Design and Flight-Qualification of an Oxygen Resupply System to Support the Transport of Live Rodents to the ISS

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The transport of live rodents to the ISS aboard a pressurized commercial cargo resupply carrier, such as SpaceX Dragon or Orbital Cygnus, requires safe and reliable delivery of gaseous oxygen. This paper will present the oxygen system design for the Animal Enclosure Module – Environmental Control (AEM-E) payload, which has undergone flight certification and safety assessment and is planned to be flight-ready by early 2014. To support an animal load of 20 mice or 6 rats and a maximum mission duration of 10 days, up to 875 liters (1.26 kg) of oxygen are required. The first design challenge was to safely store this amount of oxygen within the limited volume of a middeck-locker-sized payload. The minimum risk design uses four small composite cylinders, each containing 183 liters oxygen (at ambient pressure), compressed to 20 MPa (3,000 psig). The four independent tanks provide redundancy while limiting risk from any single tank failure. Each of the four oxygen tanks is passively flow-restricted using a precision micro-orifice (25 micron diameter), reducing the risk of cabin overpressurization or exceeding safe oxygen levels – even under catastrophic failures. For a low-power and robust oxygen release mechanism, a novel oxygen-compatible wax-actuated valve was developed and certified. Using less than 4 watts each, the 20 MPa-rated valves can be opened and closed reliably. Individual electrolytic partial pressure oxygen sensors provide the control inputs to independent analog band gap controllers for each wax-actuated valve. Oxygen concentrations are controlled with a high setpoint at nominal oxygen concentrations (20.9%) and a low setpoint at 19.6%, as required for docking to the ISS. A unique analog circuit prevents activation of more than one oxygen tank at any one time, further reducing risk from system malfunctions. System qualification of the 'Design for Minimum Risk' oxygen resupply system will be presented, together with system validation and integrated performance test results.

Nomenclature

AEM-E	=	Animal Enclosure Module – Environmental Control (not: control of O_2, CO_2, rH only)
AEM-T	=	Animal Enclosure Module – Transport
CO_2	=	Carbon Dioxide
COTS	=	Commerical Off-the-Shelf
DFMR	=	Design for Minimum Risk
FMEA	=	Failure Modes and Effects Analysis
H_2O	=	Water, within this paper: air moisture, gaseous water vapor
Pa	=	Pascal, 101,325 Pa = 14.69 psia; MPa (10^6 Pa); kPa (10^3 Pa)

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O_2 = Oxygen
rH = Relative humidity
SLPM = liter per minute gas flow rate at standard temperature and pressure conditions
STP = Standard Temperature (20ºC, 293.15 K, 68ºF), and absolute pressure (101,325 Pa, 14.696 psi, 1 atm)

I. Introduction

THE Rodent Habitat project is designed to enable physiological research on the International Space Station (ISS) by providing the means to transport live rodents (mice and rats) onboard a commercial cargo resupply carrier. The project consists of two payloads that separate the tasks required to keep the rodents alive. The Animal Enclosure Module – Transporter (AEM-T) will house the rodents, provide food and water, and manage odor and waste. The AEM-E (Environmental Control) payload performs atmosphere regeneration by providing oxygen resupply, carbon dioxide removal, and humidity removal.

Each AEM-T can support 20 mice or 6 rats for up to 10 days and the AEM-E has been designed to match this mission profile. The rodents have variable metabolic rates according to their active and sleep cycles. The AEM-E oxygen control system is activated by low concentrations of O_2 in the capsule and deactivated at high concentrations. Similarly, the humidity control system, which consists of blowers moving humid air through a bed of silica gel desiccant, will only be activated when humidity levels exceed a desired threshold. Since carbon dioxide levels in the capsule cannot be too low, the CO_2-scrubbing system, consisting of blowers moving air through a lithium hydroxide (LiOH) filter, will be activated from hatch closure and will run continuously until the payload is powered down by the ISS crew after docking, and when the ISS takes over atmosphere composition control in the docked carrier as well.

Development of the AEM-E oxygen resupply system integrated commercial off-the-shelf (COTS) components and in-house designs to meet all safety and mission profile requirements. This paper will describe the design approaches for managing flow rates, safely storing high pressure oxygen, and safely and reliably releasing oxygen only when needed. The oxygen system control and safety measures will also be discussed, followed by an overview of the flight-qualification tests currently in progress.

II. Requirements

The AEM-E oxygen resupply system requirements were derived from the cargo capsule design parameters and the expected rodent metabolic loads. The concentration of oxygen inside the capsule is required to be between 19.6%[1] and 24.1%[1], with the upper threshold defined as the O_2 concentration flammability limit, and the lower limit given by the ISS environmental interface requirements document. Metabolic rates are dependent on rodent type, body mass, age, and gender, with the worst case, used for the AEM-E design, shown in Table 1.

Table 1. Derivation of AEM-E oxygen system functional requirements (worst case design load).

Animal	# of Animals	Typical mass (g)	O_2 metabolic rate (mL/hr/g)	O_2 consumption rate (mL / min)	Mission duration	Total O_2 required	+ 20% margin
Mice	20	30	5.06	50.6	10 days	729 L	875 L
Rats	6	350	1.44	50.4	10 days	726 L	871 L

As presented at the 43rd International Conference on Environmental Systems[2], the AEM-E project team used trade studies and preliminary performance tests in the decision to use a conventional high pressure gaseous oxygen system instead of a chemically stored oxygen-regeneration system, such as potassium superoxide[2]. With the ground rule established, the total oxygen required for the full mission must be loaded prior to launch. For consistency, the total oxygen supply requirement is defined in liters of oxygen at standard ambient temperature (20ºC, 293.15 K, 68ºF) and absolute pressure (101,325 Pa, 14.696 psi, 1 atm). For the worst-case rodent load defined in Table 1, 875 liters (STP, equivalent to 1.26 kg) of oxygen are required for a 10-day mission. Storage of this large volume of oxygen required pressurization, and it was determined that a system rated for 20 MPa (≈ 3,000 psig) was suitable because it is a common oxygen pressure standard used in industries that require pressurized oxygen, including medical and aviation applications.

