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Reliability of the Gas Supply in the Air Force Emergency Passenger Oxygen System

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16. Abstract

The protective breathing equipment (PBE) procured by the U.S. Air Force as Emergency Passenger Oxygen System (EPOS; Fig. 1) was alleged to have significant numbers of inadequate oxygen cylinders. In theory, this could prevent the PBE from providing the required time of protection for the user. The Civil Aerospace Medical Institute was requested to participate in the testing for the possibility of inadequate oxygen cylinders through the U.S. Air Force Office of Special Investigations. To test for any potential leakage and therefore an inadequate quantity of oxygen, EPOS units were collected from Air Force bases and submitted by the manufacturer for a series of tests. The primary indicator in the testing was the mass (weight) of oxygen in the cylinder. A total of 92 oxygen cylinders that were manufactured for assembly into EPOS or similar models of PBE were evaluated. Estimated dates of manufacture were between January 1989 and November of 2003. Four tests were conducted. The first measurement was the oxygen concentration in the vacuum-packaged PBE. The oxygen cylinders were then removed from the PBE and any difference between the current cylinder weight and the cylinder weight at manufacture was recorded. The cylinders were then exposed to 40,000 feet altitude in a hypobaric chamber for 4 hours. Weights before and after the chamber exposure were recorded. Finally, the cylinders were emptied of oxygen and the empty cylinder weight recorded. Two oxygen cylinders had large oxygen deficits (>11 grams). Based on the results of the altitude testing, the loss did not appear to be related to diffusion out of the cylinder. Therefore, other explanations need to be examined as to why these two cylinder shortages existed.

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INTRODUCTION

An emergency aboard an aircraft can require individual protection from hypoxia, smoke, and fumes. Generally, this type of protection can be offered through the availability of protective breathing equipment (PBE), commonly referred to as a "smoke hood." PBE devices have been designed for both aircraft passengers and crew. It is recognized that crewmembers require the protection offered by PBE to successfully complete their assigned tasks in emergency situations. Performance standards for crewmember PBE call for specific, functional capabilities and have been relatively well defined (Society of Automotive Engineers Aerospace Standards 8031 and 8047, Federal Aviation Administration Technical Standard Orders C99 and C116 [7]). Safety benefits in providing PBE to passengers aboard commercial transport category aircraft are a subject of debate (6). Although some guidelines have been created (The European Organization for Civil Aviation Equipment, ED-65), no governing body currently mandates or regulates "smoke hood" type devices for transport category aircraft passengers. However, due to the potential benefits of the devices in certain circumstances, many private and military organizations have made the decision to equip their aircraft with PBE for passengers.

The United States Air Force Air Mobility Command (AMC) recognized the need for a readily accessible, portable passenger protective system to supply passengers with oxygen and protect them from the effects of altitude, smoke, and toxic fumes. After an extensive evaluation and testing of available devices suited for passenger protection, a "smoke hood" type of device was selected. The Essex PB&R Corporation manufactures the device. The U. S. Air Force calls the device the Emergency Passenger Oxygen System (EPOS). These units contain a single oxygen cylinder that is required to provide a supply of oxygen to the user. Recently, questions regarding the stability of the oxygen cylinder were presented to the Air Force. It was hypothesized that the oxygen cylinders leaked and that the severity of the leak might be sufficient to result in the EPOS being unable to meet its intended purpose. To examine this possibility, the oxygen cylinders from EPOS units were collected and tested. The Civil Aerospace Medical Institute (CAMI) was requested to perform the testing by the U.S. Air Force Office of Special Investigations.

The devices tested were the Essex VRU provided to the Air Force as a Passenger Smoke and Fume Protective Device (PSFPD), designated as the EPOS. The purpose of the testing was to evaluate the oxygen content in the cylinders from units that had been manufactured over a representative range of dates. The goal was to address a very specific EPOS component, the oxygen cylinder. Emphasis was placed on possible leakage from these cylinders as indicated by the mass (weight) of oxygen they contained.

