INVESTIGATION OF PERSONAL AND FIXED HEAD OXYGEN DEFICIENCY HAZARD MONITOR PERFORMANCE FOR HELIUM GAS

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ABSTRACT

On May 14, 2001, the Thomas Jefferson National Accelerator Facility (JLAB) conducted a planned liquid helium release into its accelerator tunnel to study the effectiveness of the JLAB facility to vent the helium and therefore limit the oxygen deficiency hazard (ODH). During the test, it was discovered that a wide range of various oxygen deficiency monitors, of different manufacturers, were providing substantial conflicting measurements of the true oxygen level where health effects are of concern. Yet, when tested separately with nitrogen gas as the diluting gas into air, the same models performed very well. This problem, which is associated with helium displacement of air, was found for both personal oxygen monitors and fixed installation monitors from many different manufacturers. By informing other facilities of its findings, JLAB became aware this problem also exists among other national laboratories and facilities. Many manufacturers do not have data on the effects of helium displacing air for their devices. Some manufacturers have now duplicated the test results conducted at JLAB. Since both fixed installation and personal oxygen monitors have become standard safety device in many research facilities and industries in the United States and abroad, it is important that these facilities are aware of the problem and how it is being addressed at JLAB. This paper discusses the methods, procedures and materials used by JLAB to qualify its ODH sensors for helium. Data and graphs of JLAB's findings are provided.

THE JLAB HELIUM SPILL TEST

Jefferson Lab maintains and operates three cryogenic plants that provide helium and nitrogen cryogens to seven laboratory user groups. The largest of these plants [1], the Central Helium Liquefier (CHL), supplies subcooled 3 bar, 2.5K supercritical helium to the JLAB accelerator tunnel. The tunnel has 20 superconducting cryomodules in each of two underground electron beam linac areas and 2¼ cryomodules in the beam injector area. Each of the two tunnel areas is approximately 4 meters wide, 3 meters high, and 300 meters long. A single cryomodule in these areas is capable of containing up to 1600 liters of

FIGURE 1. Tunnel before the Spill Test

FIGURE 2. Tunnel during the Spill Test

liquid helium. In the event of a cryogenic system accident, liquid helium could be released into the tunnel. As it vaporizes from a liquid into a gas and warms to room temperature, its volume expands by a factor of 780. This creates large amounts of helium gas for small amounts of spilled liquid. When the helium gas mixes with the tunnel air, the breathable oxygen percentage is reduced creating an ODH hazard. To control this hazard, JLAB has vertical vent stacks in the tunnel ceiling to vent the gas from the tunnel. Helium spill tests are periodically conducted at JLAB to test the performance of the ventilation design.

Since the last test, some vertical tunnel utility penetrations to the above ground service buildings had been sealed to eliminate designating these buildings as ODH and radiological controlled areas. The recent test in May 2001 consisted of spilling 300 g/s of liquid helium for 10 minutes (1000 liquid liters total) through an 18 mm valve placed in one of the tunnel cryomodule helium supply line bayonets. The test was stopped after 10 minutes when helium was detected with a portable oxygen monitor leaking past the intended ODH control area. The indicated oxygen level was 16.5-17%. FIGURES 1 and 2 (taken from a JLAB video of the spill) show the linac tunnel before and during the spill test. No one was exposed to the reduced oxygen levels during testing because of the test procedural controls that were in place. The test data for the fixed head ceiling sensors (located near the spill and every 30-50 meters along the test tunnel) did not indicate any ODH hazard less than 18.5 percent oxygen. See FIGURE 3 below.

The ODH sensors in the tunnel ceiling did not alarm during the test because their oxygen readings did not go below 18%, which was the alarm level. The alarms are normally the basis for beginning evacuation from and prevention of entry into the tunnel. The May 2001 spill test revealed two problems.

1. The spill rate can be higher than the passive ventilation rate capacity
2. The fixed monitoring system did not respond properly to an obviously high concentration of helium at the tunnel ceiling

THE SENSOR INVESTIGATION

The Test Equipment

After the helium spill test an investigation into the difference between the observed readings of one of JLAB's portable oxygen monitors and fixed installation sensors was immediately started. All of the JLAB fixed and portable oxygen monitors are electrochemical types, which are commonly used for this application. JLAB had two hand held

He Spill Test 5/14/01

FIGURE 3. Helium Spill Test Indicated Ceiling Oxygen Levels

(HH) models for portable personal use and two fixed installation models for the various site locations. All of these were periodically checked and calibrated with nitrogen as the diluting gas. Sources of possible error were quickly eliminated including, calibration error using nitrogen as the diluting gas, temperature, pressure, electronic non-linearity, and sensor non-linearity. When a reason for the error was not found, an investigation began to determine the sensor response to air dilution by helium gas.

