HELIUM SENSITIVITY IN OXYGEN DEFICIENCY MEASUREMENT EQUIPMENT

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Abstract

Most accelerators in operation today use liquid helium based superconducting technology in some capacity. Many of these facilities also use fixed and portable oxygen monitors to detect an oxygen deficient atmosphere were the helium to be accidentally released. When released, helium can expand 800 times its liquid volume.

Recent helium spill tests at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) uncovered a fundamental flaw in certain types of oxygen deficiency monitoring equipment. The ensuing investigation found that the problem is endemic to a class of electrochemical oxygen sensors used throughout both the research and industrial communities. This paper describes the results of the Jefferson Lab investigation and steps taken to date to both solve the problem and inform the safety community at large.

1 HELIUM SPILL TEST

Jefferson Lab maintains a central helium liquefier (CHL) and two satellite helium compressor facilities to support the superconducting accelerators, targets, and research and development facilities. In all, there is an inventory of over 150,000 liquid liters of helium on site.

The worst credible accident that could result in a helium spill has been evaluated to be approximately 3200 ll in a matter of minutes. Helium has an expansion ratio of approximately 780 from 2 K to room temperature, so the volume available to displace oxygen is 2.5 million gl.

Spill tests are periodically conducted to verify the effectiveness of helium control measures. In the intervening period between the last test and the previous one, the tunnel vertical penetrations were sealed in order to eliminate the requirement for designating the surface buildings as oxygen deficiency hazard (ODH) areas and radiologically controlled areas. During the last such test in May, 2001, two problems were found. 1.) The spill rate can be higher than the passive evacuation rate, thus allowing helium to build up in the tunnel and spill over to uncontrolled areas, and 2.) The fixed monitoring system did not respond properly to an obviously high concentration of helium at the tunnel ceiling.

Figure 1 shows the response of the tunnel oxygen monitoring system during the test. The monitors are located in the tunnel ceiling and spaced approximately 30-50 meters apart. At no time did the indicated oxygen level drop below 18%, the oxygen deficiency evacuation alarm threshold. Measurements were also taken at the
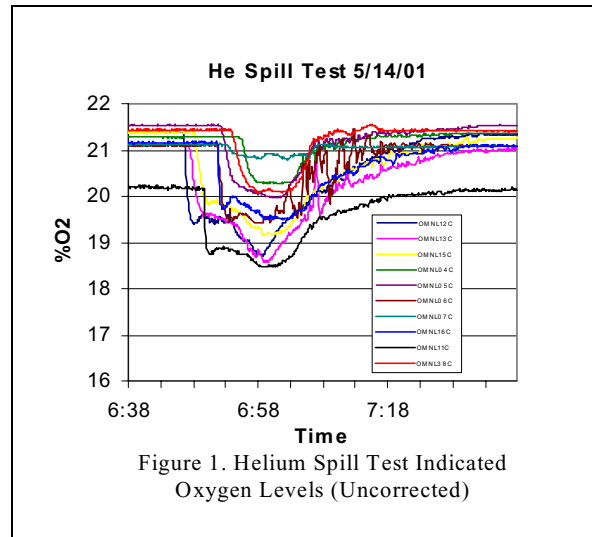
Figure 1. Helium Spill Test Indicated Oxygen Levels (Uncorrected)

ceiling using portable oxygen monitors. These monitors read as low as 11% in the immediate area of the spill. Portable monitor readings were closer to 16% indicated O2 in the area of the fixed monitor sensors. When the O2 level at the bottom of the helium lintels and dams reached 17% indicated, the test was suspended.

2 MONITOR BENCH TESTS

Immediately after the test, an investigation was launched into the cause for the discrepancy between the fixed and portable monitor readings. The following sources of error were eliminated:

- Calibration error
- Temperature
- Pressure
- Electronics non-linearity
- Sensor non-linearity using a nitrogen as a calibration gas

The sensors were then tested with a crude helium/air mix. At this point a significant error in response was noted. As an expedient verification of the test gas set-up a sampling mass spectrometer was used to test the calculated mixing ratios. The mass spec verified the mix within +/- 1.5 % indicated O2. This was too much error to make a quantitative estimate of the response non-linearity but good enough to qualitatively verify the presence of the error.