The rate of delivery for oxygen is dependent on metabolic rates of the rodents being supported. Using the nominal (averaged over the day) rodent definition (Table 1), the flow rate of oxygen required is 51 mL/min. Given the high pressure of the stored oxygen, the pressure must be reduced by a regulator or flow-restrictor device to accurately control the flow rate. It was decided early on that a regulator would not fit in the allocated mass and volume of the AEM-E middeck locker. The AEM-E design was programmatically constrained to be a mid-deck locker sized payload (10 inch x 17 inch x 20 inch, 2 ft^3, or 57 liters), therefore all oxygen, CO_2, and humidity systems must fit within this design envelope. As a powered locker in the envisioned concept of operation aboard the unmanned resupply carriers, AEM-E can draw no more than 75 W for all blowers, fans, actuators, and electronics. The volume and power limitations imposed by the powered locker requirement would drive many of the design decisions in the AEM-E project.

III. Design Approach

The design of the AEM-E oxygen system was primarily driven by the hazards associated with high-pressure oxygen. Storage of high-pressure oxygen required COTS cylinders that would fit within the AEM-E payload, along with the CO_2 and humidity removal systems. The controlled delivery of conventional pressurized oxygen systems typically utilize a pressure regulator and solenoid valve(s), neither of which could be sized to meet the volume, mass and power limitations. Therefore, the remaining solution was an in-house valve design that uses a flow-restricting orifice and a thermal actuator to control oxygen delivery. The AEM-E oxygen system uses the design for minimum risk (DFMR) process, whereby safety-critical components "achieve fault tolerance through rigorous design, analysis, testing, and inspection practices rather than through true physical redundancy."[3] The DFMR approach requires increased margins and factors of safety and high-quality materials for all pressurized components where redundancy is impractical.

A. Flow Regulation

The standard approach in medical and aviation oxygen systems is to use a cylinder storing high-pressure oxygen, a relief valve to protect the cylinder from over-pressurization, and a shut-off hand valve to seal the cylinder when not in use. The oxygen flow path out of the cylinder first passes through a regulator to step-down the pressure from the typical 2,000 – 3,000 psig to a more modest 50 – 100 psig. A flow restrictor, usually adjustable, is used to control the oxygen flow rate and a low-pressure valve is actuated on-demand. A representative schematic of such a design is shown in Figure 1.

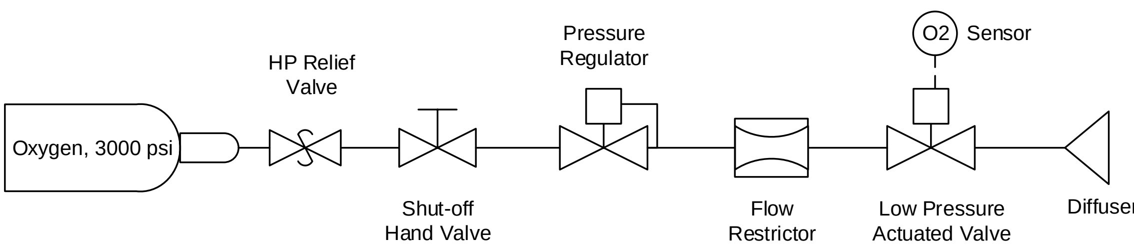

Figure 1. Standard conventional approach to high-pressure oxygen delivery system design.

Using failure modes and effects analysis (FMEA), the following failure modes and effects were identified:

(1) The regulator fails open and downstream (low-pressure) components are exposed to high pressure oxygen.
(2) The regulator fails closed, and the remaining oxygen in that cylinder is inaccessible.
(3) The low pressure valve fails open and the remaining oxygen supply is released.
(4) The low pressure valve fails closed and the remaining oxygen supply is inaccessible.

The first failure mode is addressed by adding a relief valve downstream of the regulator that will activate and limit the downstream pressure below the low pressure system maximum allowable design pressure. The second failure mode could be addressed by adding a parallel flow path, but the components required (e.g., a second regulator) would exceed the volume and mass limitation. Instead, the mitigation strategy is to divide the total oxygen into multiple independent cylinders, thus reducing the impact of losing a single cylinder. The third failure mode is addressed by adding another low-pressure valve in series with the first, ensuring that both valves must be open for the oxygen to be released. The disadvantage of this design is that the power required for each actuation is doubled. To address the fourth failure mode, an alternative flow path is required for oxygen to be released, which would consist of an additional two low-pressure valves in parallel with the first set.

In the first failure mode, the concern remains that if the regulator were to fail open and the remaining oxygen is released through the relief valve at a very high flow rate, oxygen saturation and over-pressurization of the capsule could occur. The mitigation was to use a robust high-pressure flow restrictor. According to the principle of choked flow of compressible fluids, the flow rate through such a small orifice is only dependent on the upstream pressure.

For example, the maximum possible flow rate through an orifice with a diameter of 0.0001-inch (25.4 micron) would be limited to 1.1 liters/minute at the initial upstream pressure of 20 MPa (3,000 psi). The modified oxygen system is shown in Figure 2:

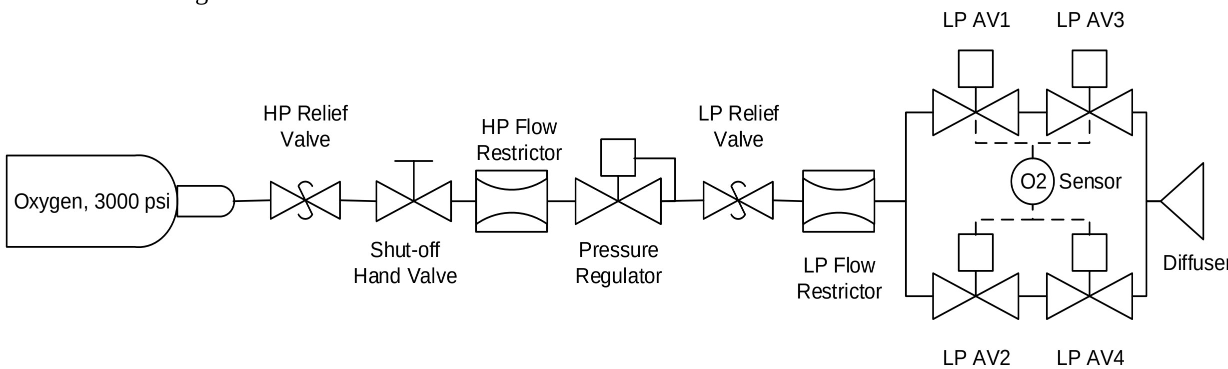

Figure 2. Single fault-tolerant oxygen system design, with high-pressure flow restrictor.

