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# Operational Considerations in Monitoring Oxygen Levels at the National Transonic Facility

M. A. Zalenski, E. L. Rowe,
and J. R. McPhee
*Wyle Laboratories*
*Hampton, Virginia*

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# OPERATIONAL CONSIDERATIONS IN MONITORING OXYGEN LEVELS AT THE NATIONAL TRANSONIC FACILITY

by M.A. Zalenski, E.L. Rowe, J.R. McPhee

## Summary

Initially, each oxygen ($0_2$) monitoring channel in the National Transonic Facility (NTF) system was calibrated each day to read 21% oxygen by volume as specified by the manufacturer's instructions. This required adjusting 60% of the channels every day. It was recognized that some tolerance was needed to eliminate unnecessary daily adjustment. Therefore, a band of $\pm$0.5% at 21% was established. This reduced the daily adjustment from 60% to 40% of the total channels. With experience gained and observations made related to local environmental conditions, over the next year daily adjustments were further reduced to 20% of the channels.

By implementing the technique outlined in this report, i.e., calculating the daily actual $0_2$ percentage, making no adjustments unless sensor output exceeds established limits, and making all adjustments, including newly installed sensors, to the daily calculated percentage value, the NTF system is now maintained with only approximately 1% of the channels adjusted each day. This technique also permits identification of weak or malfunctioning cells since sensor drift can be discriminated from atmospherically induced aberrations.

Although the study was concerned primarily with the NTF Oxygen Monitoring System as supplied by one manufacturer, the comments and conclusions are generally applicable to any system employing electrochemical sensors for $0_2$ monitoring.

## Introduction

The National Transonic Facility (NTF) is a transonic wind tunnel located at NASA Langley Research Center. It is designed for full scale Reynolds ($R_N$) number testing of scale models of flight vehicles over a Mach number range of 0.2 to 1.2. The high $R_N$ capability of the NTF is achieved by operating at super cold temperatures and at pressures up to 9 atmospheres. The low temperature is attained through the injection of liquid nitrogen ($LN_2$) directly into the tunnel where it vaporizes. This allows operation with a cold gaseous test medium at temperatures as low as 300°F below zero. For tunnel operation, $LN_2$ is pumped from a 250,000 gallon storage tank into the tunnel at rates up to 9000 gpm. Due to the necessity of handling and containing a large volume of $LN_2$, extreme care must be taken to prevent situations where gaseous nitrogen ($GN_2$) could escape from the tunnel or piping system and displace the oxygen in the atmosphere whereby a non-life sustaining environment would exist. To safeguard against such a hazard, the NTF is equipped with an oxygen monitoring system with sensors located throughout the facility.

During tunnel operations requiring $LN_2$, the Oxygen Monitoring System is activated 24 hours per day. Hence, it is necessary that the system be able to function reliably over an extended period and provide accurate alarm indications in the event of oxygen depletion. Frequent false alarms could desensitize the personnel the system is intended to protect.

During start-up and checkout of the NTF, the Oxygen Monitoring System gave several false alarms (those situations where oxygen depletion was indicated but in fact had not occurred). It became obvious that any combination of system faults or lack of understanding of the system which contributes to false alarms was unacceptable. Suspected causes of such alarms included equipment failure, long term drift, and a system intolerance for normal atmospheric variations.

To this end, a study was undertaken to

1) Evaluate the system's false alarm history and determine the cause(s) and,
2) Evaluate the effects of atmospheric variables such as barometric pressure ($P_B$) and water vapor content ($P_{H_2O}$) on the indicated system output.

## System Description

The NTF Oxygen Monitoring System consists of an active, voltage-generating oxygen sensor or cell (galvanic type) and an electronic process monitoring device. The galvanic-type cell is one of two broad catagories of electrochemical $O_2$ detectors, the other class being the polarographic or Clark cell. The working principle of the galvanic $O_2$ cell will be examined later in this report. For the present, however, the oxygen detector can be described as a device which develops a dc potential proportional to the concentration of molecular oxygen in the atmosphere surrounding the device.

