X-59 Life Support System Design and Testing

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The Low Boom Flight Demonstrator project seeks to manifest quiet supersonic flight by tailoring the outer mold line of an aircraft design. The goal is to produce a less disruptive sonic boom signature as perceived by observers on the ground. The airplane currently being built in this effort, the X-59, is designed to, in coming years, validate by way of in-flight and ground measurements the design concepts behind this effort. A variety of quantitative (sonic boom pressure signatures) and qualitative (community response surveys) data sets are planned to be acquired to this end. The mission profile for the X-59 airplane calls for brief excursions above 50,000 ft pressure altitude - an inhospitable environment which imposes special considerations and stricter certifications on the life support system supplying oxygen to the sole pilot of the airplane. A primary oxygen system was designed, integrating previously flight-rated components from existing aircraft to supply gaseous oxygen from a liquid oxygen vessel. In the event of an ejection or primary system failure, a specially designed ejection-seat-mounted emergency oxygen system will provide the same functionalities, drawing oxygen from a smaller auxiliary bottle. Moreover, independent regulators selected for both systems can induce positive-pressure breathing, a physiological requirement should the pilot become exposed to the low atmospheric pressures associated with the peak operational altitudes. At the end of either oxygen supply chain, a partial pressure suit is supplied in addition to the pilot's oxygen mask. This upper-body vest provides vital counter-pressure to support the chest if positive-pressure breathing is engaged. This novel assembly of a liquid oxygen supply, positive-pressure breathing capability, and a partial pressure suit was thoroughly evaluated in hypobaric chambers in the summer of 2019 to assess the viability of the system. Chamber pressures were regulated to represent the pressure altitudes experienced by unpressurized aircraft components and the pressurized cabin as needed to simulate various nominal and emergency scenarios including level flight, emergency descents, and rapid cockpit decompressions. Additional testing evaluated multiple system configurations that were assembled to activate different flow paths that would be seen in three primary situations: nominal operation, primary system failure, and ejection. Flow rates, pressures, and temperatures throughout the system were measured to assess system performance in each permutation of these scenarios, with regard to existing breathing impedance and flow supply standards for life support systems. Findings during these qualification tests drove design evolution on both the primary and emergency oxygen systems, ultimately leading to a validated functional design.

I. Nomenclature

A. Acronyms

ABO = Aviator Breathing Oxygen
AFRC = Armstrong Flight Research Center
ASIC = Air and Space Interoperability Council
ECS = Environmental Control System
EOS = emergency oxygen system

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LOX = liquid oxygen
LPM = liters per minute
LSS = life support system
mm Hg = millimeters of mercury
NASA = National Aeronautics and Space Administration
PA = pressure altitude
PMBR = panel-mounted breathing regulator
PPB = positive-pressure breathing
psig = pounds per square inch
REOS = regulated emergency oxygen system
VPBS = Variable Profile Breathing System

B. Variables

D = tube diameter
ε = roughness characteristic length
f_s = Darcy-Weisbach friction factor
K_b = tube bend loss coefficient
L = straight tube section length
ΔP = pressure drop
ρ = density
R_b = tube bend radius
Re = Reynolds number
θ = tube bend angle
v = flow velocity

II. Introduction: The Low Boom Flight Demonstrator

As a projectile passes through a fluid at speeds at or above the speed of sound in that fluid, the projectile creates shock waves: disturbances in the fluid field characterized by sharp gradients in the fluid properties such as pressure across the shock. These shock waves propagate through the fluid with the instigating projectile. Aircraft traveling at supersonic speeds are no exception. Shock waves emanating off of various geometric features on the aircraft coalesce into two shocks: a bow shock ahead of the aircraft and a tail shock behind it. These two shocks propagate to the ground, where the pressure discontinuities manifest themselves to ground observers as distinct sounds known as sonic booms[1].

These sonic booms are perceived as disruptive enough to have warranted a Federal Aviation Administration (FAA) mandate banning supersonic overland flight with the exception of a select few restricted areas[2]. These regulations make overland commercial supersonic flight unrealizable. Commercial flight activity is thereby restricted to high-subsonic, low-transonic speeds, and subjected to the aerodynamic inefficiencies inherent to this regime of flight.

The Low Boom Flight Demonstrator (LBFD) project is an effort to develop a supersonic airplane, the X-59, with characteristically quieter sonic booms. The outer mold line geometry of the airplane is tailored to prevent shock waves from coalescing into two distinct shocks, resulting in a less drastic pressure wave observed on the ground. The distinctively long airplane, flying at high altitude, is expected to produce sonic booms no louder than 75 perceived level decibels (PLdB) [3] - roughly akin to the sound produced by a nearby car door closing.

A rigorous evaluation campaign is planned for the airplane, including measurements of the shock wave pressure differential from the ground, at low altitude, and in the near vicinity of the airplane. These measured data will serve to validate real-world performance against design parameters and predictions. Moreover, the test program calls for community overflights and populace surveys to gauge public acceptance of the quieter sonic boom. The goal of the community acceptance study is to provide data that may support reconsideration of current supersonic overland flight restrictions, opening the door for using “low boom” design and validation methods to usher in commercial overland supersonic flight without causing a public nuisance.

The X-59 mission profile includes brief interludes of flight in excess of 50,000 ft pressure altitude [3], beyond the certified altitudes for most airborne systems. A life support system (LSS) was designed at the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) (Edwards, California) to supply the pilot with oxygen to sustain him in both normal flight operations and emergencies ranging from single-point system malfunctions to ejection and egress from the airplane. Due to the high altitudes to which the airplane will be subjected, special design considerations were implemented to negotiate the physiological demands of potential exposure to that environment. This paper outlines the system-level design of the LSS and describes in greater detail the qualification test program the system has been subjected to, to date.

III. Design Overview of the X-59 Life Support System

At the highest level, the X-59 LSS is comprised of a primary oxygen supply for normal operations and an emergency oxygen system (EOS). Each system is capable of operating independently of the other, as described below.