METHODS

A total of 92 cylinders were checked. All of the cylinders were of the same design. A representative range of dates of manufacturer was desired. To achieve this, the Air Force Office of Special Investigations collected two different groups of EPOS. The first group totaled 46 cylinders with estimated dates of manufacture between January 1999 and November 2003. The second group (n=23) of cylinders came from units manufactured between August 1996 and November 1997. The manufacturer provided a third group of cylinders. The estimated date of manufacture of these PBE (n=8) fell between March 1992 and April 1993. Older samples of individual cylinders were also provided. They totaled seven cylinders from the January 1989 to the August 1990 timeframe. For each cylinder, the following information was recorded: the unit serial number, the cylinder bottle number, the production batch designation, and the weight at manufacture. Four tests related to the potential loss of oxygen from the cylinders were conducted.

Test 1. The EPOS units were received in their standard vacuum-packaged condition. This process is designed to minimize exposure to humidity that might compromise the carbon dioxide scrubbers. The first test took a gas sample from the units in which the vacuum packaging appeared to be intact. A hypodermic needle was attached to the sampling line of a mass spectrometer (Perkin-Elmer, Model MGA-1100). The needle was inserted into the vacuum packaging, and a 20-30 second sample was taken at one sample per second. Cylinders in which the vacuum packaging had obviously been compromised were excluded.

Test 2. The EPOS units were carefully disassembled so as not to activate the oxygen release. Each unit and cylinder had the aforementioned information recorded. Then the cylinder was weighed (in grams) on an electronic balance (Ohaus, Model TP4KD). The difference between the present cylinder weight and the weight stamped on the cylinder at manufacture was calculated.

Test 3. A primary interest serving as the basis of the testing was whether or not the cylinders were leaking oxygen over time. It was theorized that if this were the case and the leakage was based on diffusion, the process would be accelerated by altitude exposure. Therefore, the cylinders were placed in the CAMI hypobaric research chamber and exposed to a simulated altitude of 40,000 feet for 4 hours. They were weighed after the exposure and the pre- and post-flight weight difference calculated.

Test 4. The oxygen was released from the cylinder, and the cylinder was weighed. The difference in weight between the empty cylinder and all previous weight determinations was calculated.

RESULTS

The concept underlying the first test was that leakage from the cylinders would increase the oxygen concentration in the vacuum packaging protecting the EPOS. If the volume of leakage was large enough, it could potentially rupture the packaging. Of the 69 EPOS units collected by the Air Force Office of Special Investigations, the vacuum seal of four had been compromised. Two of the four had obvious signs of intentional alteration. A square hole had been cut in one package, and the other had been partially opened in a manner consistent with the instructions. The other two compromised packages were a bit more suspicious. Both were ruptured along the seam of the packaging. This is an area that is probably most susceptible to the issues of an increase in pressure. A graph of data representative of the results obtained from testing the other 65 EPOS is presented in Figure 2. The atmospheric oxygen concentration was 20.9±0.1% prior to sampling from the package; the oxygen concentration in the package was 20.9±0.1%, and atmospheric oxygen was 20.9±0.1% after sampling from the package. These numbers supported a conclusion that no significant amount of oxygen leaked out of the cylinders and increased the package internal oxygen concentration. This assumes that the packaging is impermeable to atmospheric gases.

The differences in the current cylinder weights and the cylinder weights at manufacture (expressed in oxygen weight) are presented in Figure 3. Weights for all 92 cylinders are presented in order of increasing production batch designation. At manufacture, the cylinders are designed to contain 24.7±0.6 grams of oxygen. Seven cylinders, 7.6%, fell outside of the range of two standard deviations, assuming the difference represents a loss of oxygen. The average and standard deviation of oxygen shortage for this subset is 6.8±5.1 grams. Two cylinders that were light by 14.4 and 12.8 grams were the major contributors to the large variance. These were the same two cylinders that had the vacuum packaging ruptured along the seams. Four of the seven cylinders that were not within manufacturer weight specifications were from the same production batch-designation.