Since measuring the full range of residual oxygen was of interest, a method of blending a controlled amount of volumetric helium gas flow into a controlled flow of air was quickly devised to determine the sensor performance. This crude experimental apparatus consisted of two 65 mm scale rotameters (Alltech #7906, 0-1.15 ml/min air with a 65 mm scale) with inlet metering valves. Calibration sheets were obtained from the manufacturer for helium, nitrogen and air to correctly convert the rotameter millimeter scale readings into units of flow for each gas.

One rotameter was connected to a source of air supply. The second was connected to a source of nitrogen or helium as a diluting gas. The rotameter outlets were tubed together to mix the gases. The common discharge tube was then inserted into a clear glove bag in which the sensor under investigation was placed. The glove bag was not sealed completely but had a small vent hole to allow the glove bag to remain at 1 atmosphere. This apparatus was first tested with nitrogen as the diluting gas, then with helium. This was a very crude but practical method of quickly determining if a problem existed.

The flow mixture apparatus data was checked with another set of data and tests using helium/air bottled mixtures, which were made by pressure charging. The sample bottle tests had the same results as the flow mixture tests. The rotameters were later changed to more accurate soap film volumetric flow calibrators (Gilian Instruments "Gilibrators"). A test chamber was fabricated to replace the plastic glove bag. A laser diode oxygen analyzer (Oxygraf Model O2) was then added as a bench calibration standard for helium or nitrogen mixtures.

Both the oxygen standard and new flow calibrators confirmed the mixture ratios used for the former testing with the rotameters. FIGURES 4 and 5 show the present test and calibration equipment.

Figure 4. Mixture Flow Calibrators

Figure 5. Sensor Test Chamber

Determining The Mixtures

When nitrogen or helium is mixed into a stream of air, the original components of the air (oxygen and nitrogen) are reduced in equal proportion. That is, the diluting gas displaces the oxygen and nitrogen equally in proportion to their original percentage. As an example, if a helium diluting gas was mixed equally by volume with air (50/50), the percentage of oxygen in the mixture would be approximately 21% of half of the total mixture percentage (which is air) resulting in 10.5% oxygen. This makes it easy to calculate a table of values for expected levels of oxygen when using nitrogen or helium as the diluting gas. Equation 1 below defines the expected oxygen mixture concentration (C_{O2M}) in percentage when the initial oxygen concentration percentage (C_{O2A}) in the air source, the volumetric air (Q_{AIR}), and the volumetric helium flow (Q_{HE}) are known.

$$C_{O2M} = C_{O2A} \left(\frac{Q_{AIR}}{Q_{HE} + Q_{AIR}} \right) \quad (1)$$

TABLE 1. He/Air Mixture Concentrations Used by JLAB

% Air	% Helium	% O ₂	mm Air Scale	Air ml/min	mm He Scale	He ml/min
100	0	21	50	902	0	0
95	5	20	48	857	8	45
90	10	18.9	45	812	13	90
85.7	14.3	18	44	773	16	129
80	20	16.8	42	722	20	180
70	30	14.7	38	631	25	271
60	40	12.6	35	541	29	361
50	50	10.5	30	451	27	451
40	60	8.4	27	361	34	541
30	70	6.3	23	271	36	631
20	80	4.2	18	180	38	722
10	90	2.1	12	90	40	812
0	100	0	0	0	42	902

A helium/air test table was developed based on a fixed total mixed sample flow of 902 ml/min. The 902 number was chosen because the flow value was attainable with both the helium and air calibration sheets for the rotameter. TABLE 1 was used for mixing with the rotameters and Gilian calibrators. Each millimeter (mm) scale reading listed in the table has the equivalent flow value listed next to it in units of ml/min. The scale conversions are the manufacturer's rotameter calibration values for each gas. The Gilian flow calibrators indicate the ml/min flow values directly and did not require a conversion of scale.

The Test Results

The typical raw data results from the flow mixtures in TABLE 1 are shown in the following FIGURE 6 graph for both of JLAB portable hand held models (HH#1 and HH#2). The graph covers the data for the most interesting levels of oxygen from 14 to 21 percent.