A. Physiological Context

At the most fundamental level, the purpose of respiration is to deliver oxygen from the inhaled gas into the bloodstream. Oxygen must be supplied to the lungs at a sufficient partial pressure in the inhaled gas to drive diffusion into the bloodstream through the alveoli[4]. The X-59 LSS supplies Aviator Breathing Oxygen (ABO) - purified oxygen approaching 100-percent concentration - as the breathing gas. This selection, instead of atmospheric air (which is primarily nitrogen) results in maximal oxygen partial pressure for a given breathing gas supply pressure. Additionally, this choice saturates the bloodstream with oxygen, which is less prone than nitrogen to coming out of solution in the bloodstream during ambient decompression events. Such a physiological occurrence could result in the serious consequences of decompression illness (DCI); use of ABO as a breathing gas thus helps mitigate the risk of such hazards.

The cabin is pressurized according to a pressure differential schedule: above an activation altitude, the environmental control system (ECS) pressurizes the crew cabin with air to a fixed pressure differential greater than the outside ambient air pressure. As a result, under normal operations with a functioning ECS the pilot would never experience pressure altitudes above 22,500 ft. In an emergency, however, such as ECS failure, rapid decompression, or ejection, there do exist scenarios that would expose the pilot to the extremely low pressures of the ambient atmosphere.

In most aircraft, an oxygen system essentially operates to make a volume of oxygen available at ambient cabin pressure to the pilot for breathing. When the pilot needs to inhale, a breath is drawn from this available volume. At pressure altitudes above approximately 40,000 ft, however, ABO supplied at this ambient pressure would be insufficient to induce an adequate pressure gradient to allow diffusion into the bloodstream[4]. A higher induced supply pressure is required: positive-pressure breathing (PPB) is a mode of operation that forces air into the pilot’s mask at pressures greater than the passive volume supply seen before. Another pressure schedule based on ambient pressure altitude is implemented here, with a maximum of 70 mm Hg pressure above the ambient being supplied for extremely high pressure altitudes. This same positive pressure of oxygen is supplied to a vest worn over the chest, providing counter-pressure to the chest cavity to prevent lung rupture due to over-pressurization during PPB[5]. Special breathing regulators must be selected with PPB functionality, and special training must be implemented for pilots to handle a PPB supply, due to the un-instinctive nature of being supplied high-pressure oxygen.

These physiological requirements represent the baseline performance requirements for both the primary and emergency oxygen systems.

B. Primary Oxygen System Functionality

The primary oxygen system is characterized by legacy, flight-proven components, connected in a novel configuration, to create a system meeting the unconventional system requirements with minimal development and qualification of new hardware. At the beginning of the flow path is a liquid oxygen (LOX) converter common to the F/A-18 jet airplane (McDonnell Douglas, now The Boeing Company, Chicago, Illinois), selected because of its ease of availability and serviceability. This unit stores oxygen in its dense, space-efficient liquid state and converts it to gas for supply to the rest of the system. The now-gaseous oxygen is routed through tubing from the unpressurized LOX converter compartment (at ambient pressure altitude) forward into the pressurized cabin, to a heat exchanger near the rudder pedals. This passive heat exchanger model uses coiled finned tubing to raise the temperature from the cold flow output from the LOX converter to the ambient cabin temperature - a state that the pilot can breathe comfortably. From the heat exchanger the oxygen flows through a pressure reducer and into a panel-mounted breathing regulator (PMBR) on the cockpit console. The pressure reducer serves to protect the PMBR from over-pressurization, while maintaining a positive pressure in the range the PMBR requires to function. The PMBR is a simplified version of an existing operational regulator. Instrumentation in the primary oxygen flow path includes a LOX quantity gauge and a pressure sensor upstream of the reducer, with both readouts available to the pilot.

Having been regulated to the appropriate pressure based on the cabin altitude, the oxygen flow is routed by way of hoses to a CRU-122 manifold (Cobham Life Support, Davenport, Iowa) mounted on the pilot’s chest. This pass-through directs the ABO to three locations: the pilot’s mask, upper pressure garment (UPG), and helmet bladder.

The mask supplies oxygen to the pilot for breathing, either on demand or by way of PPB. Oxygen supplied to the over-the-chest UPG becomes a factor during PPB, providing the aforementioned chest counter-pressure protection from lung rupture. The helmet bladder is a small elastic vessel at the back of the helmet that inflates during PPB. If air is being forced out of the mask at positive pressure, the mask will tend to separate from the pilot's face and inhibit breathing; the helmet bladder inflates in order to force the pilot's head forward in the helmet-mask assembly to maintain a proper seal with the oxygen mask and facilitate PPB[5].

A schematic illustrating the oxygen flow path under the primary oxygen system is shown in Fig. 1.

C. Emergency Oxygen System Functionality

An airplane EOS is designed to be activated in emergency situations in which the primary system cannot be operated. In some cases, such as a failure of the primary oxygen system, the EOS will need to fill the same requirements as the primary system. In the event of an ejection, however, the oxygen supply will need to travel with the pilot during egress. As with all EOS designs then, the X-59 EOS is thus required to be self-contained within the ejection seat. A 50-in^3 regulated EOS (REOS) compressed gaseous oxygen bottle, as is used on multiple frontline fighter and attack aircraft, is the oxygen supply for the system. This bottle is mounted in the bottom of the seat with the seat survival kit.

The head of the REOS bottle regulates the oxygen flow to a fixed pressure range at the output of the bottle head. The bottle is opened prior to flight, pressurizing an oxygen line that is stopped at a closed binary actuation valve behind the pilot. This seat-mounted valve is the bottle head of the emergency oxygen bottle used on the ejection seat of a Northrop T-38 airplane, and contains a breakaway shear plug, discussed below. Downstream of this valve are additional hoses and tubing that route the flow to the same chest-mounted CRU-122 unit described for the primary oxygen system. However, whereas the primary flow path through this unit simply served as a pass-through manifold, the flow path of the EOS includes a regulator. This regulator actively maintains the emergency flow pressure along the same schedule that the PMBR operates on, including PPB at high pressure altitudes. As such, for proper functionality, the chest-mounted regulator requires an input of the same significant positive pressure range as does the PMBR. Downstream of the chest-mounted regulator, the connections to pilot garments are identical to those seen on the primary flow path.