The altitude test was performed to determine if an increased pressure differential led to a loss of oxygen from the cylinder. The weight changes are presented in Figure 4. Although one bottle lost 0.4 grams of oxygen after altitude exposure, the oxygen level of this particular bottle remained within manufacture specifications. Weight consistency after altitude exposure suggested that any oxygen loss from an increased pressure differential was functionally non-existent. This conclusion was further supported by the fact that the Air Force Office of Special Investigations had collected a number of the EPOS that had been installed aboard aircraft. The weights of these units were no different than the ones yet to be used on flights.

The difference between the current weight and the empty cylinder was considered as the mass of oxygen contained in the cylinder. These levels are plotted in Figure 5. As anticipated, the differences between the weight designation at manufacture and the current weight is representative of a low oxygen level. In the cylinders that were low, the sum of this difference and the oxygen mass measured (23.2±0.2 grams) was below the level that the cylinders were supposed to contain at manufacture. The two cylinders with the lowest oxygen levels (10.3 and 11.9 grams) were from production batch designations indicating manufacturing dates between March and May of 1997.

DISCUSSION

The reason for these tests was to determine if the EPOS had oxygen supply deficits that would prevent them from performing as intended in an emergency situation. In general, the results indicated that the large majority of cylinders contained a level of oxygen consistent with cylinder design specifications. Seven of the 92 cylinders tested had oxygen levels below what is specified. These findings should be considered in functional, statistical, and historical terms.

Theoretically, the cylinders are designed to contain approximately 17.3 liters of oxygen (~24.7 grams). This

supply is required to provide a viable gas mixture for breathing to the user. If 15 minutes is considered as a representative time frame, an average of 1.15 liters of oxygen per minute would be provided. This volume represents a little over three times what a 198-pound (90kg) individual would be anticipated to utilize at rest. It would be expected to support a work level in the range of 80-85 watts. The actual demand placed on the device probably would fall between these two extremes. Picking the average between these two values results in an oxygen consumption level of ~0.73l/min which supports a work rate in the range of 50-55 watts. Using this scenario, only the most deficient cylinders (i.e., those containing 10.3 and 11.9 grams of oxygen) would fail to provide 15 minutes of breathable gas. The other five would be provide 18 minutes or more under this scenario.

Another approach might be to consider the oxygen levels in the context of FAA Technical Standard Order (TSO)-C116. For a 90kg individual, the exercise profile outlined could be expected to demand about 19.7 liters of oxygen. Thus, the PBE design meeting the TSO has two oxygen cylinders. If the findings from these samples were projected onto testing of that design, the only combination that would fail due to insufficient oxygen would be the one that had the two most deficient bottles built into the same hood. Together, those two cylinders would supply roughly 78% of the required oxygen. Any other combination of cylinders would be anticipated to pass the performance criteria for oxygen supply. A single-cylinder EPOS is designed to provide 88% of the demand required by the TSO. Between 69-81% would be provided by the five cylinders that had a reduced oxygen level. The preceding hypothetical analysis demonstrates the disparity between a manufacturing specification of a component and the overall performance of a device. This relationship makes statistical characterization of the results very difficult in terms of EPOS performance.

Means of analyzing "one-shot" devices have been established (3, 5). Again, the problem that presents itself in this particular case is whether or not the cylinder oxygen levels below specifications result in EPOS units that functionally fail to meet intended use requirements. If all those cylinders are considered hood "failures," there is no way a confidence level for reliability consistent with the mandates of the TSO-116 could functionally be achieved. In practice, this holds true even if only the two most deficient oxygen cylinders are considered to represent PBE failures. It must be recognized that the mandates of TSO-C116 are not the performance criteria required by the Air Force.