The additional components required to achieve fault-tolerance add complexity and potential sources of failure. The design in Figure 2 demonstrated that a micro-orifice can limit the flow rate in the event of a regulator failure and downstream components, the low-pressure flow restrictor and the low-pressure valve matrix, is not required. The oxygen system design can therefore be simplified to an oxygen cylinder, a high-pressure flow restrictor, and an on-demand high-pressure valve (Figure 3). The challenge was that most commercial off-the-shelf valves rated to 20 MPa (≈ 3,000 psi) require large actuators (e.g. solenoid) that would not fit in the payload, and draw in excess of 10 W during actuation. As an alternative, a thermally-actuated high-pressure oxygen valve was designed and developed at BioServe Space Technologies for this purpose and is currently patent-pending. The simplified AEM-E oxygen system design is shown in Figure 3.

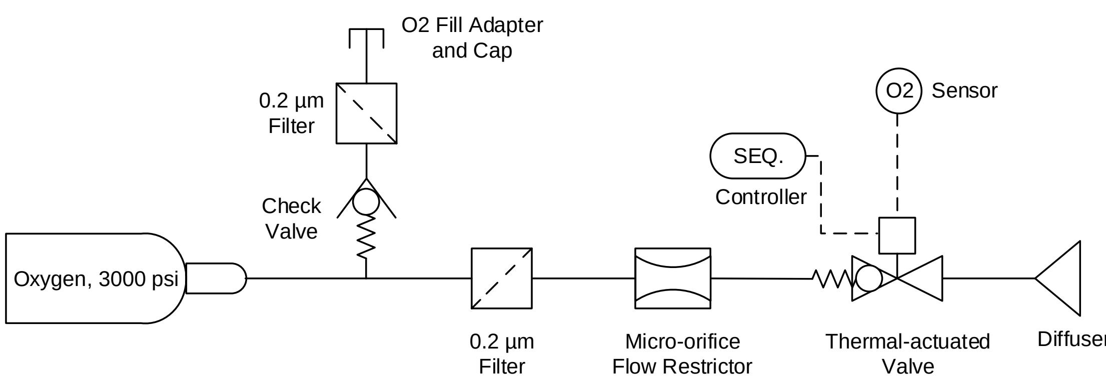

Figure 3. AEM-E oxygen system design, with high-pressure flow restrictor, no pressure regulator, and custom-designed, thermally-actuated valve.

B. Oxygen Storage

The total mass of oxygen required for a nominal rodent load (20 mice, or 6 rats) and mission duration (10 days) was defined for AEM-E as 1.26 kg. In the aviation and medical industries, the capacity of an oxygen cylinder is typically expressed in liters of oxygen, at standard temperature (25°C) and pressure (14.7 psi). The oxygen requirement can therefore also be expressed as 700 L.

A single cylinder storing the total oxygen supply presents two problems: (1) the dimensions of the cylinder (length and diameter) exceed the interior dimensions of the middeck-locker-sized AEM-E payload; and (2) a single-point failure of that cylinder would lead to flammable oxygen concentrations in the cabin, and over-pressurization of the capsule resulting from the rapid release of all 700 L of oxygen. Using a modeled environment, the release of 732 L of oxygen was shown to increase the oxygen concentration to 31.2% and the pressure would exceed 15.1 psi, assuming a 4 m^3 free-volume environment. In actuality, the capsule would trigger its protective cabin overpressurization relief valves (e.g. 14.9 psi in SpaceX Dragon), and, depending on the cabin air mixing, large amounts of oxygen would be vented to space, thus reducing the capacity to support mice for the remaining mission after the pressure relief valves close again. The modeled oxygen concentration and capsule pressures are shown in Figure 4.

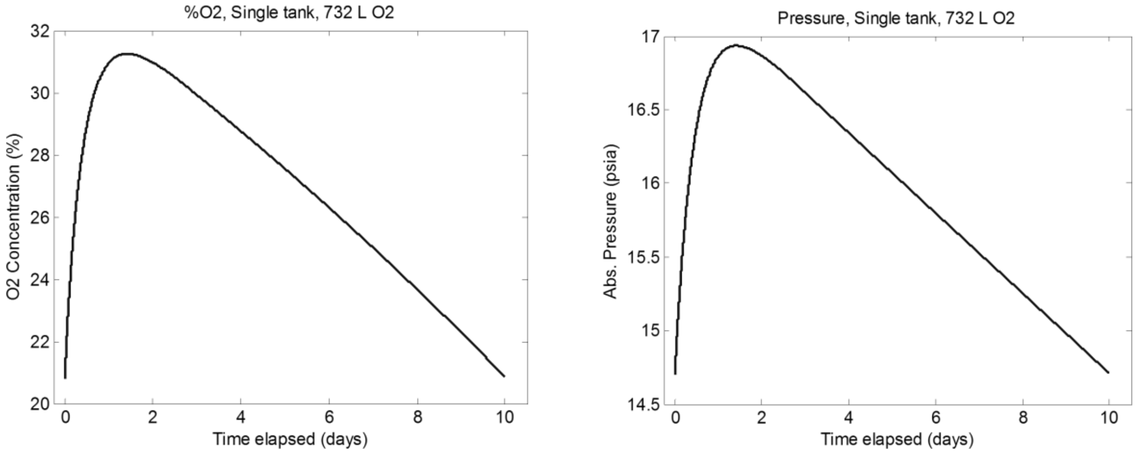

Figure 4. Simulated O_2 concentration and absolute pressures as a result of the entire 732 L O_2 supply venting through a 25-micron flow-restricting orifice into a sealed cabin with $4m^3$ of free air volume.

To reduce the risk of both overpressurization and exceeding safe oxygen concentrations, it was decided that the oxygen supply should be divided into smaller individual volumes such that a single-cylinder failure would neither increase the oxygen concentration above flammability limit (24.1% O_2) nor exceed the pressure of the capsule relief valves (14.9 psia, with a typical cabin design pressure of 17.2 psia). Given a free volume of 4 m^3 (4000 liters) in the spacecraft, oxygen cylinders sized to 183 L of O_2 reduced the hazards of oxygen saturation and cabin over-pressurization cause by a single-point failure. A trade study of high-pressure oxygen cylinders identified composite-overwrapped pressure vessels (COPVs) rated to 3000 psi that would fit within the AEM-E payload dimensions. The modeled oxygen concentration and capsule pressures are shown in Figure 5.