During normal operations when the EOS is not engaged, the EOS flow reaches a dead end at the actuation valve. To open this valve, the pilot pulls a handle that actuates a mechanism to break the shear plug, opening an orifice for oxygen to flow through. Oxygen can now be supplied all the way from the bottle to the pilot.

A schematic illustrating the emergency oxygen system flow path is shown in Fig. 1.

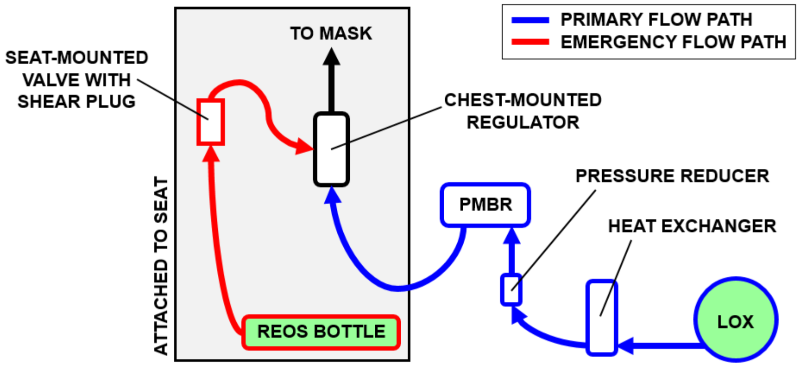


Fig. 1. Schematic of oxygen flow paths in the X-59 life support system (lengths and sizes not representative).

IV. Preliminary Life Support System Functionality Modeling

Prior to hardware assembly for systems qualification testing, a simple fluid mechanics model was created to provide confidence in the ability of the primary oxygen system to provide adequate supply pressure to the PMBR for normal functionality. Pressure losses due to friction and bending in the oxygen lines could potentially drop the pressure to a level that is too low to drive the PMBR. This evaluation served to ensure that the flow pressure at the pressure reducer upstream of the PMBR was greater than or equal to the reducer target pressure of 55 psig, meaning that the pressure reducer would be capable of supplying the PMBR with a consistently appropriate pressure range, enabling the PMBR to function properly.

The pressure drop across a length of tubing can be approximated by Eqs. (1) and (2) [6] [7]:

$$\Delta P = \frac{1}{2}\rho v^2 \left[f_s(Re,\varepsilon,D)\frac{L+\pi R_b \frac{\theta}{180}}{D} + K_b(R_b,D,\theta)\right] \tag{1}$$

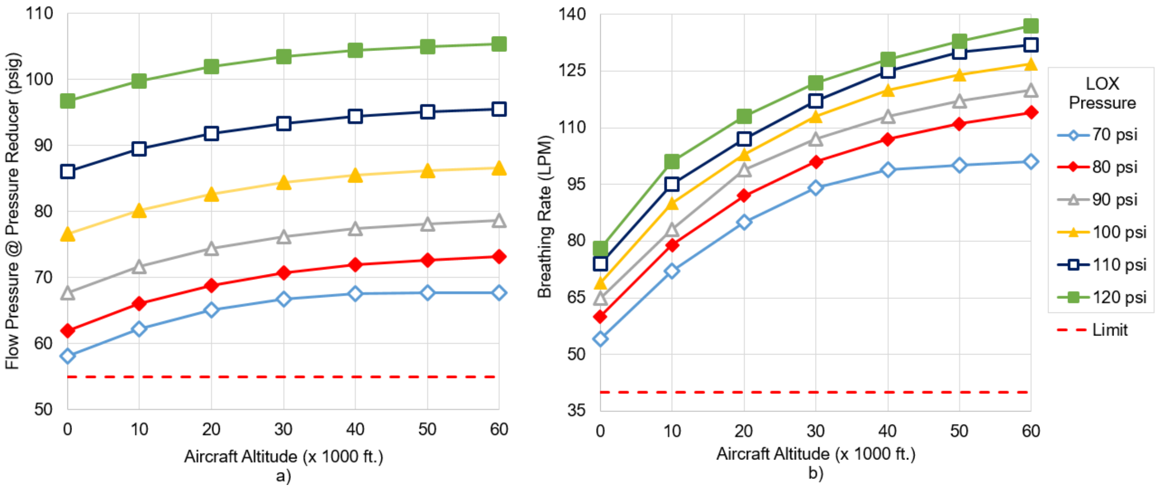
$$f_s = \frac{.25}{\left(log\left(\frac{\varepsilon/_D}{3.7}+\frac{5.74}{R_e{}^2}\right)\right)^2} \tag{2}$$

The first term in parentheses, associated with f_s, governs the pressure drop due to frictional energy losses in the boundary layer of flow through the tube. The second term, associated with K_b, accounts for the momentum change associated with bends in the tube geometry. The Darcy-Weisbach coefficient, f_s, governs the frictional losses and is estimated analytically as seen, while the bend loss coefficient, K_b, is interpolated from lookup tables[6].

The complete primary oxygen system was reduced to segments, including individual tubing lengths or components as called for by the design. Each segment, down to the miscellaneous connecting fittings between tubes, was analyzed for its induced pressure drop. Numerous assumptions were made to simplify the problem, with care taken to ensure that these would be "worst-case" assumptions resulting in worse performance (greater pressure drops) than would be realized in actuality. Noting that higher density correlates with greater pressure drops according to Eq. (1), these assumptions were:

1) Oxygen departs the LOX converter at its boiling point: as cold and dense as gaseous oxygen can be.
2) Thermal increases are negligible except in the heat exchanger, keeping the flow as dense as possible.
3) The heat exchanger induces only an increase in flow rate due to thermal expansion, ignoring pressure increases due to thermal expansion.
4) Fluid properties within the heat exchanger are uniform at the low-temperature, high-density inlet values.
5) Roughness, ε, is the roughest surface finish that a certified stainless steel sample is permitted to have[8].