The Air Force did not specifically define the required duration of use in the Technical Order that originally described the PBE systems that were being considered for procurement. They characterized the duration of use into heavy, light-to-moderate, and sitting workloads for a 154-pound (70 kg) individual. The device was designed to function for 5, 20, and "up to" 60 minutes, respectively, for each of these conditions. Meaningful interpretation of these guidelines in light of human variation is difficult. Working through these durations of use from rest may provide some insight. Expected oxygen requirements at rest would be 0.245 L/min for a 70kg person. This results in duration of use of approximately 70 minutes. The deficient cylinders would provide 29.4, 34.0, 55.5, 56.9, 61.5, 64.0, and 65.2 minutes of oxygen. Obviously, only the two most deficient cylinders fall out of the designated range. Assuming a heavy workload uses all of the oxygen in 5 minutes, the individual would be using 3.5 L/min. This would require oxygen utilization at approximately 50 ml/kg/min. That is about 14 times the resting metabolic rate and a power output of 250 watts. A 20-minute duration allots 0.865 L/min. This projects to an oxygen utilization of 12 ml/kg/min or about 3.5 times the resting demand representing a power output of 60-65 watts. These are reasonable workloads, but each level calculated represents a number of assumptions, though valid, may or may not be applicable. Without more definitive performance specifications, definitive characterization of the manufacture specification for the cylinders is not possible.

From a historical perspective, protective breathing equipment of this general design has been in use for at least 15 years. The devices have been tested with human subjects in terms of performance at low altitudes (4), evacuation from aircraft (8), and in comparison with other PBE designs (9). Oxygen levels have been specifically monitored in more recent tests related to the performance of the EPOS (1) and EPOS improvements (2). There is no indication in the reports involving human subjects that the PBE had to be doffed as a result of lack of oxygen. Similarly, no oxygen deficiency was observed in performance testing. Database searches of aviation-related literature did not identify any reports of crewmember PBE failures related to oxygen want. This accumulated information related to the general design of the EPOS suggests that it is a reliable piece of equipment. That does not mean that the large oxygen shortage observed in two of the cylinders should not be addressed and remedied.

Maybe the most important question to be considered is "Why did the cylinders have low amounts of oxygen?" The data collected do not indicate a systematic leakage either with time or increased pressure differential. The deficient cylinders were simply low. Although circumstantial evidence of the packaging being torn could indicate

leakage from the cylinder, the conditions that stopped the process during altitude testing are hard to imagine. The simplest explanation would appear to be that the cylinders were not adequately filled during manufacture. This could be a function of manufacturing processes, component cleaning, or other quality control issues. These and any other possible explanations need to be investigated if they have not already been accomplished. The cylinders with the largest oxygen deficiencies were manufactured in 1997. The possibility exists that the reasons underlying the deficiency have been identified and addressed in terms of specific remedial action. The potential reduction in oxygen represented by the worst-case cylinders would represent a significant reduction in the duration of protection for the user.

SUMMARY AND CONCLUSIONS

Data collected from cylinders representative of the oxygen supply built into Air Force EPOS protective breathing equipment did not indicate any type of systematic leakage. However, some cylinders (7, 7.6% of the total) had oxygen levels below the design specification. For five of this group that were only slightly below the required oxygen level, it is not definitive whether the deficiency would represent a meaningful change in the performance characteristics specified by the Air Force for the device. The other two have to be considered a limitation to the functional capabilities of the EPOS. Steps should be taken to identify why the cylinders were deficient and definitive steps taken to correct the problem.

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[1]This publication and all Office of Aerospace Medicine technical reports are available in full-text from the Civil Aerospace Medical Institute's publications Web site: www.faa.gov/library/reports/medical/oamtechreports/index.cfm