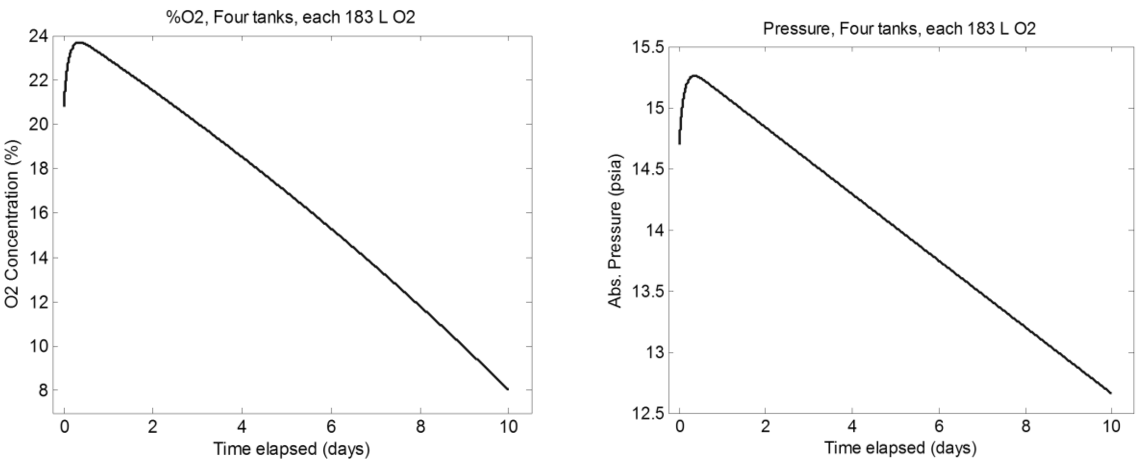

Figure 5. Simulated O_2 concentration and absolute pressures as a result of a 183 L O_2 supply venting through 25-micron flow-restricting orifice into a sealed cabin with $4m^3$ of free air volume.

C. Thermally-Actuated Valve

The high-pressure oxygen valve developed at BioServe Space Technologies (patent pending) uses a thermal wax actuator to open the valve and release oxygen. The Rostra Venatherm thermal actuator provides over 1 mm (0.04 in) of piston travel during actuation. Using an Instron machine, the stroke distance of the thermal actuator was measured for various pre-load forces and temperatures. As shown in Figure 6, below, the majority of the actuator stroke occurs at temperatures between 50°C and 60°C. To ensure reliable valve opening, the valve was designed to open within this temperature range.

In the event of a payload power failure, the concern is that an open valve may continue to release oxygen and the loss of circulating fans would lead to oxygen build-up inside the payload and a localized flammability hazard. The AEM-E oxygen valve design is intrinsically safe because in the event of power failure, the thermal actuator would cool and the valve will close in less than 4 minutes.

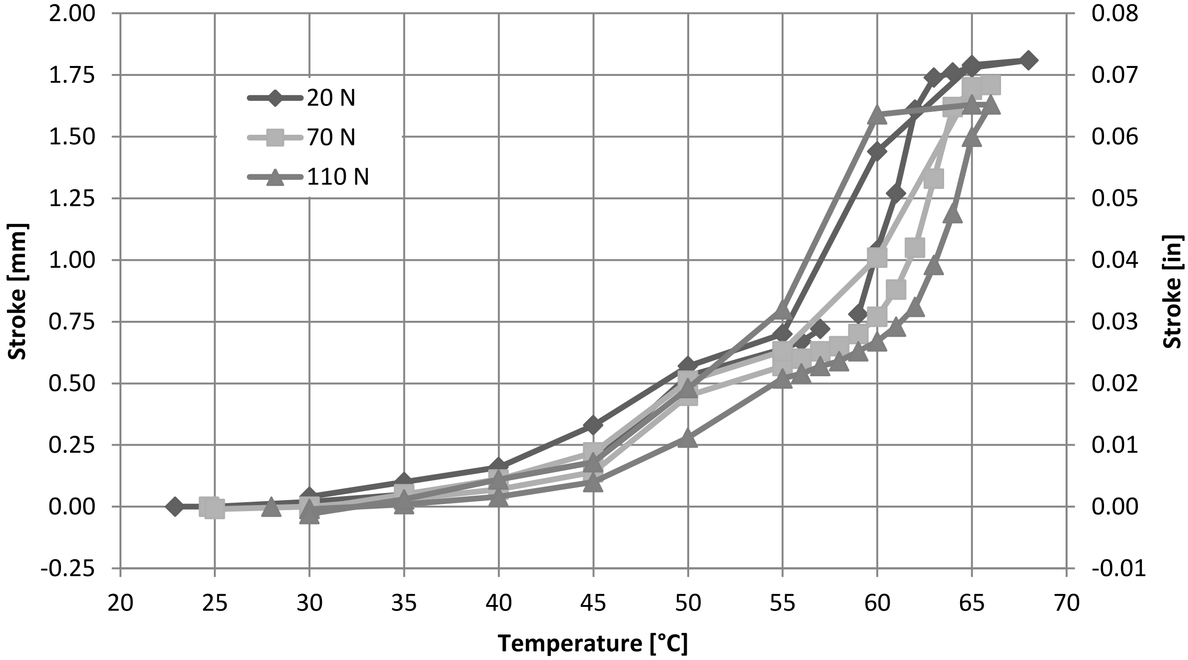

Figure 6. Experimental stroke distance measurements at various temperatures and preload forces.

The valve assembly, which consists of the inlet fill valve, release valve and thermal actuator, was designed to mount directly onto the oxygen cylinder, eliminating the need for additional tubing or mounting hardware. The materials of construction for this valve are primarily Monel alloy and PEEK (polyether ether ketone) polymer, in order to be oxygen compatible. Figure 7 shows the AEM-E cylinder assembly with the valve assembly installed.

Figure 7. Cylinder assembly and valve assembly with major oxygen system components identified.

IV. System Controls and Safety

The risks associated with oxygen release could be minimized as described above through multiple smaller systems, providing fault tolerance in case of failures of tanks or valves, both for risks to the vehicle (flammability, over-pressurization) as well as the rodents (suffocation). The task of the AEM-E control system is to detect low oxygen or high humidity, and take appropriate action by either opening or closing the oxygen valves for oxygen partial pressure control, or by activating the air flow through the humidity scrubbers. Both control functions use a band gap control, i.e., humidity and oxygen will change between an upper and lower limit, thus providing some immunity to sensor signal noise while using simple on-off controls. For a robust and reliable system, only analog electronics without the use of microcontrollers, computers and dedicated software were considered for the design. While the humidity control system posed little risk and no catastrophic hazards to the vehicle or crew, failures of the oxygen control system could result in catastrophic hazards with potential for loss of crew or vehicle through overpressurization or flammable oxygen concentration, both resulting from a release of oxygen when none is needed.