Boundary conditions for this analysis comprised of the initial pressure at the LOX converter, the ambient pressure of operation, and the flow rate entering the mask. The operational analogues of these parameters are the volume of LOX available in the tank, the altitude of operation, and the pilot's breathing rate, respectively. By permuting across a range of these parameters, the performance of the system could be evaluated throughout its operational envelope. Figure 2(a) illustrates the pressure realized at the pressure reducer across the LOX quantity/altitude domain, assuming the pilot is breathing at a rate consistent with the requirement to which the flow capacity of the system was designed. To demonstrate the capacity of the system to handle higher breathing rates, Fig. 2(b) illustrates the maximum breathing rate that it can sustain without choking the pressure reducer, again in the LOX quantity/altitude domain. Note that the lower limit of the operational pressure output of the LOX converter is at 70 psi, not an empty converter.



a) b)

Fig. 2. a) Pressure modeled at the pressure reducer across the operational envelope, at the mandated "minimum required breathing rate;" and b) maximum sustainable breathing rates to supply the pressure reducer with the mandated minimum required pressure.

In Fig. 2(a) and Fig. 2(b) it can be seen that across the operational envelope, the modeled pressure supplied to the pressure reducer (Fig. 2(a)) and the modeled maximum sustainable breathing rate (Fig. 2(b)) exceed the minimum limits set forth by component and physiological guidelines[9], respectively. Greater margins between the modeled output variables and the critical values indicated by the red dashed lines demonstrate superior performance. In general it can be seen, as could be predicted from Eq. (1), that the system performs better at higher LOX quantities, higher altitudes, and lower pilot respiration rates. The worst-case scenario thus consists of a LOX quantity at its lowest operational threshold and operations at sea level. Even in this worst-case scenario, however, the system model still performs with a comfortable margin. The analytical model having successfully passed evaluation, the system was prepared for assembly and thorough hardware testing to capture any idiosyncrasies that were not evident from the model.

V. Qualification Testing Overview of the X-59 Life Support System

A rigorous battery of tests was prescribed to evaluate the functionality of both systems of the LSS in a variety of operational conditions. To simulate these different conditions, in the summer of 2019 the system was shipped to hypobaric chambers operated by KBR, Inc. (KBR) (Houston, Texas) at Brooks City Base in San Antonio, Texas.

A. Objectives

The overall objective of the qualification testing was to investigate, by way of a combination of manned and unmanned testing, four items: EOS activation procedures, breathing impedance, system functionality in rapid decompression scenarios, and EOS duration. Manned tests featured volunteers breathing through the LSS, while unmanned tests utilized a Variable Profile Breathing System, (VPBS) machine drawing programmed "breath" profiles through the LSS. Human test subjects were equipped with a backup oxygen supply in addition to the system under test. Different test hardware configurations were designed to replicate aircraft configurations in flight scenarios relevant to each objective.

1. Emergency Oxygen Activation

The interconnected nature of the primary and emergency oxygen systems led to the question of how the EOS should be activated without interference from other components. Both the primary and emergency oxygen systems interface with the pilot's chest-mounted regulator. In the event of an ejection, the EOS would be the only system connected. The primary system hose would break off at the chest-mounted regulator and be left in the stricken airplane, completely out of the oxygen supply loop. In other situations, however, such as the contamination of the primary system, it would be desirable to activate the EOS while the primary system is still mechanically functional. This study investigated to what extent the primary system would be required to be disengaged when the EOS is activated, to prevent it from impeding the emergency oxygen flow. The PMBR could be turned off but left connected to the chest-mounted regulator, or it could be disconnected at the chest-mounted regulator hose connection, removing it from the loop entirely. An alternative theory was that when both the primary and emergency flows meet at the chest-mounted regulator, the EOS could overpower the primary flow despite operating at an identical schedule. If this were found to be true, it would mean that in an emergency the pilot would not need to take any special action dealing with the primary system; merely activating the EOS would be sufficient.

This objective was tested by supplying the primary system with pure nitrogen and the EOS with pure oxygen, and sweeping the system through a full range of altitudes to determine which flow path dominated at each altitude for each investigated configuration. A mass spectrometer analyzed gas concentrations in the mask to determine which system was dominating the flow path. The successful configuration would be marked by oxygen dominating the mask volume at concentrations approaching 100 percent, indicating that the mask was being supplied solely by the EOS as desired. This test series comprised entirely of unmanned tests with the VPBS configured with a moderately high breathing rate. The conclusion of this test sequence would be used to configure the EOS for subsequent tests.

2. Breathing Impedance

Although the breathing pressure required for sustained oxygenation through breathing is predictable from physiological methods, it must also be shown that the pilot is capable of drawing sufficient volumes of air through the LSS in order to maintain breathing comfort. Moreover, the pilot should be capable of doing so without significant exertion: sustained forcible inhalation and exhalation to overcome resistance in the system could result in injury to the pilot. The Air and Space Interoperability Council (ASIC) mandates specific limits on inhalation pressure, exhalation pressure, and the difference between these two pressures as a function of peak breathing volumetric flow rate for each breathing cycle of one inhalation and one exhalation[10]. The impedance of each system (primary and emergency) was then assessed as a combination of these three parameters. Breathing impedance altitude profiles consisted of level flight profiles at a variety of altitudes. As seen in the preliminary modeling, varying pressure altitude would impact pressures and flow rates in the LSS, thereby resulting in different impedances. In manned breathing impedance tests, breathing rates were altered by having the volunteer test subjects perform tasks such as reading portions of text while riding a variable resistance stationary exercise bicycle. In unmanned tests, the VPBS was simply operated at each of its four different breathing rates of distinct volumetric flow rates and breathing cycle frequency.

The altitude profile for each individual test run was a constant specified altitude. None of the prescribed altitudes exceeded the maximum scheduled cabin altitude, because, in the event of a cabin depressurization, an emergency descent would be initiated immediately, instead of continuing level flight at high altitude. In any case, breathing impedance is reduced at higher pressure altitudes due to lower ambient pressures. Thus, little value would be gained from comprehensively testing breathing impedance at higher altitudes. Breathing impedance investigation could be seen as a "normal-operation" experiment for both LSS flow paths, ensuring that the pilot could sustainably breathe comfortably through both systems.