The final test set up is shown in figure 2. It used bubble flow meters, a primary standard, to measure volumetric flow into the chamber as well as a laser based oxygen analyzer to verify the oxygen content in the test chamber.

Pressure in the chamber was maintained at 1 atmosphere during the tests.

Figure 2. Volumetric mixing test set up.

The concentration of a given gas, in this case oxygen, when mixed with a diluting gas using the volumetric flow method [ref. 1] is given in equation (1). C_{O2M} is the concentration of oxygen in the final gas mixture. The concentration of helium in the room air, typically <0.17%, was ignored for the purpose of this test.

$$C_{O2M} = C_{O2}\left(\frac{q_{air}}{q_{air} + q_{gas}}\right) + C_{He}\left(1 - \frac{q_{air}}{q_{air} + q_{gas}}\right) \quad (1)$$

Figure 3 shows measurement results for 6 different models of electrochemical cells. A range of responses is shown, however, the non-linearity of certain types of sensors is obvious.
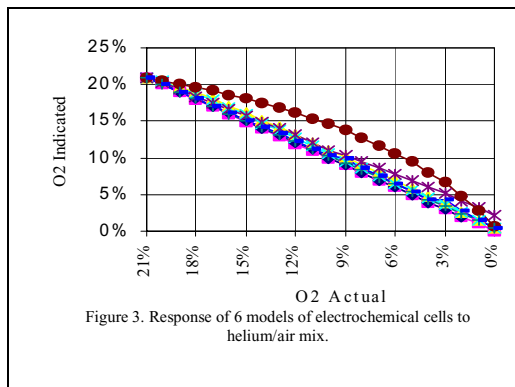

Figure 3. Response of 6 models of electrochemical cells to helium/air mix.

Measurements found that all styles of the JLab fixed monitors and all but one of the portable monitors show the nonlinear response. The portable monitor that showed a linear response was the same model that was used to measure oxygen concentration at the tunnel ceiling during the spill test. Therefore the discrepancy between the portable and fixed measurements was solved.

3 DISCUSSION

Electrochemical cells are the most widely used method of oxygen measurement due to their simplicity, small size, and low cost. The cell essentially is a battery that uses oxygen to reduce a catalyst and produce a current. Oxygen is diffused into the cell through a permeable diffusion membrane that is exposed to atmosphere.

Investigation into the electrochemical cell response led to the discovery that a particular type of diffusion barrier, the capillary type, is directly responsible for the non-linearity. Unfortunately, this is the most popular type of barrier due to its ability to allow for compensation for barometric pressure and temperature variations. Figure 4 shows a photo and diagram of a capillary type and full area diffusion barrier sensors. Cells that have a linear response use a full diffusion barrier that covers the entire surface area of the cathode.

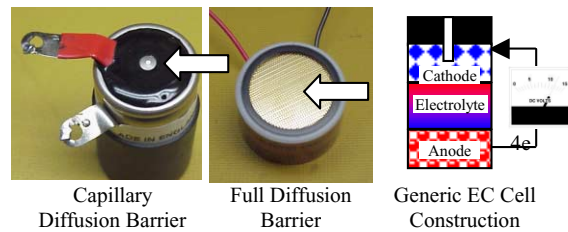Capillary Diffusion Barrier   Full Diffusion Barrier   Generic EC Cell Construction

Figure 4. Examples of Electrochemical Cells.