The basic function of the electronic process monitoring device is to amplify the low-level signal from the sensor(s), compare the sensor output to preset levels established as alarm points, and provide outputs suitable for driving audible and visible alarms when the limits are exceeded. It is important to note that the system output is displayed in terms of percent $O_2$ by volume, a standard practice among manufacturers of oxygen detection equipment.

## Evaluation of Electronics

To isolate system problem indications for analysis, the signal conditioning (electronics) package was evaluated independently of the sensors. Since the sensor is an active, voltage generating device, the testing of the electronics consisted of substituting a voltage source

for the sensor and testing for drift and linearity. In this manner, it was determined that the electronics were stable and of little significance in the problem under investigation. The testing indicated performance that was equal to or better than the manufacturer's specifications.

## Sensor Measurement Principle

The sensor is an electrochemical cell consisting of a gold cathode centered in a lead cup which functions as the anode. Figures 1 and 2 show the cross sectional and exploded views of a sensor. To function as an oxygen sensing device, the lead cup of the sensor is filled with an aqueous solution of potassium hydroxide (KOH) which acts as the electrolyte. The top of the cup is covered with a gas-permeable teflon (fluorinated ethyl propylene; FEP) membrane. The membrane is sealed with an o-ring and secured in position by the upper part of the cell casing.