3. *Rapid Decompression*

A dramatic emergency scenario is rapid decompression, in which the cabin pressure rapidly drops to that of the ambient atmosphere. This scenario could be caused by cabin pressurization failure or canopy egress immediately prior to ejection. In cases in which the airplane remains flyable, an emergency descent is initiated. Otherwise, the pilot ejects and descends by free fall to breathable altitudes on the order of 10,000 ft, at which point the parachute deploys. As such, the altitude profile for these tests consists of a nearly impulsive increase from the cabin pressure altitude to the ambient altitude (rapid decompression), followed by a descent (compression). The primary system was tested to simulate in-cockpit rapid decompression scenarios. Testing the emergency system replicated both in-cockpit rapid decompressions that compromise the primary system as well as ejections from the cockpit. The rapid decompression testing sequence focused on ensuring that both paths of the LSS could provide the mask with the appropriately scheduled pressures in the PPB regime during emergencies.

4. *Emergency Oxygen System Performance and Duration Testing*

The final primary objective of the qualification testing program was to ensure that the limited capacity of the EOS oxygen bottle could be actuated as designed and sustain a pilot long enough to descend to a breathable altitude, whether in the airplane or during ejection. Consequently, the altitude profile for performance and duration testing is an emergency descent from maximum operating altitude to the breathable pressure altitude of 10,000 ft. The bottle would be run empty, so this test would be run exclusively as an unmanned test with the VPBS. The EOS would be activated at high altitude, and the point at which the bottle was empty - evident from pressures and gas concentrations in the mask - would be noted. A successful test would be one in which the altitude would reach breathable altitudes prior to the exhaustion of the EOS bottle.

B. Notes on Test Setup

Two adjacent and connected, but independently sealed, hypobaric pressure chambers were used in conjunction with each other to accurately portray both the ambient atmospheric pressure (the "aircraft-side chamber") and the associated scheduled cabin pressure (the "cabin-side chamber"). The LOX converter, which in the X-59 airplane is to be mounted in an unpressurized compartment, was located in the aircraft-side chamber, with tubing running through a pressure bulkhead to the remainder of the major components in the cabin-side chamber. This setup replicates the anticipated actual setup upon installation in the X-59 airplane. The two chambers could then be independently pressurized to appropriate pressure altitudes to recreate various flight conditions.

In order to make testing practical and economical, several discrepancies existed between the actual system and the test setup. Considering the oxygen supply first, in addition to the LOX converter and EOS oxygen bottles that will supply the LSS, testing leveraged the ready availability of large gas cylinders. These "K-bottles" could be manually throttled to specific output pressures, and were used as the supply for many tests when appropriate. Liquid oxygen was used to supply the primary system for a single series of breathing impedance tests and a single series of rapid decompressions to verify functionality in each scenario. Likewise, EOS bottles were used in rapid decompression tests and the duration tests, where the available volume is critical and the supply pressure / available volume dynamic could not be replicated with a K-bottle. For other tests, however, a constant pressure would suffice to meet the objectives and a K-bottle could be used to save the time, cost, and effort associated with refilling LOX converters and EOS bottles.

The tubing connections between the major components in the primary system were also not identical to the actual design: a consequence of the difference in available space between the hypobaric chambers and the X-59 fuselage design. Instead, Eq. (1) was once again leveraged to determine different tubing runs that would fit in the chambers yet induce the same pressure drops as the actual design lines, complete with their miscellaneous connector fittings. Additionally, because the exact geometry of the X-59 LSS tubing was not finalized at the time of testing, additional design evolution was accounted for in the lines being tested with KBR. The test lines were each extended to create an even greater pressure drop than the current design, thus allowing significant growth in the system without invalidating the results of the qualification test program. Ultimately, the tested configuration would still be a more conservative assembly than the evolved, to-be-installed, system lines.

Finally, despite emphasis being given to the specific parameters described in the testing objectives, miscellaneous pressures and flow rates were measured throughout the system. Sensors were concentrated particularly around the regulators, for system debugging during the test sequence and additional insight into the dynamics of the system.

A summarized test matrix, presenting an overview of the permutations of the test objectives and experimental configurations, is presented in Table 1; several key components of the test setup are illustrated in Fig. 3.

Table 1. Summarized test matrix.

Test	Flow paths tested	Breathing type	Gas supplies	# Trials
EOS actuation	Primary & emergency	Unmanned	K-bottles (O_2 and N_2)	5
Breathing impedance	Primary & emergency	Manned & unmanned	LOX & K-bottles (O_2)	90
Rapid decompression	Primary & emergency	Manned & unmanned	LOX & K-bottles (O_2)	29
EOS performance and duration (off seat)	Emergency	Unmanned	EOS bottles	4
EOS performance and duration (on seat)	Emergency	Unmanned	EOS bottles	TBD

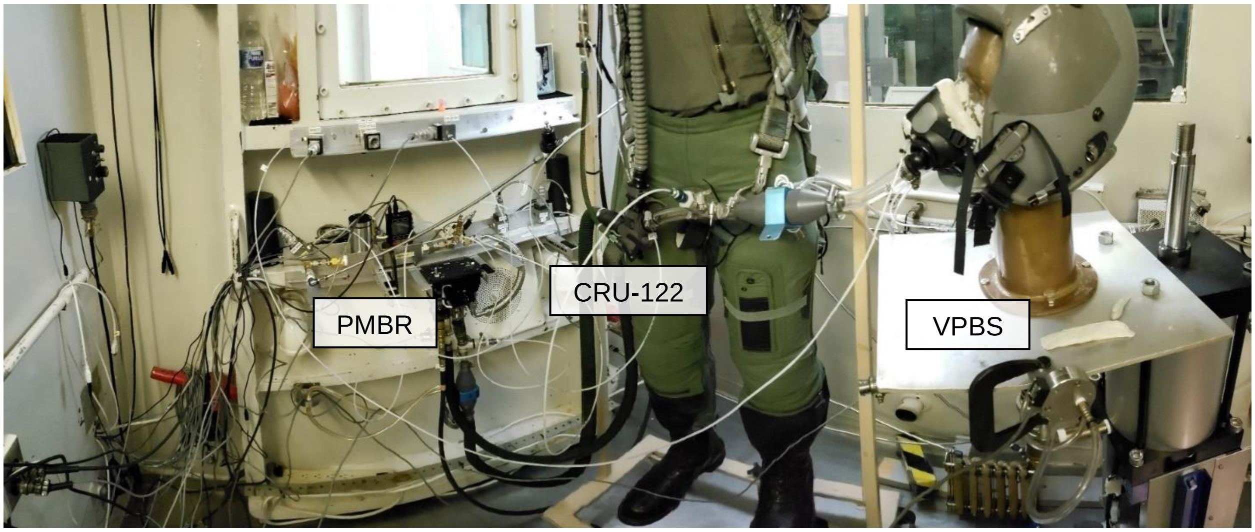


Fig. 3 Photograph of a test dummy and sample test configuration in the "cabin-side" pressure chamber.