One of the key challenges therefore was to ensure that under any credible failure scenario, only one oxygen system can release oxygen in response to a low partial pressure oxygen reading. Since the design can tolerate a single, uncontrolled or undesired oxygen system release without exceeding safe limits (one-fault tolerant), the control system now has to ensure that a second uncontrolled oxygen release is not credible (design for minimum risk), or can be controlled by independent means (two-fault tolerant). Since the mechanical system uses already DFMR philosophies, this design philosophy was also carried forward to the analog oxygen release system. A functional block diagram of the system for 4 small, individual bottles is shown in Figure 8. If any of the 4 systems shown releases uncontrolled oxygen (leak, stuck valve, sensor malfunction to perceived low oxygen), the other remaining systems would measure that high oxygen concentration and would not release further oxygen. For minimum risk, only one of the 4 systems can even be powered at any one time, and only in response to measured low oxygen. Therefore, only an "enable" and simultaneous "low oxygen" signal will power the one system that detected the low oxygen system (Figure 9). The design employs individual oxygen sensors for each bottle, providing both redundancy (3 more sensors that can detect low oxygen for their bottle, in case sensor fails "high"), as well as minimum risk from undesired release in case a single sensor fails low.

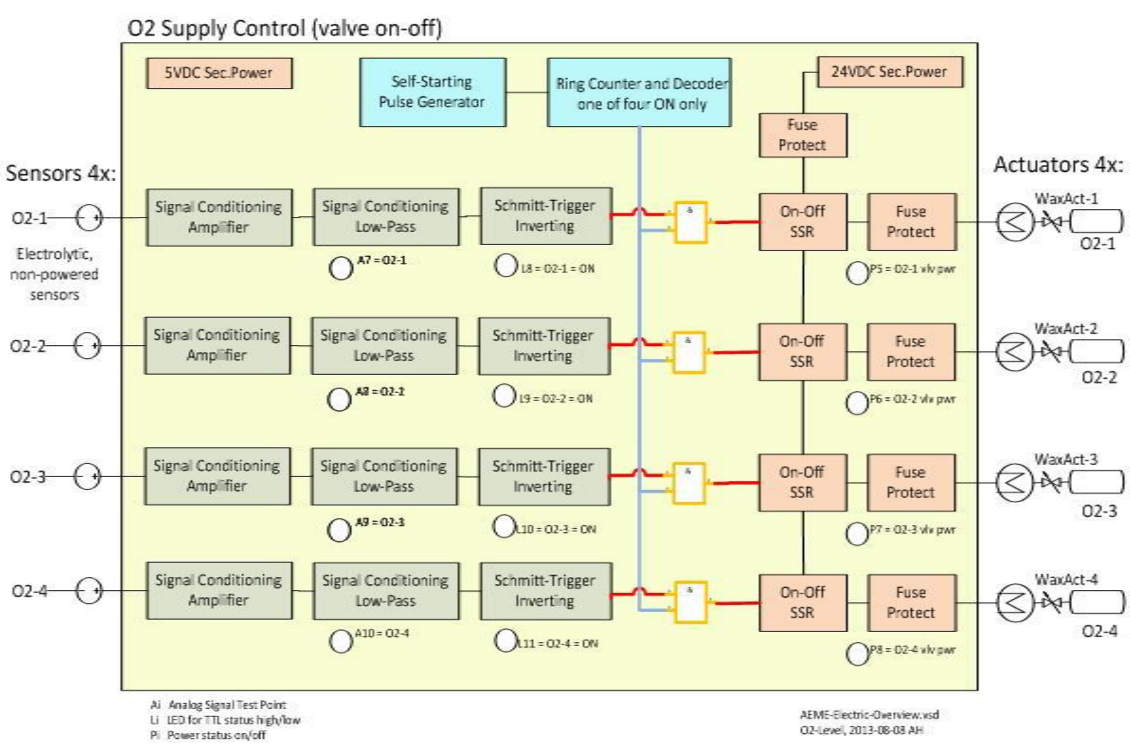

Figure 8. Functional block diagram for the 4 independent oxygen release systems. Each of the 4 systems has its own dedicated partial pressure sensor, signal conditioning system, and associated valve control switch. A so-called digital ring counter ensures that only one of the 4 systems is enabled to release oxygen.

The failure of the self-starting ring counter, a simple, robust and reliable combination of an analog timer IC chip and robust logic chips for analog decoding of the pulse signals (Figure 9) carries very little risk. The chosen timer implementation and decoder enables each of the 4 systems for 30 minutes, following a self-starting and fixed sequence. Over time, all tanks will be depleted more or less simultaneously. Due to the very low oxygen demand rates, and the passively choked small flow rates through the micro orifices described above, the required valve opening times for the chosen band gap control between 19.6% and 20.9% oxygen can last from several minutes (fully charged bottle) to several hours with empty tanks. Statistically, these long required flow times, combined with the 30 minute ring counter time period, ensure almost simultaneous depletion of oxygen in all bottles. This is further illustrated in Figure 14.

With independent oxygen sensors for each of the 4 cylinder assemblies and a robust ring counter, the only other failure mode not related to a control error would involve a mechanical failure. This failure mode was addressed by designing or choosing valve assembly components with a minimum factor of safety of 2.5. In many cases, the designed factor of safety exceeded this minimum requirement. The exception is the oxygen cylinder, which has a rated pressure of 3,000 psig, but is hydrostatically-tested to 5,000 psig every 5 years and has a designed burst pressure of 10,000 psig.

Since the AEM-E is implemented as a "payload" inside the unmanned carrier capsule, it is supplied with only a single, non-redundant power system. Similarly, within AEM-E, there is only a single power supply and control electronics system, and no functional redundancy for these components could be provided. Only components with higher failure rates, such as cooling fans and air treatment blower are provided redundantly. Functionally, for the survival of the rodents, AEM-E is zero-fault tolerant to external power failure. The failure of one of the four oxygen systems to deliver oxygen can be tolerated due to built-in reserves, as well as the fact that oxygen can be drawn down to below 19.6% without risk of suffocation, allowing to reach the ISS or earth with sufficient oxygen concentrations. For the safety of the crew and the hosting vehicle, however, the AEME system provides single fault tolerance, as well as being designed for minimum risk, both in its mechanical and electrical systems.

The AEME system design has undergone safety review to Phase 2 by the NASA Payload Safety Review Board (PSRP) at the NASA Johnson Space Center in 2013, and is currently undergoing flight qualification according to the associated hazard and interface verification requirements. Phase 3 safety review and approval is expected for the first half of 2014.