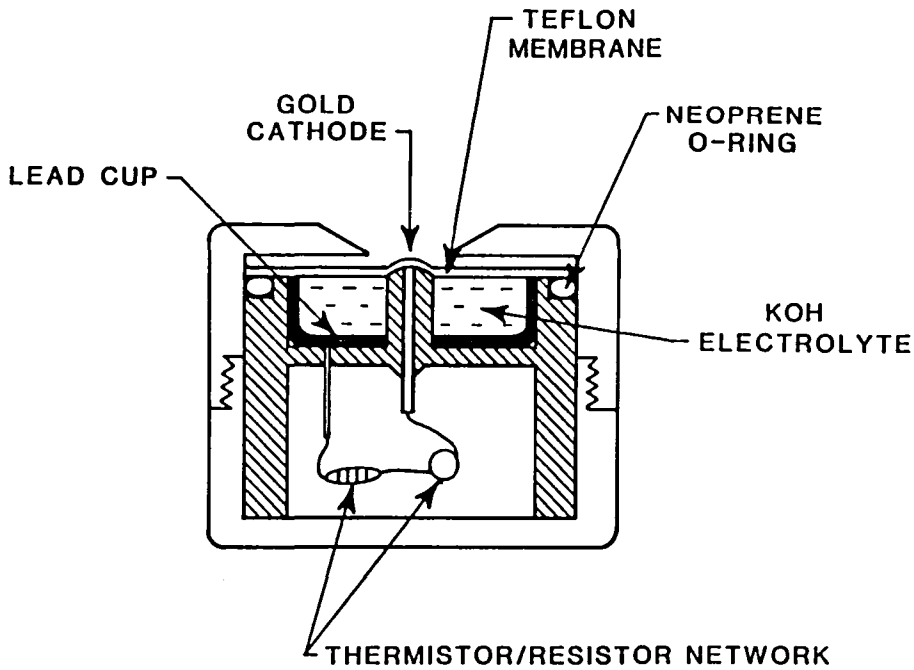


FIGURE 1. CROSS SECTION OF $O_2$ SENSING CELL

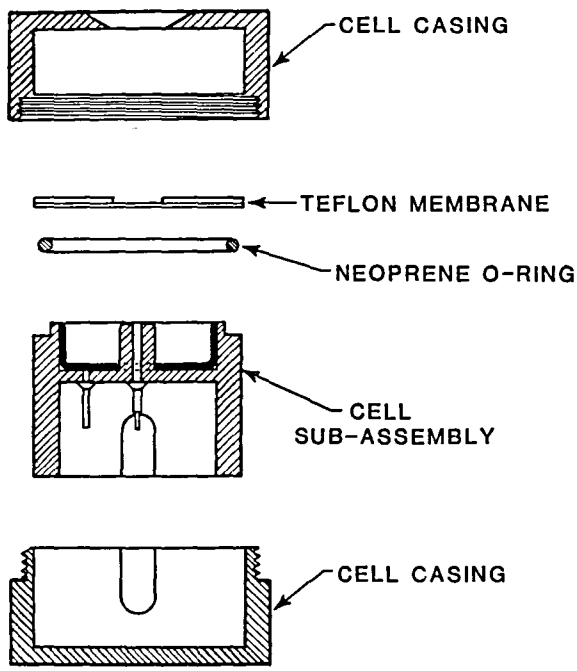


FIGURE 2, EXPLODED VIEW OF $O_2$ SENSING CELL

Oxygen diffusing into the sensor through the membrane enters into the chemical reaction:

$$\text{Cathode;} \quad O_2 + 2H_2O + 4E^- \langle\!=\!=\!=\!=\!\rangle 4OH^- \qquad (1)$$

$$\text{Anode;} \quad Pb \;\; {}^{-}\!\langle\!=\!=\!\rangle \;\; Pb^{++} + 2E^- \qquad (2)$$

The galvanic action within the cell is based upon the cathodic reduction of molecular oxygen diffusing through the membrane at the gold working cathode and the oxidation of lead at the sacrificial anode. The current path is completed externally to the sensor by a resistor/thermistor load network. The potential developed across the network is the sensor output and is a function of the current generated by the cell, which in turn is a function of the rate at which oxygen diffuses through the membrane into the cell. The diffusion rate is directly proportional to the pressure of the oxygen acting on the outer surface of the membrane. It therefore follows that when the sensor is used to measure the oxygen content of a gas mixture, such as air, the output is directly proportional to the partial pressure of oxygen in the mixture. The

sensor is therefore an oxygen partial pressure sensing device.

## Sensor Critical Considerations

As indicated by the given reaction, the sensor life is determined by the presence of water and lead. Since the sacrifical lead anode is much larger than required to sustain the reaction, sensor life is then theoretically a function of the availability of water in the electrolyte solution. As the electrolyte dries from a liquid to a paste, the sensor approaches and finally reaches the end of it's useful life.

In practice however, it has been determined that there are additional considerations regarding sensor life. Primary among these is the maintenance of a consistent membrane/cathode interface. Between the membrane and the cathode is a thin layer of electrolyte. It is critical that this layer be maintained unchanged throughout the life of the sensor. When a sensor is assembled, this layer must be such that sufficient oxygen can diffuse through the membrane to the cathode to limit the degree to which the cell can become polarized. Displacement of the membrane from it's original position will result in wide extremes in sensor output due to changes in this interface. For example, a point-source displacement of the membrane toward the cathode can produce an extremely high output, while a slight movement away from the cathode can decrease the output to near zero.

Since the membrane/cathode interface is critical to cell operation, it follows that compression loading sensitivity of the sensor could induce erratic operation or failure due to resultant membrane movement. With the sensors initially used at the NTF, the compression sensitivity is compounded by the fact that the manufacturer's field mounting device is a compression mount with holders across the face of the cell used to secure the device in place. Also, with these sensors, since the portion of the membrane directly over the cathode is a thin teflon film with no mechanical reinforcement, temperature changes and handling can also

induce errors due to membrane wrinkling and shift.

An analysis of the various sensor failure modes was performed (fig. 3). From the analysis using a sample group of several hundred sensors, it was established that, with the exception of water loss or air trapped under the membrane during manufacture, diaphragm shift was the only credible high rate failure mode causing system faults. The failures due to water loss or trapped air were determined to be controllable through quality control in manufacturing and/or the use of proper storage procedures and facilities. Membrane shift, however, can occur during manufacture, installation, or use of the cell. Methods used to control this phenomenon are discussed later in this report.