VI. Qualification Testing Results of the Life Support System

A. Preliminary Benchtop Tests of the Emergency Oxygen System

Prior to hypobaric chamber testing, limited testing was conducted at AFRC to conceptualize the EOS design and mature it to the state that was tested with KBR. A key distinction uncovered was the limited compatibility of components designed for a free-flowing EOS versus those designed for a demand regulator. At the heart of the EOS concept was the actuation valve with the breakaway shear plug, borrowed from the T-38 EOS. The X-59 seat being a T-38 ejection seat, use of this component and its associated actuation mechanism was critical to avoid lengthy redesign and certification of a new mounting scheme; however, this bottle head could not be used as the X-59 bottle head due to an incompatibility between the free-flow design philosophy and the demand design philosophy. In the T-38 design, this head contains a ceramic flow controller plug that permits oxygen through the orifice at very low flow rate. Downstream of the head, there is no additional regulation, because the associated chest-mounted regulator essentially serves as a pass-through - the pilot simply has one large volume of oxygen approximately at cabin pressure from which to breathe. An initial attempt to modify the ceramic plug to allow for a larger pressure, sufficient to drive pressure breathing in the chest-mounted regulator, encountered difficulties. It was realized that there was no way to simultaneously regulate pressure and flow rate with this orifice design. Modifying the configuration to supply higher pressures to the chest-mounted regulator would create higher flow rates, thus making it impossible to maintain a constant pressure between the head and the regulator. Instead, pressure regulation was accomplished at the REOS bottle head. All internal regulation in the T-38 bottle head was removed except for the breakaway shear plug, making the bottle head effectively a simple on/off valve. The pressure output from the REOS head is therefore carried all the way to the CRU-122 chest-mounted regulator, where it is in the appropriate range for driving the regulator. The CRU-122 unit then supplies flow to the pilot on an "on-demand" basis. In this manner, oxygen is successfully supplied to the regulator at the correct pressure, the T-38 legacy actuation scheme is preserved, and all components are already flight-rated.

B. Emergency Oxygen Activation

The emergency oxygen actuation scheme test series produced conclusive evidence as to how the primary system will need to be disabled prior to EOS activation. When both systems are connected to the CRU-122 chest-mounted regulator, activated, and supplying the mask, the system that dominates over the other is inconsistent and dependent on pressure altitude. Since both systems are driven by regulators operating on the same schedule, this condition is not particularly surprising. The altitude bands in which each system dominates are simply a product of slight variations in the pressure schedules in the individual units themselves (within manufacturing tolerances).

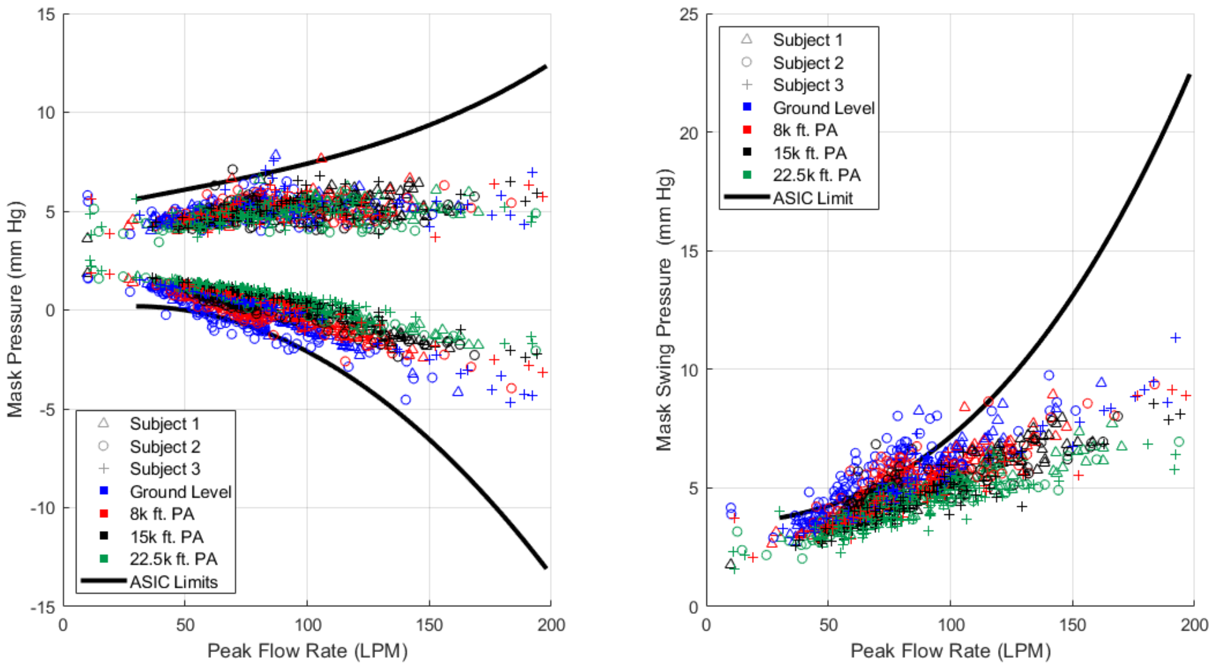
Next, the primary system was disabled but not disconnected. The PMBR remained connected to the CRU-122 unit, but was turned off and therefore not supplying oxygen. Results were once again unsatisfactory. The mask was supplied with pure oxygen from the EOS as desired - however, without any positive pressure in the hose between the dormant PMBR and chest-mounted regulator, the EOS oxygen was also flowing down this hose and being released through a regurgitation valve in the PMBR. While effective in supplying oxygen to the pilot, this configuration would result in undesirable oxygen losses into the cabin. When the PMBR hose is disconnected at the CRU-122 unit entirely, however, a spring-loaded one-way valve in the CRU-122 unit closes, preventing flow from escaping along that flow path. With the PMBR turned off to prevent oxygen from flowing into the cabin, and the hose disconnected from the manifold, the EOS is the only source feeding the CRU-122 unit and its flow is entirely directed towards the mask side as desired. It thus stands to be set as standard procedure that when the EOS is activated, the primary system hose shall be disconnected from the chest-mounted regulator and the PMBR deactivated.