FIGURES

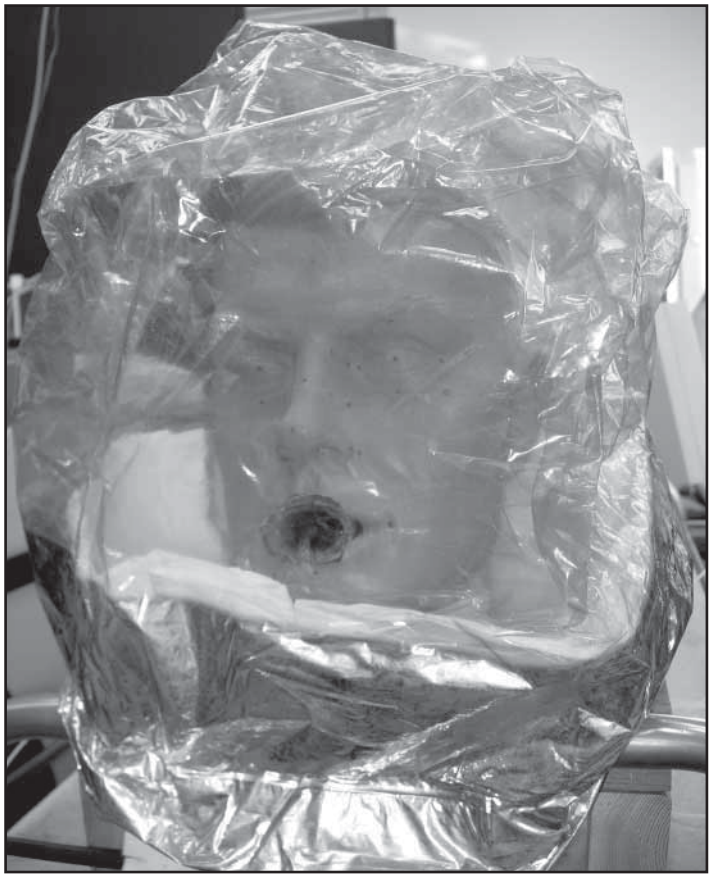

Figure 1. The Emergency Passenger Oxygen System evaluated in this study. The unit contains a single oxygen cylinder (not visible) that is normally opened to the interior of the unit when taken from the packaging for donning.