| | NUMBER OF SENSORS AFFECTED | | FAILURE MODE | | |
|---|---|---|---|---|---|
| FAILURE CAUSE | SINGLE | MULTIPLE | IMMEDIATE | GRADUAL | PROBABILITY |
| 1. $H_20$ LOSS | X | | | X | HIGH |
| 2. TRAPPED AIR | X | | X | | HIGH |
| 3. DIAPHRAGM SHIFT | X | | X | X | HIGH |
| 4. BAD ELECTROLYTE | | X | | X | MEDIUM |
| 5. CLOGGED MEMBRANE | X | | | X | LOW-MEDIUM |
| 6. SOCKET LOOSE OR CORRODED | X | | X | X | LOW-MEDIUM |
| 7. POOR SOLDER JOINT | X | | X | | LOW |
| 8. CORROSION &/OR DEPOSIT IN BASE OF CUP | X | | | X | LOW |
| 9. DAMAGED MEMBRANE | X | | X | | LOW |
| 10. OPEN THERMISTOR | X | | X | | LOW |
| 11. OPEN RESISTOR | X | | X | | LOW |

FIGURE 3, $O_2$ SENSING CELL FAILURE ANALYSIS

## Effect of Atmospheric Variables on Sensor Output

Based upon the previously given operating principles, it can been seen that the NTF Oxygen Monitoring System is used to determine the presence

of excess nitrogen by sensing any reduction of $P_{O_2}$ in the atmosphere. It follows from this that $P_{O_2}$ will also be affected by a variation in the constituent amounts of other atmospheric elements or by a change in barometric pressure.

One atmospheric variable of concern is water vapor content. Water vapor in the atmosphere will exert a partial pressure $P_{H_2O}$ based upon temperature and degree of saturation (relative humidity) and is a pressure-independent variable. Under local (mid-Atlantic coastal) summer conditions of 90°F with 73% relative humidity (RH), $P_{H_2O}$ = 26.4 mmHg. Approximate typical local extremes for $P_{H_2O}$ would be 1 mmHg (15% RH at 40°F) to 44 mmHg (90% RH at 100°F). Variations in $P_{O_2}$ of 10 to 20 mmHg within the course of twenty-four hours could be expected in the local area due to fluctuations in $P_{H_2O}$.

The most pronounced effect on the $P_{O_2}$, however, is the variation in $P_B$. For example, consider the effect of $P_B$ as a function of altitude. At sea level, the atmosphere is composed (by volume) of approximately 20.9% $O_2$, 78.1% $N_2$, 1% Argon and a variety of trace gases. With increasing altitude, this mixture remains reasonably consistent to approximately 60 000 ft. However, beyond elevations of about 18 000 ft., even though the percent of $O_2$ by volume remains unchanged, life cannot be sustained through normal respiration. At the 18 000 ft. level, $P_B$ has dropped to 379 mmHg, half of that at sea level. The partial pressure of $O_2$ has dropped in direct proportion.

As previously mentioned, the NTF display and alarm activation points are expressed in terms of percent $O_2$ by volume. The system is designed to alarm in two stages. At a level of 19%, a local visible alarm is actuated in the area concerned. At a level of 16.5% in any area, a general audible and visible system is actuated requiring evacuation of the entire facility.

With the Oxygen Monitoring System set to indicate the available $0_2$ in percent by volume and with the alarm limits set by this scale, a clarification of the relationship of this scale to the partial pressure of $0_2$ sensed by the system is necessary. For this, the altitude comparison is appropriate.

On a nominal day at sea level, the $P_{0_2}$ is approximately 159 mmHg (760 mmHg x 20.9%). Figure 4 shows the relationship between cities at sea level, and those at approximately one half mile and one mile altitudes. The NTF system alarm points of 19% and 16.5% are shown by the horizontal lines. These are given in terms of $P_{0_2}$ referenced to sea level. The comparisons with Tucson and Denver are based on equivalent days with no additional factoring for $P_{H_20}$ or air contamination. If an oxygen monitoring system was calibrated in Hampton, Virginia, with alarm