C. Breathing Impedance

Software was provided by KBR to isolate each breathing cycle and return three characteristic parameters: inhalation pressure, exhalation pressure, and peak flow rate for the breathing cycle. These parameters are the key measurements in a breathing impedance investigation. Plotting the pressures against volumetric flow rate versus the peak flow rate, with the ASIC limits for their values on the same plot, produces a graphic confirmation of the efficacy of the system with respect to those standards. Similarly, taking the difference between the inhalation and exhalation pressures and plotting these against the peak flow rate for the breathing cycle permits comparison to the ASIC limit for this so-called "swing pressure."

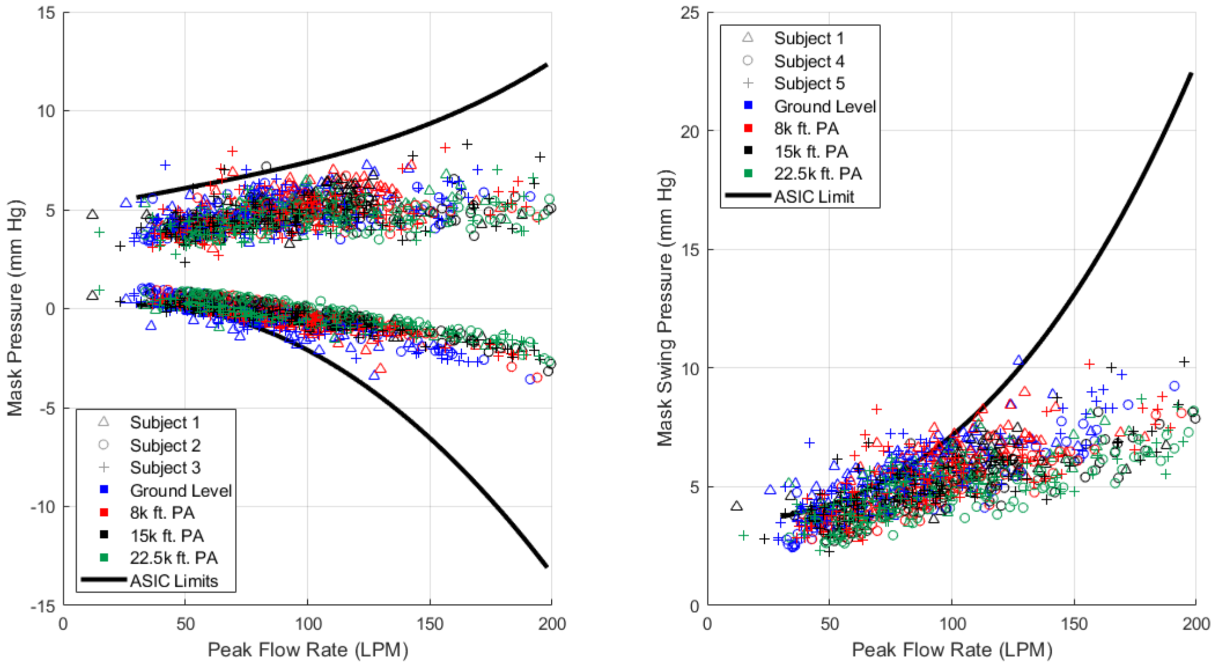
Impedance testing motivated one significant design change in the primary oxygen system. Originally the hose connecting the PMBR to the chest-mounted regulator/manifold consisted of two hoses with a quick-disconnect fitting connecting them. This quick-disconnect was mounted on the seat: one hose led from the PMBR to this fitting, and another led from the fitting to the manifold. It was discovered, however, that due to the sharp turns the flow path encountered in negotiating the geometry of the fitting, significant limitations in flow rate were induced. This condition severely increased the impedance of all primary system tests well beyond the ASIC specified bounds. With this discovery, the seat mounted quick-disconnect was removed and a single, longer hose was used to directly join the PMBR to the manifold.

With this design change implemented, breathing impedances were found to generally fall within the acceptable ranges for the varied parameters of altitude and breathing profile for both the primary and emergency systems, for both unmanned and manned test runs. Several excursions from the accepted ranges in manned tests were noted at ground level and at 8,000 ft pressure altitude. These excursions were deemed non-critical, however, as the atmosphere at these low altitudes - below the altitude at which the cabin begins to be pressurized - is inherently breathable even without the oxygen system. Consequently, if impedance were to become a problem, the pilot could thus easily remove the mask to resolve the problem. Figure 4 and Fig. 5 illustrate selected impedance data for manned test runs with the post-modification primary oxygen system design configuration and the EOS, respectively.



a) b)

Fig. 4. a) Exhalation and inhalation data for manned test breathing cycles on the primary oxygen system, plotted with ASIC standards; and b) manned test breathing cycle pressure swing data on the primary oxygen system, plotted with the ASIC standard.



a) b)

Fig. 5. a) Sample exhalation and inhalation data for manned test breathing cycles on the emergency oxygen system, plotted with ASIC standards; and b) sample manned test breathing cycle pressure swing data on the primary oxygen system, plotted with the ASIC standard.

As expected, higher altitudes correlate to reduced exhalation and inhalation pressures, indicating reduced breathing impedances. With a limited number of exceptional low-altitude, low-flow-rate data points outlying the ASIC limits, both systems are observed to consistently permit oxygen delivery throughout a range of breathing profiles.