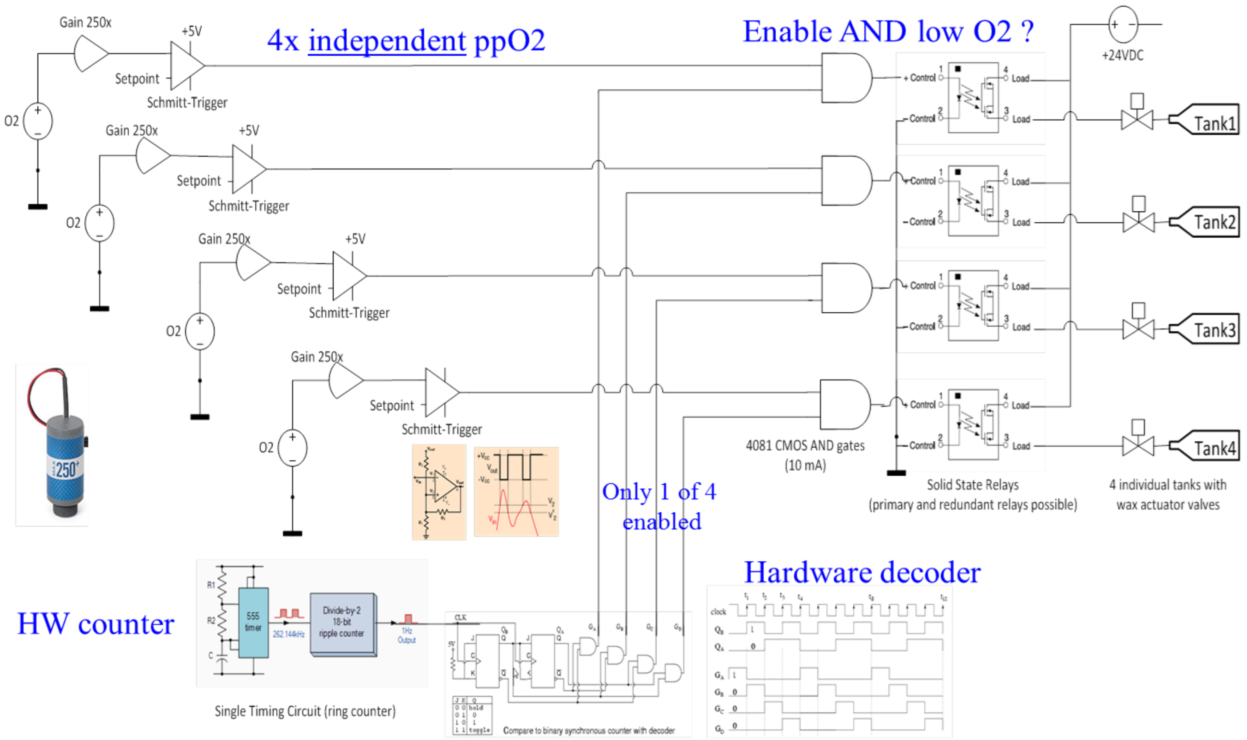

Figure 9. The analog control system ensures that only one of the 4 valves can be enabled, and that only one system can release oxygen if it is enabled and senses low oxygen. The employed logic chips are very robust and no software or microprocessors are employed in this design. All setpoints are hard-wired.

V. Flight-Qualification Test Results

The flight-qualification of the AEM-E oxygen system required a series of progressive tests to verify pressure stability (low or no leak rate) at rest and reliable oxygen delivery (pressure release) during valve actuations. Initial concepts were first tested using a ground support equipment (GSE) prototype of the valve assembly, which allowed both pressure and temperature instrumentation. These GSE tests were also performed using nitrogen, as opposed to oxygen, to mitigate the hazard associated with oxygen, and potential oxygen build-up in the test lab. The flight components, which utilize neither pressure nor temperature sensors, were used to repeat the integrated mission simulations in a flight configuration and using pure oxygen.

Gas leak rates, flow rates, and fill rates were calculated from data collected by a pressure transducer connected to the cylinder assembly. The rate of pressure change (psi / time) can then be converted into a mass flow rate using the ideal gas law and accounting for temperature changes caused by adiabatic compression / decompression and external environmental factors.

The mission simulations first used nitrogen as the test gas (inert and non-flammable) and then repeated the same tests with oxygen in an enclosed chamber with mice. The purpose of the mission simulation tests was to integrate the oxygen storage, valves, and actuator with the controller electronics.

A. Pressure Stability

A significant concern with storing high-pressure oxygen is that a small leak may lead to oxygen saturation and over-pressurization of the cargo capsule. This is primarily a concern between hatch closure and launch because the AEM-E payload may lose power for an indeterminate period, during which time the lack of air-circulating fans could lead to oxygen build-up in the payload. Similarly, after docking with the ISS, the AEM-E payload will be powered-down and placed in soft-stowage for a return trip to Earth. During this dwell period, the AEM-E oxygen system must contain the remaining pressurized oxygen in its cylinders.

To date, the AEM-E oxygen system has been tested at various pressures between 500 – 3,000 psi for over 68 hours with no measurable leaks reported. Leak rates are derived from data collected by a pressure transducer connected to the cylinder assembly. The pressure data is adjusted for temperature changes in the oxygen system, primarily from adiabatic compression (heating, during fill) and decompression (cooling, during release). Evidence of adiabatic heating is also shown at the beginning of the test results in Figure 10 (note on temperature).

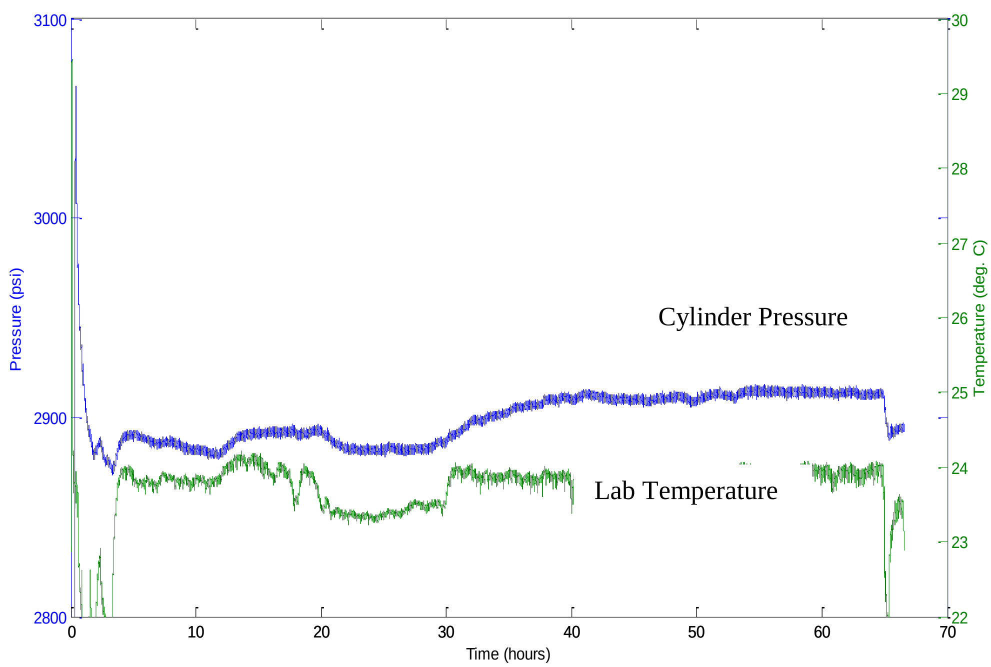

Figure 10. Pressure history and leak rate determination over time from fill to end of test (68 hours).