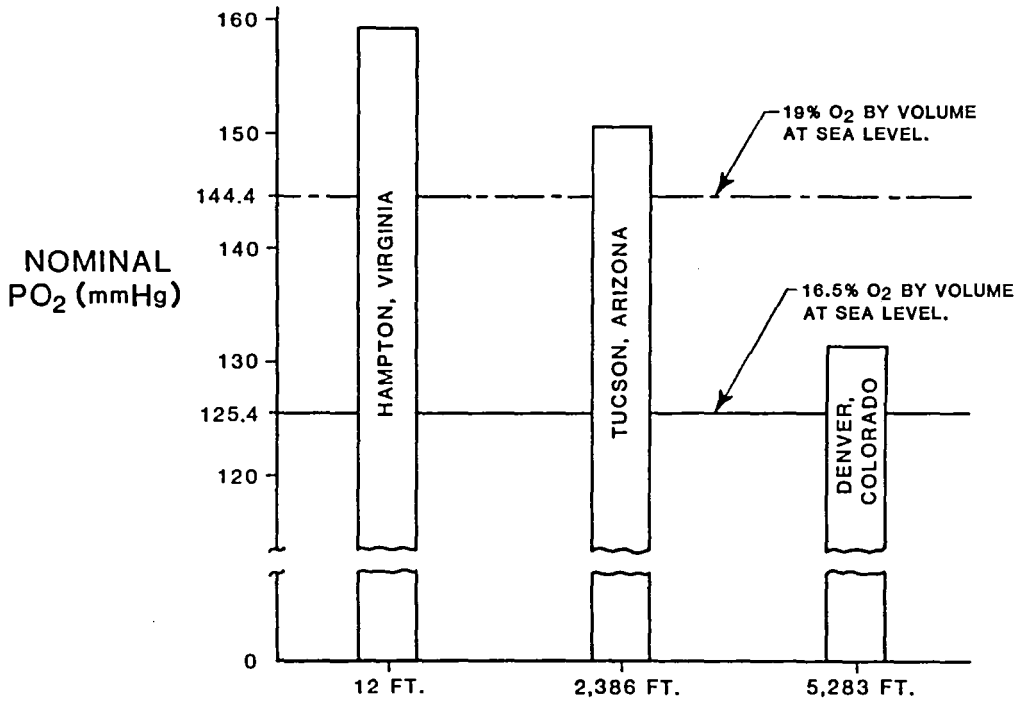


FIGURE 4, MEAN ELEVATIONS (FT. ABOVE SEA LEVEL)

limits set at 19% and 16.5% and then transported to the other cities without recalibration, it would indicate approximately 20% $O_2$ in Tucson (assuming the actual conditions were 21%). In Denver the indication would be approximately 17.5%, and the 19% alarm would be active. In that locality, only a 1% change would also actuate the 16.5% alarm.

As was noted previously, oxygen on a percent by volume basis remains consistent to about 60 000 ft. This would seem to indicate that the Hampton system, transported to Tucson and Denver was responding incorrectly, such however, is not the case. The oxygen monitoring cells sense the partial pressure of oxygen. As $P_B$ decreases as a function of altitude, $P_{O_2}$ decreases in direct proportion, and the cell output drops accordingly. Atmospheric variables affect $P_{O_2}$ in any given location and must be taken into account for proper interpretation of system output

$$P_{O_2} = 0.21\ (P_B - P_{H_2O}) \tag{3}$$

As a check on the effect of atmospheric variables on sensor output, groups of sensors were tested. The systems were calibrated and were allowed to operate for a two-week period without adjustment. On initial setup, the channels were adjusted to read the actual percentage of $O_2$ as determined on a partial pressure basis. Each day $P_{O_2}$ was recalculated and plotted along with the output of each channel. Figure 5 shows the results of the two-week test. From this it can be seen that the sensors, allowing for some scatter, track the partial pressure of oxygen with reasonable accuracy. Following the initial test, one group of sensors was readjusted and allowed to operate for an additional week. During this period, the sensors tracked even more closely (fig. 6) presumably because of taking the initial stabilization period into account.