The theoretical response of an electrochemical cell is given by equation 2 [ref. 2].

$$S = K \ln \frac{1}{1 - C} \quad (2)$$

Where S is the sensor output in arbitrary units as defined by K, a scaling factor. C is the concentration of the measured gas. The fact that the error appeared to be diffusion related led to the conclusion that the non-linearity must be related to Graham's law of effusion, which is given by [ref. 3]:

$$\frac{dE_1}{dE_2} = \sqrt{\frac{M_{g2}}{M_{g1}}} \quad (3)$$

Where dEx is the rate of effusion for gas x. JLab measurements show the effect of a light gas such as helium to be more exaggerated than the simple Graham's law which has led to the modified equation 4 where M is the correction factor for gases with molecular weight

$$M = \left(\frac{M_{air}}{M_{(air+He)}}\right)^n \quad (4)$$

significantly different that that of air and n is set to 0.65. A plot of Graham's law (n=0.5), a typical electrochemical cell measurement and the modified model (n=0.65) are shown in figure 5.

Figure 5. Measured vs. Modeled non - linearity of oxygen sensor.
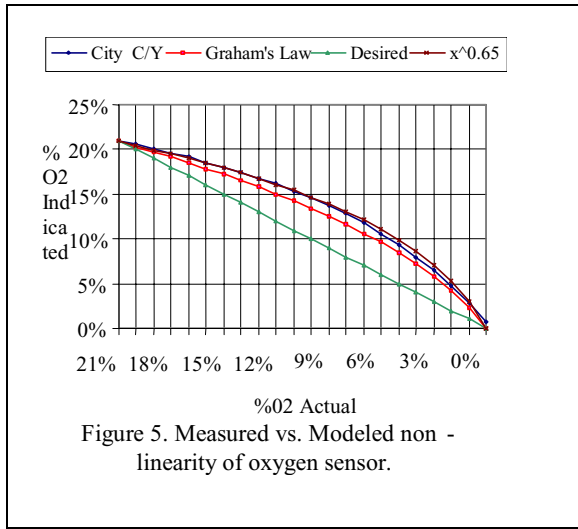
4 RESOLUTION OF THE PROBLEM

Once the non-linear effect could be quantified, steps were taken to recalibrate the installed sensors to alarm at a known 18% oxygen concentration in air as diluted by helium. A portable version of the volumetric flow test set up was used to inject a known 18% O2 mix into the sensor. The sensor was recalibrated and the alarm set point adjusted accordingly. Recalibration introduced another variable into the response function. The model was also modified to reflect recalibration at 18% O2 in helium (5)

$$S = 0.851 M \ln\left(\frac{1}{1-C}\right) \qquad (5)$$

Figure 6 shows the effect of recalibration at 18%. A linearization to rescale the analog readback was applied as shown in (6). The linearization closely matches the ideal down to 5% indicated O2.

$$S = Ci * \left(\frac{28.90574}{(118.879 * (Ci - (Ca - Cc))) - 4.0076}\right)^{0.65} + 0.22$$

$$\qquad (6)$$

Where S is the corrected readout value, Ci is the uncorrected oxygen readback, Ca is the concentration of oxygen in air (0.2095) and Cc is the concentration at which the sensor is calibrated, in this case 0.18.

5 CONCLUSIONS

Tests made at Jefferson Lab have identified a class of electrochemical oxygen monitors that exhibit a significant

non-linearity in the presence of light gases such as helium. The effect is greater than that which would be predicted solely by the standard effusion equations of air and air plus helium. It has been determined that the use of capillary type electrochemical cells is commonplace in the accelerator community for both fixed and portable oxygen monitoring equipment. With proper calibration, the installed units can be set to alarm at the proper level. Linearization equations can be developed to scale the readbacks to a true 0 to 21%. However, Jefferson Lab intends to replace the present set of sensors with linear devices.

6 REFERENCES

[1] ISO Standard 6145/1 "Gas Analysis – Preparation of calibration gas mixtures – Dynamic volumetric flow methods – Part 1: Methods of calibration, October 15, 1986.

[2] Application Note: "Oxygen Sensor Operating Instructions", City Technology Ltd.

[3] J. Kotz, K. Purcell, "Chemistry and Chemical Reactivity", Saunders College Publishing, 1987.

Figure 6. Relinearization of sensor calibrated at 18% oxygen in air/helium.

Figure 7. Sample spill test data (OM13) relinearized using (6).