As the cylinders were pressurized with nitrogen, they reached a temperature of 29.5°C (ambient temperature 24°C), and the measured peak pressure (from the fill bottle regulator) was approximately 3,050 psig. Over the next 4 hours, as the cylinders cooled to ambient room temperature, the pressure in the cylinder dropped to just below 2900 psig. During a regular fill, the fill procedure requires multiple cool-down periods to achieve the desired fill pressure at or below the maximum allowable fill pressure per DOT certificate (20.5°C). The bottle was filled at rates well below the manufacturer's recommended fill rates, explaining the minimal heating during fill. The nominal fill procedure includes stabilization periods to achieve the nominal 3,000 psig fill pressure (at 20.5°, per DOT certificate) before disconnecting the filling supply.

B. Valve Cycling

Following the pressure stability tests, the next phase oxygen system tests focused on the performance of the thermally-actuated valves. In particular, the three main test objectives were:

(1) ensure that valves will open at an actuator temperature of > 50°C and release gas at the calculate flow rate,
(2) ensure that valves do not exceed 100°C during actuation, in a variety of air flows, including simulated lack of convection on orbit, and
(3) ensure that valves will close and remain sealed at an actuator temperature of ≤ 50°C.

Prior to integrating the thermally-actuated valves with the sequencing controller and oxygen sensors, the control signal was generated from a LabVIEW virtual interface. Without oxygen sensor feedback to determine when the valves should be open, and given that nitrogen was substituted for oxygen in early tests, the timing signal was simulated. The initial tests used a simple on/off ratio that repeated every hour and was independent of the pressure remaining in the cylinders. These cycles were typically 10 or 15 minutes of heating the thermal actuators, and then 50 or 45 minutes, respectively, of dwell between actuations. Using this test procedure, the GSE valve assembly had a combined total of 700 successful actuations at pressures ranging from 3,000 psig down to 50 psig. The pressure measurements from one of these repetitive tests are shown in Figure 11.

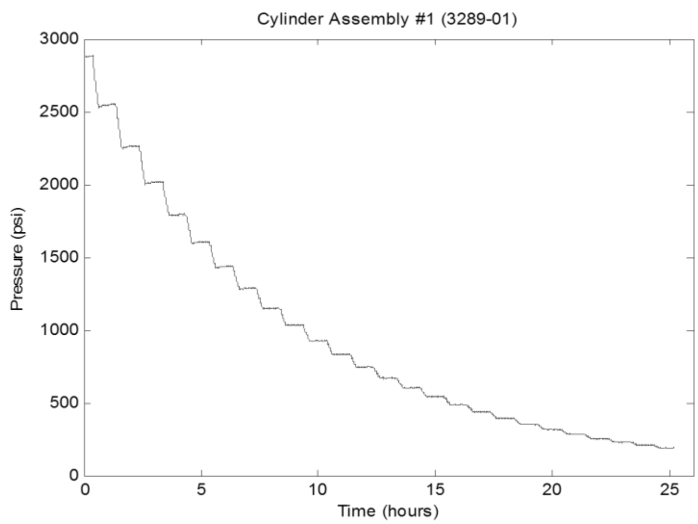

Figure 11. Incremental pressure release over time.

From the pressure plots, the flow rates during each of the valve actuations were calculated and shown in Figure 12 along with the predicted flow rate curve, for comparison. During actuation, the expansion of gas flowing through the oxygen system components lower its temperature, and therefore the measured pressure is lower. This accelerated pressure drop results in a higher calculated flow rate that is not temperature-adjusted.

Using a 3.7 W resistive heater, the temperature of the wax actuator is heated from 25°C to approximately 80°C over a period of 15 minutes, as shown in Figure 12. These tests were conducted in ambient lab air flow conditions and later repeated with the cylinder assemblies mounted in the AEM-E engineering test unit with flight air flow conditions. During operation, the cylinders are exposed to a mixing air flow of nominal 14 cfm (318 liters per minute).

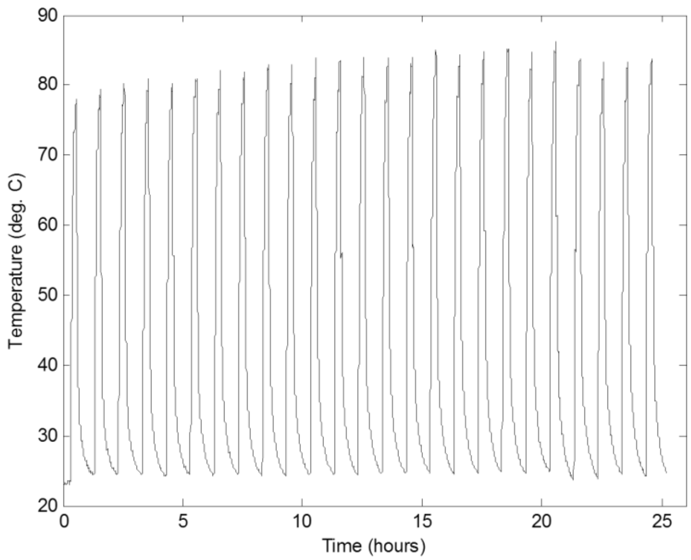

Figure 12. Temperature history during valve actuations, with ambient air circulation.

The second phase of valve actuation tests used a simulated environment to generate the valve actuation schedule shown in Figure 13, below. In a 4 m^3 capsule with oxygen concentrations controlled between 19.6 – 20.9 % O_2 and a cylinder sequencing delay of one hour, the following actuation schedule was generated (Figure 13).