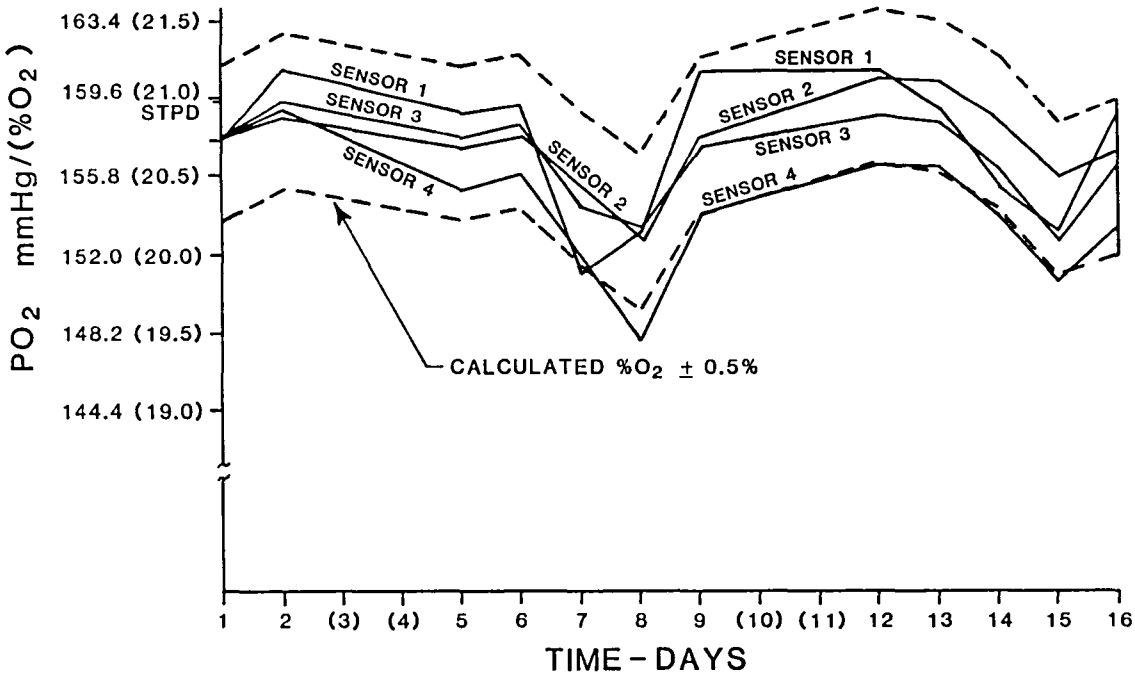


FIGURE 5, $P_{O_2}$ TEST RESULTS AFTER TWO WEEKS

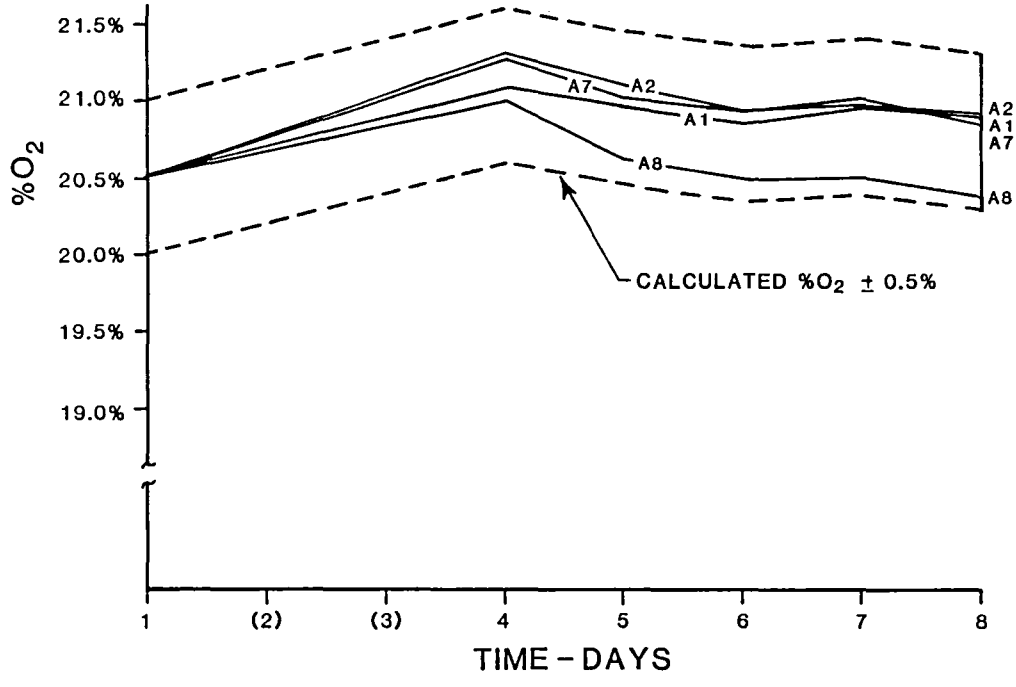


FIGURE 6, $P_{O_2}$ TEST RESULTS AFTER THIRD WEEK

Other points that become clear from a review of figures 5 and 6 are;