To provide an independent check of the flow mixture measurements, sample bottles were prepared with helium and air for with 0, 5, 10, 15, 18, and 21% oxygen content. The sample bottles were prepared by calculated charge pressures of air and helium gas. The following TABLE 2 shows the displayed oxygen reading data. FIGURE 7 is a graph of the readings. The tested sensors were the handheld models HH#1, HH#2, and one of the tunnels fixed installation sensor heads.

Similar results to the flow mixture method results were obtained with the sample bottles. At the completion of the sensor testing three separate methods of confirming the non-linearity of the oxygen readings had been completed. These methods included calculated flow mixing, measurements against an oxygen calibration standard, and measurements with sample bottle charge concentrations.

FIGURE 6. Handheld #1 and #2 Measured Performance Against Oxygen Standard

TABLE 2. Handheld and Fixed Sensor Readings VS. %O2 Prepared Sample Bottles with He/Air Mixture

%O2	HH #1	HH #2	Fixed
21.0	21.2	21.0	21.0
18.0	18.5	19.6	19.6
15.0	15.2	17.9	17.9
10.0	9.7	14.0	14.1
5.0	6.2	9.7	9.7
0.0	0.3	0.0	0.0

FIGURE 7. Handheld and Fixed Sensor Reading VS. Prepared Sample Bottle He/Air Mixtures

All tested JLAB sensors performed very poorly with helium except for the portable HH#1 model. Because of this HH#1 is the only portable model unit now used at JLAB. The test results for the fixed installation monitors were nearly identical to those of the HH#2 model shown in Figure 7. The test data indicates a sufficient false high reading of the true oxygen content for the JLAB fixed sensors and its portable HH#2 model. This was of importance in the JLAB facility where early accurate detection of the hazard is necessary to allow ample time for the area evacuation and the prevention of entry into an unsafe environment. The fixed sensors alarm points have been reset at JLAB to obtain the correct ODH alarm point for helium. JLAB plans to replace the fixed sensors completely due to the non-linearity over the complete measurement range and because the alarm setting and readings for helium is not the same as it would be for nitrogen for the same oxygen concentration. The current reset of the fixed sensors for helium gas makes the sensor more sensitive to normal nitrogen content fluctuations in the surrounding air. JLAB has successfully completed some testing of possible replacements for its fixed sensors.

As a note, HH#1 was the same model used to detect the unwanted helium leakage into the non-ODH area during the spill test, which triggered the end of the test. This was the explanation for the sensor reading difference during the spill test when this sensor was compared to the fixed installation sensor readings. The oxygen levels measured by the

HH#1 model were lower than the values measured by the fixed installation sensors during the test.

Suggested Cause of the Inaccuracy

Sensor manufacturers have responded quickly and responsibly to JLABs inquiries about the application of displacement of air by helium gas. Many have indicated the problem may be associated with the use of a capillary tube in the diffusion barrier which normally covers the cathode of the electrochemical cell. If true, this would be unfortunate for helium applications since the capillary type diffusion barrier is the most common type of cell used. It enhances the performance of the cell by minimizing temperature and pressure change effects on the sensor. It should be noted that all of the JLAB sensors, which were found not suitable for this application, were of the capillary type. The single acceptable JLAB handheld model (HH #1) has a full diffusion type sensor. To illustrate the design difference, a typical capillary diffusion barrier and full diffusion barrier is shown in FIGURE 8.

CONCLUSIONS

Today, personal and fixed installation oxygen monitors are currently very common in the research and industrial community for oxygen deficiency hazard mitigation. One of these devices, the electrochemical cell is widely used and has advantages of cost, size and simplicity. During a routine helium spill test, JLAB noted an unexpected difference between fixed installation and personal safety electrochemical oxygen monitor readings. Initially it was believed only one personal monitor may have been at fault. It was discovered through testing under the actual application conditions, that the majority of the JLAB oxygen monitors were not suitable where helium gas displaces air. Yet, the same

FIGURE 8. Top: Capillary diffusion barrier. Bottom: Full area diffusion barrier

sensors were found suitable for conditions where heavy gases, like nitrogen, was the displacing gas. An important "lesson learned" was the need to qualify applications under the specific expected conditions. It was not a question of faulty sensors but a question of selecting and testing the sensors for the intended application.

Sensor and monitor manufacturers have been very responsive to JLABs inquiries concerning its findings. Some have already duplicated the JLAB test data and are actively working on developing solutions for the application. Some manufacturers already have products, which appear suitable. A number of other research facilities have now discovered the same results in their oxygen safety monitors for helium service. Users of electrochemical oxygen monitors for light gas service are urged to contact their equipment manufacturer for specific application information or perform testing if the sensor response is not known.

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