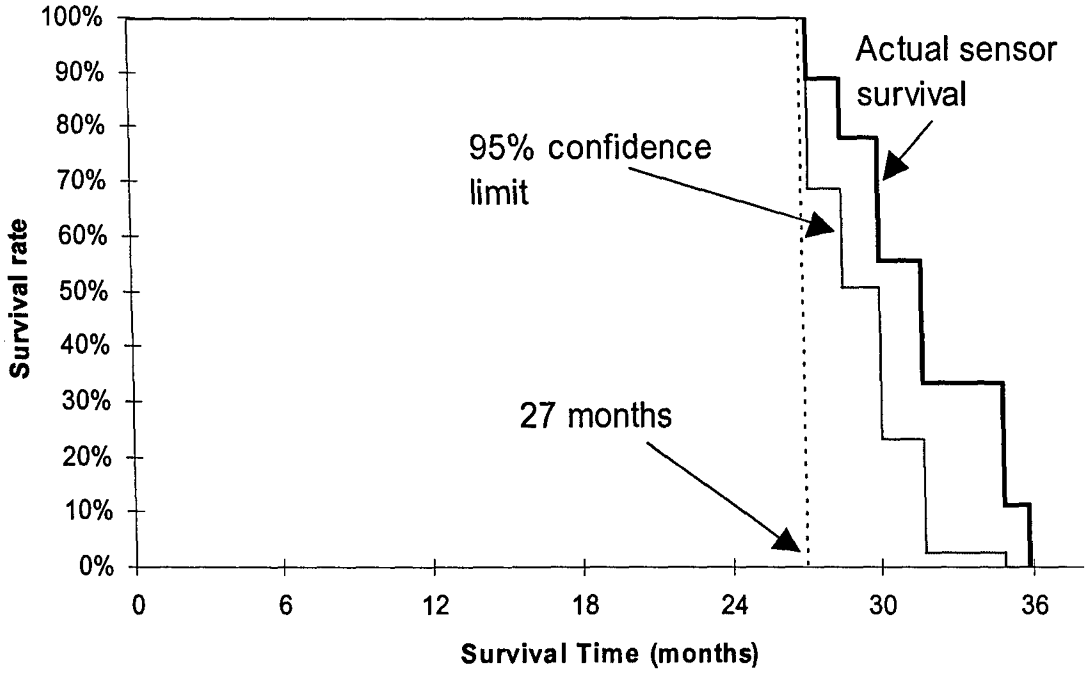

Figure 6. Actual sensor survival rate and the lower 95% confidence limit for R-10DN oxygen sensors.

TABLES

Table 1.

Summary of the specification for the R-10DN and the R-10DV. The specification for the R-10DN are per drawing C-74016: "SPEC. CONTROL DWG OXYGEN SENSORS CLASS R-10DN" faxed by Mr. Antieau at Teledyne. The specifications for the R-10DV are from Teledyne's sales brochure. Significant differences are highlighted.

Parameter	***Limits for the R-10DN (new sensor)***	***Limits for the R-10DV (old sensor)***
Output	25 ±2 mV in air at 25 °C, sea level	25 ±2 mV in air at 25 °C, sea level
Range	0 – **1.3 ATM** PO_2	0 – **1 ATM** PO_2
Accuracy	within ±2% of full scale at constant temperature and pressure (when calibrated with 100% oxygen)	within ±2% of full scale at constant temperature and pressure (when calibrated with 100% oxygen)
Response time	less than **6 seconds** for 90% of final value	less than **30 seconds** for 90% of final value
Offset	less than 0.5% of O_2 equivalent at 25 °C (77 °F) in zero gas after 36 seconds	not specified
Relative humidity (RH)	0 to 99% (non-condensing)	0 to 99% (non-condensing)
Operating temperature range	0 to 40 °C (32 to 104 °F)	0 to 40 °C (32 to 104 °F)
Storage temperature	0 to 50 °C	0 to 50 °C
Average expected cell life	**36 months** in air at 25 °C and 50% RH, sea level	**18 months** in air at 25 °C and 50% RH.
Shelf life	24 months	24 months
Weight	1.9 oz (54 g)	not specified
Load	6 kOhm (required)	6 kOhm (required)

Table 2.
Influence of temperature on the output voltages.

Temperature		***Mean***	***SD***	***Highest***	***Lowest***
10 °C	50 °F	-0.3%	2.3%	3.6%	-5.5%
20 °C	68 °F	-1.0%	1.1%	4.1%	-4.0%
30 °C	86 °F	0.9%	0.7%	3.1%	-1.7%
40 °C	104 °F	0.9%	2.8%	6.8%	-5.1%

Table 3.
Drop in voltage when loaded with different resistors. The resistance listed includes the fixed 6.19 kOhm.

Resistive load (kΩ)	Drop in signal	
	mV	%
6.2	0	0
4.0	2.7	2.2%
3.3	4.3	3.5%
3.0	5.5	4.5%
2.5	7.2	5.9%
1.3	17.5	14.2%
0.55	35.7	28.9%
0.29	56.5	45.7%