1) Daily adjustment of channels to an arbitrary 21% reading (as suggested by at least one manufacturer) would introduce errors into the system. In nearly all cases, such errors would decrease the margin of safety by artificially expanding the range between the true daily reading and the alarm point, e.g., if on a 20% day, the channels were adjusted to read 21%, it would be necessary for the output to fall an additional 1% before the (fixed) alarm levels would be reached.
2) Typical local area atmospheric conditions can drive the $P_{O_2}$ to near the 19% alarm point. It has been shown, in practice, that extreme conditions, such as the sudden movement of a violent weather front through the area, can result in the 19% limit being exceeded. This is particularily true of sensors on the exterior of the facility that experience the full effects of a rapidly decreasing barometer and increasing humidity.

## Sensor Rebuilding and Experimental Modifications

The sensors used at NTF during the early part of this study are designed to be refurbished when no longer useable. This procedure consists of removing the upper part of the sensor casing and membrane, and cleaning the dried electrolyte from the lead cup. The cup can then be refilled with electrolyte solution and reassembled. Critical aspects of the procedure include:

1) Assurance that the membrane has not been punctured,
2) Removal of all air from under the membrane before sealing the unit,
3) Maintenance of the proper membrane cathode interface.

In the course of sensor rebuilding, it became obvious that several elements act to limit the success ratio.

Attached to the upper surface of the membrane is an annularly shaped piece of plastic material. When the sensor is assembled, this material

is in contact with upper part of the cell casing to which it adheres tightly. During assembly, the upper part of the casing is screwed on to the lower part, and when the membrane is tightened against the o-ring, the adhesion of the membrane to the upper sensor casing causes distortion in the membrane. This can result in membrane wrinkling across the cathode and an unusable sensor. Releasing agents were tried to alleviate the problem but with limited success.

The second, and most serious problem, is the lack of rigidity of the membrane itself. This is the basic problem in maintaining the proper membrane/cathode interface. Experiments were conducted in using stainless steel wire mesh reinforcement above the membrane. It was found that this significantly decreased the sensor's sensitivity to compression loading. A survey of oxygen monitoring cells indicated that those in use at NTF were unique in having no means to control the membrane/cathode interface.

## Comparison to Similar Systems

A literature search, along with a limited side-by-side comparison, was done to relate the sensors in use at NTF to similar types. The sensors of other manufacturers were found to vary considerably in design and construction. Some were designed to be reactivated at the end of their useful life while others were not. In general, however, all incorporated rigid or reinforced membranes. One such unit made available for testing, exhibited a very low sensitivity to compression loading induced error.

The effect of the different construction principles is evident in the sensor life expectancy. Some units are warranted for one year with an actual life expectancy of up to two years. The failure rate of the original NTF units indicates that life expectancies of significantly more than six months are unlikely, and even after rejuvenation failure in the short term is probable.

A second generation sensor from the original manufacturer was made available late in the study period. This sensor incorporates improved membrane rigidity and assembly techniques. Further evaluation is planned for this and similar sensors.

## Conclusions

The installed electronics are stable and, insofar as can be determined, have not contributed to any apparent false alarms. During the period of this investigation and since, the electronics packages have exhibited a low failure rate that could typically be expected of this type of equipment.

The lack of stabilization of the membrane/cathode interface is the weakness in the sensors initially installed in the NTF system. Other manufacturers and a second generation sensor from the original manufacturer provide some means of preventing or correcting this problem. Sensors that do not incorporate some form of membrane stabilization exhibit a significant random failure rate. Sensors that incorporate this feature in some manner have shown significantly improved performance.