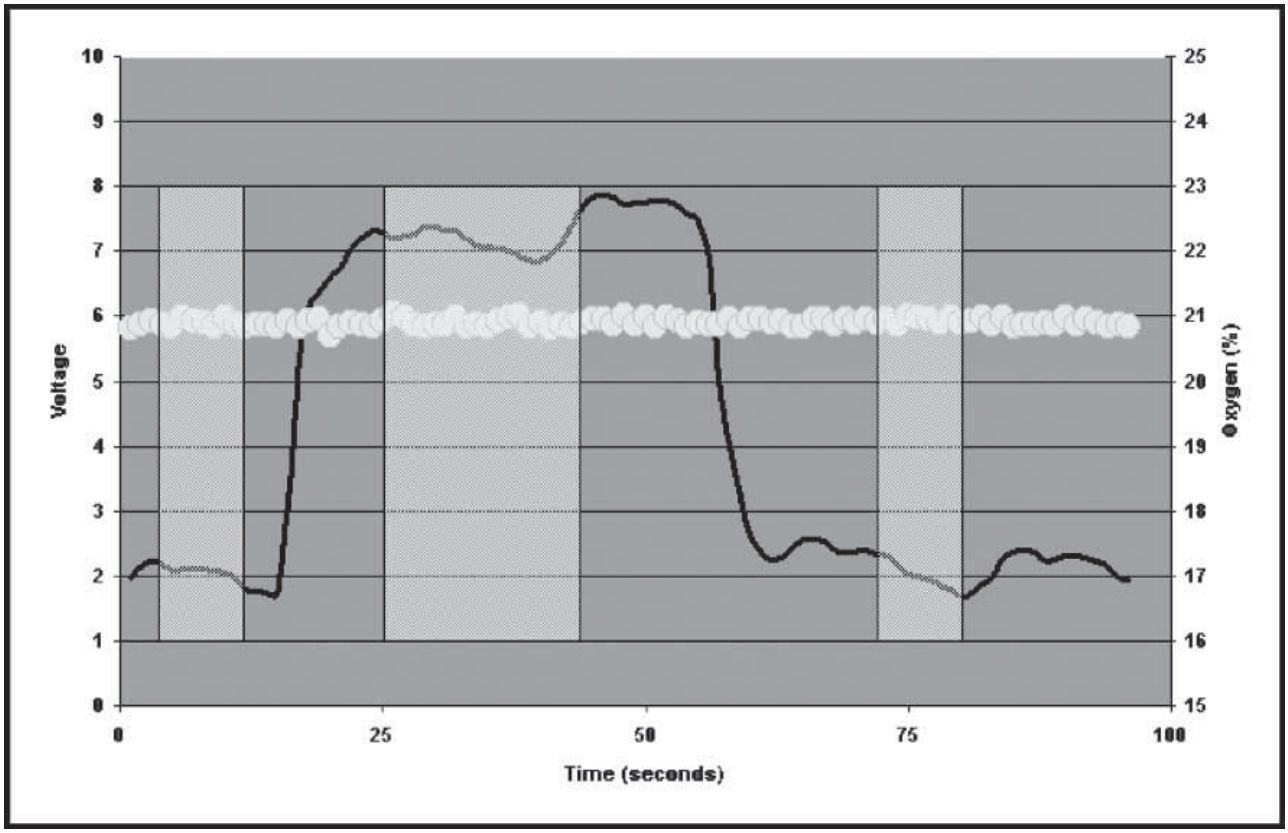

Figure 2. Sampling of gases within the EPOS packaging. This is a representative trial from Test 1. The dark line is a voltage signal use to delineate the sampling period (left y-axis). The light gray boxes are the sample collection periods used for comparison. The circles are the oxygen concentration (right y-axis).