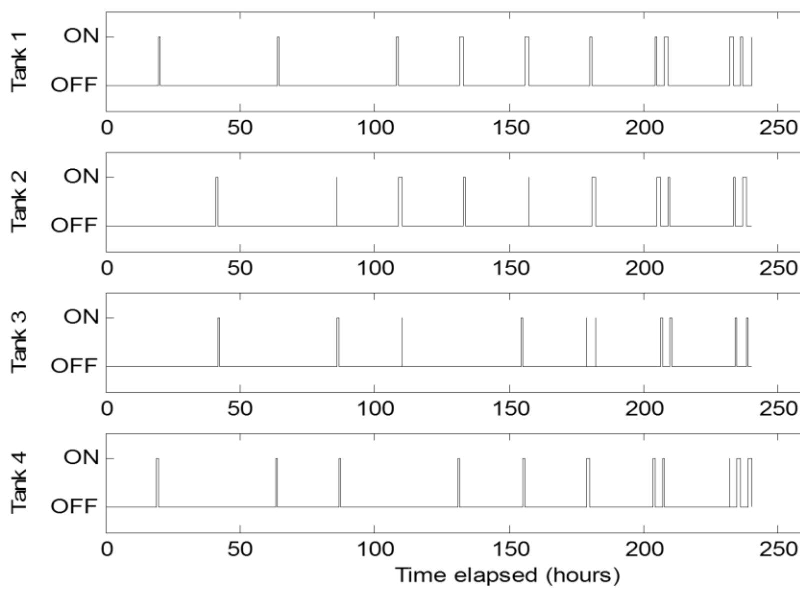

Figure 13. Simulated valve actuation tests from predicted mission simulations.

Using the simulated actuation schedule, four cylinder assemblies were tested over a period of 10 days. The results from this test are compared with the simulated oxygen system performance in Figure 14.

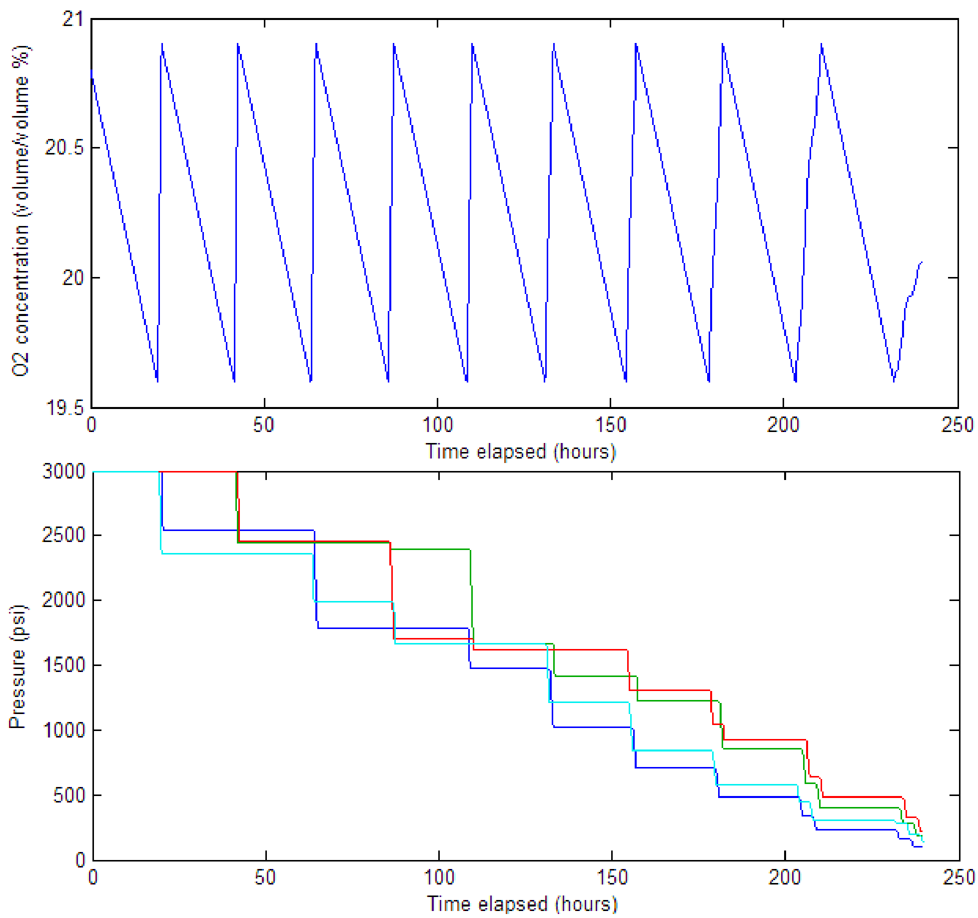

Figure 14. Simulated environment and oxygen system performance over 10-day mission. O_2 concentration in the environment and pressure remaining in each of four cylinders are shown.

C. Mission Simulations

In June of 2013, the AEM-E CO_2 and humidity removal systems were used in an integrated test with 32 mice over a period of 13 days. At the time of the integrated test, the oxygen system design had not yet been finalized so a regulated oxygen supply from a standard laboratory gas cylinder was used instead. The next integrated test, to be performed in June 2014, will use an AEM-T to house the mice and the flight-ready AEM-E oxygen system will be tested. The results of this test will be presented at ICES 2014 with a detailed analysis of the oxygen system performance.

VI. Conclusion

The AEM-E oxygen system is a fault-tolerant, intrinsically safe, and elegant minimal-component design. Using four independent cylinders, and sizing those cylinders such that a single-point failure will not exceed the O_2 concentration or the pressurization limits, represents an optimized design for minimum risk. As such, the system represents minimal risk for the resupply carrier, ground or flight crew while docked to the ISS, and ensures flexible integration into missions. AEM-E may be used for launch or return of living cargo requiring oxygen supply, carbon dioxide and humidity scrubbing due to metabolic activity and respiration.

Such life support systems are typically an integral part of the carrier, and its safe operation is assessed as part of the carrier design. AEM-E shows an alternative approach, where effects of an atmosphere-altering payload (here, the rodents inside the AEM-T) are compensated by another cargo-payload, the AEM-E. This approach to life support and associate hazard mitigation to both the rodents, carrier, flight and ground crew required novel hazard control approaches and close cooperation between the involved parties, both within NASA and its commercial transport providers. The challenges resulting from the programmatically imposed constraints to accomplish the life support task within a middeck locker equivalent payload required several non-traditional design solutions. AEM-E now provides the means to transport atmosphere-altering cargo on board un-manned resupply carriers not equipped with atmosphere control system (Cygnus), thus enabling more flexibility in utilizing ISS as a life support research laboratory.

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