Sensors of this type respond accurately to $P_{O_2}$. This is significant since $P_{O_2}$, rather than oxygen percent by volume, is the critical measure regarding human aerobic metabolism. Confusion does arise, however, due to the common practice of expressing the available oxygen in terms of percent by volume. Manufacturer's literature generally recommends setting the sensor output to read 21% when initially installed. However, due to the effects of $P_B$ and $P_{H_2O}$, the true percent by volume indication may differ substantially from 21% at installation time. If the measurement period is of short term (one day or less) or if the sensor is used simply to detect gross changes in available $O_2$, the differential between the true and supposed levels may be immaterial.

However, in the case of long term measurements or where the incremental variation verses fixed alarm points is significant, such a differential can be quite important. Failure to recognize and account for such differentials can be the basis of false alarms and apparent erratic system operation. The variations in atmospheric constituents must be taken into account in evaluating cell output. Sensor drift should be considered only that portion of any apparent instability remaining after atmospheric effects are taken into account.

To simplify the daily routine of determining the actual percent $0_2$ by volume as affected by $P_B$ and $P_{H_20}$, the referenced calculations were committed to a computer program (Fig. 7). Personnel responsible for system calibration use a hand-held computer which requires entries of $P_B$, temperature, and relative humidity. The computer output is presented directly in terms of millivolts, requiring no further conversion to arrive at the true daily calibration value.

```
 10: "A" clear
 11: Pause DAILY OXY. CALCULATION
 15: Input BAROM (MB) = :A
 20: Input TEMP (F) = :T
 30: Input R.H (%) = :R
 35: R = R + 0.01
 40: T = 0.55 + (T - 32)
 45: T = 17.369 + T/(T + 238.88)
 50: T = 6.1121 + EXPT
 60: T = T/1.333
 70: A = (A-R + T)/1013
 80: A = A + 20.95 + 4
 90: PRINT CALC. OXY. MV = :A
100: 2nd
```

FIGURE 7, COMPUTER PROGRAM FOR CALCULATING DAILY $0_2$ VALUE IN MILLIVOLTS.

The NTF Oxygen Monitoring System is required to operate continually during periods of tunnel nitrogen use. In researching other uses of similar equipment it was found that, in most cases, measurements are taken over a relatively short period of time (in some cases one day or less). In such a situation, a limited amount of system drift or atmospherically induced variation may have little effect. By comparison, the NTF requirement is particularly demanding.

This report should be interpreted neither as an endorsement nor as indictment of any particular manufacturer's hardware. It is intended only as an overview of the problems associated with bringing the NTF Oxygen Monitoring System to a fully operational state and the resolution of those problems.

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15. Supplementary Notes
Langley Technical Monitor: Walter E. Bruce, Jr.

16. Abstract

Laboratory monitoring of the level of oxygen in sample gas mixtures is a relatively straight-forward process which can be performed with accurate and repeatable results. However, making such measurements on the ambient atmosphere in the workplace is somewhat more complex.

Operations at the National Transonic Facility require the storage and pumping of large volumes of liquid nitrogen. To protect against the possibility of a fault resulting in a localized oxygen deficient atmosphere, the facility is equipped with a monitoring system with an array of sensors. The system is designed to provide a local alarm at a first level oxygen deficiency indication, and a general alarm if the deficiency progresses to a second level.

During the early operational stages, the system produced recurrent alarms, none of which could be traced to a true oxygen deficiency. A thorough analysis of the system was undertaken with primary emphasis placed on the sensor units. These units sense the partial pressure of oxygen which, after signal conditioning, is presented as a % by volume indication at the system output. It was determined that many of the problems experienced were due to a lack of proper accounting for the partial pressure/% by volume relationship, with a secondary cause being premature sensor failure.

Procedures were established to properly consider atmospherically induced partial pressure variations. Sensor rebuilding techniques were examined, and those elements contributing to premature sensor failure were identified. The overall effort was successful in essentially eliminating false alarms, and the system now operates with a high degree of confidence and reliability.

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