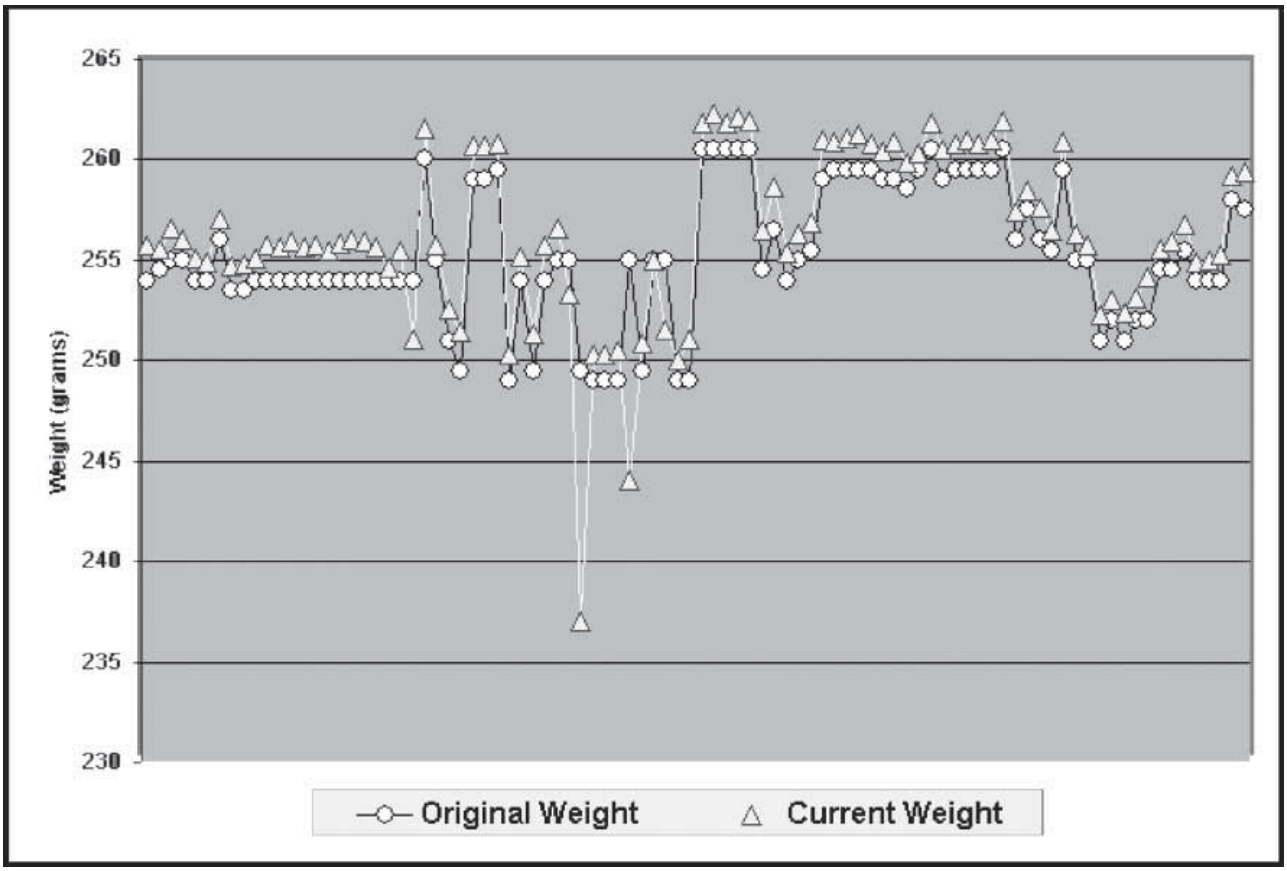

Figure 3. Differences in weight observed between weight at manufacture and the current weight. The production batch number (x-axis) is roughly equivalent to the date of cylinder manufacture. Values listed on the cylinders for weight at manufacture appear to be representative batch weights, not the actual measured weight of each individual cylinder.

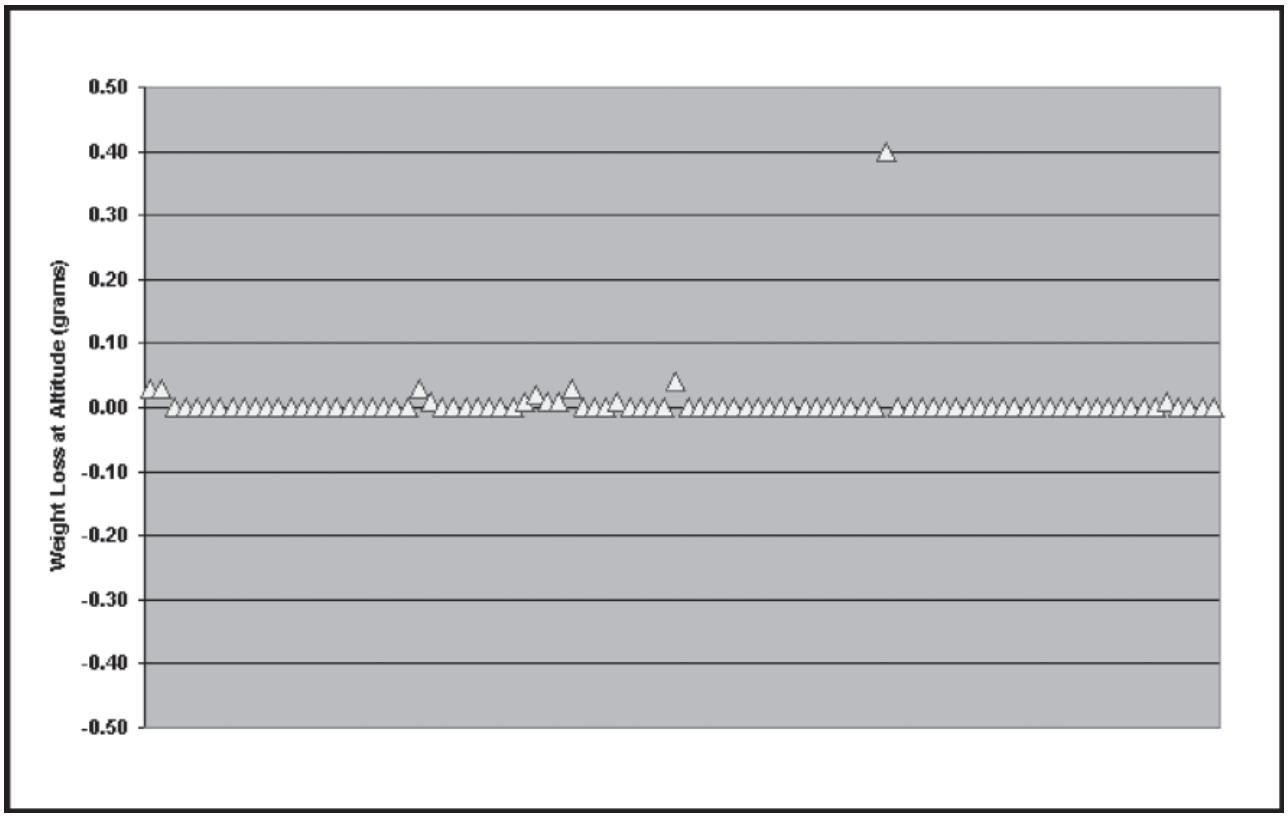

Figure 4. Weight changes resulting from a 40,000-foot altitude exposure. No meaningful weight change was observed as a result of altitude exposure. Again, cylinders are listed by increasing production batch designation.

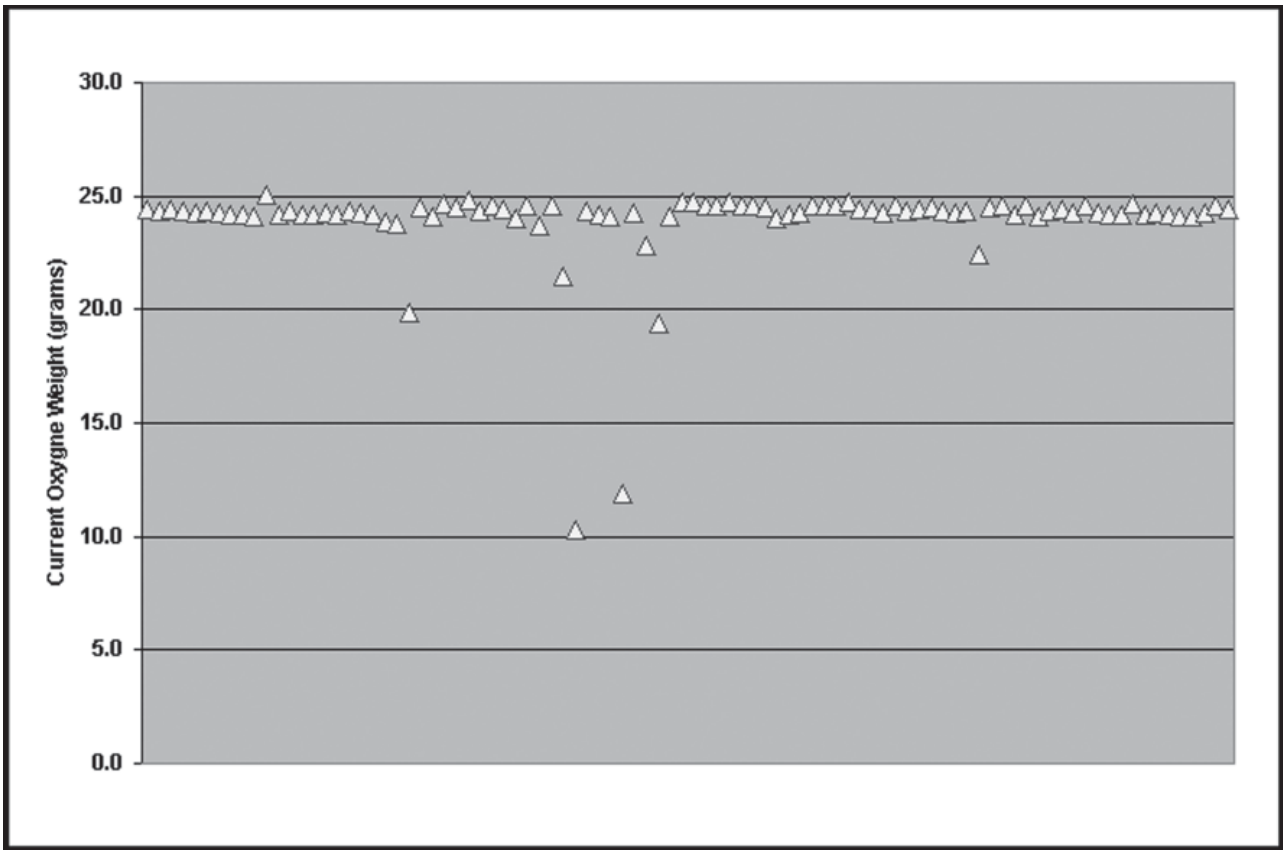

Figure 5. Mass of oxygen contained within the cylinders. The majority of deficiencies are clustered around production batch numbers and a time frame of assembly in 1997.