D. Performance and Duration Testing of the Emergency Oxygen System

The final step in the qualification process involved demonstration of the EOS being able to sustain a pilot through a descent from altitude. After the successful completion of proof-of-concept benchtop testing, a similar test setup was taken to the KBR facilities and evaluated. Final mechanical design and fabrication work for necessary seat modifications is currently being completed for installation of the EOS on an actual ejection seat. Distinction must then be made between “off-seat” and “on-seat” tests. The off-seat configuration that has been tested at AFRC and in KBR hypobaric chambers is extremely similar to what will be the final on-seat EOS configuration, the discrepancy being slightly different line lengths. Additionally, it bears an alternate activation method since the only way to actuate the breakaway shear plug is by way of a seat-mounted handle mechanism. These two differences, however, are fluid-mechanically minor and inconsequential. The off-seat duration test conducted should provide a close approximation of the actual EOS bottle duration in its final configuration. Nevertheless when the on-seat configuration is finalized, the duration tests will be repeated for maximum system confidence.

The off-seat configuration successfully completed an unmanned chamber descent from maximum altitude to breathable altitudes with oxygen to spare at moderate and high VPBS breathing demand profiles. Figure 6 illustrates such a simulated emergency descent. The sudden increase in measured mask pressure near the beginning of the time history indicates the activation of the EOS bottle. Slight cyclic pressure excursions outside of the regulator tolerance are briefly observed at the beginning of the descent; however, the mean mask pressure is maintained within tolerance, indicating that the regulator is performing nominally and these transient excursions are attributable to the breathing profile, not hardware. The sudden drastic oscillation and eventual termination of pressure cycles toward the end of the time history indicates the depletion of the oxygen in the bottle. These large excursions outside of the tolerance are indicative of higher breathing suction pressures (higher impedance) being required to draw a fixed, programmed volumetric flow rate from the nearly-depleted bottle. As this condition occurs well below the activation altitude for PBA, it is not indicative of any problem in the regulator schedule - in this regime, the regulator is merely supplying a passive volume of air at ambient cabin gauge pressure, not performing regulation.

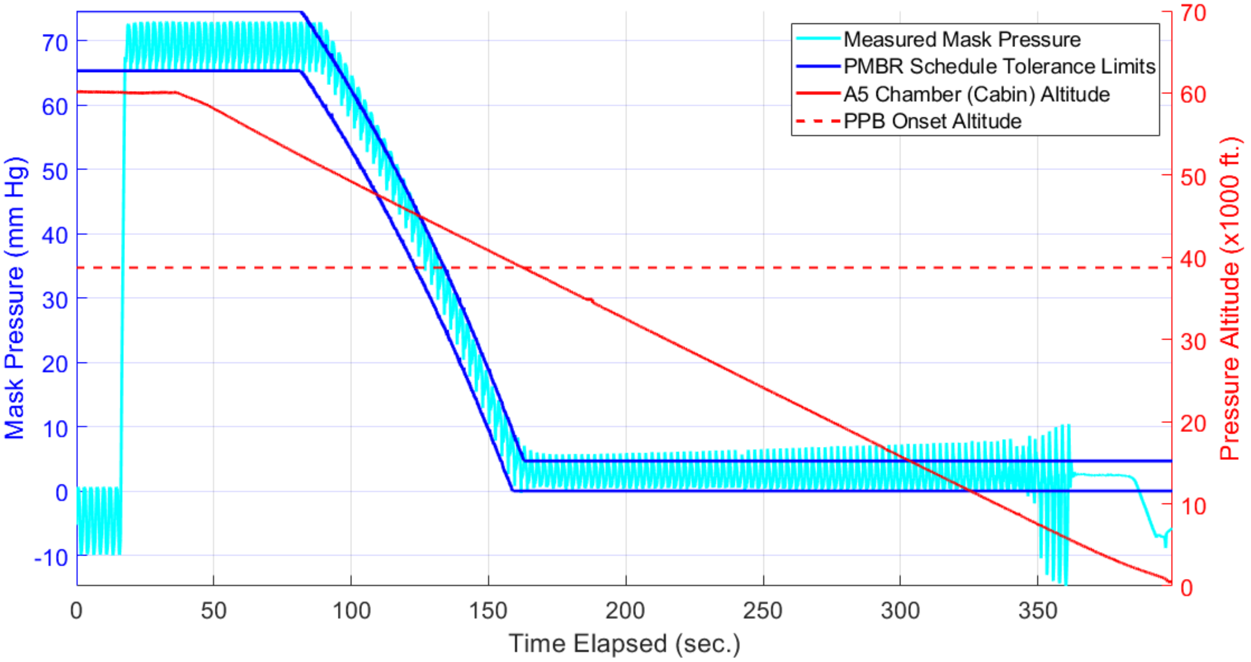


Fig. 6. Sample unmanned emergency oxygen system performance and duration test data.

The EOS bottle is observed to sustain this maximum breathing rate demand for a descent profile including a short delay prior to initiating the emergency descent. The bottle does not deplete until the airplane has descended to a low altitude well within the breathable lower atmosphere. Notably, this profile includes traversing the entire PPB regime, which is naturally associated with heightened levels of oxygen supplied from the bottle. This result demonstrates the sufficiency of the system and oxygen supply for sustaining a pilot in an emergency descent.

E. Rapid Decompression

Rapid decompression testing demonstrated that both the primary oxygen system and the EOS could successfully operate during a rapid decompression from cabin altitude to ambient atmospheric pressure and the ensuing descent to breathable altitude. In both cases, the respective regulators were found to maintain positive supply pressures to the mask within their design tolerance ranges throughout the decompression and descent stages, including matching the PPB supply pressure schedule. Figure 7 illustrates the adherence of the PMBR of the primary oxygen system to tolerances in the rapid decompression tests. This adherence was verified in the rapid decompression tests for the EOS as well.

The time history is generally similar to the previous EOS duration test descent profile, the lone exception being the step-command in altitude early in the data, indicating a rapid decompression event. Both ensuing rapid descents, however, illustrate the two oxygen systems following the pressure schedules of their respective breathing regulators.

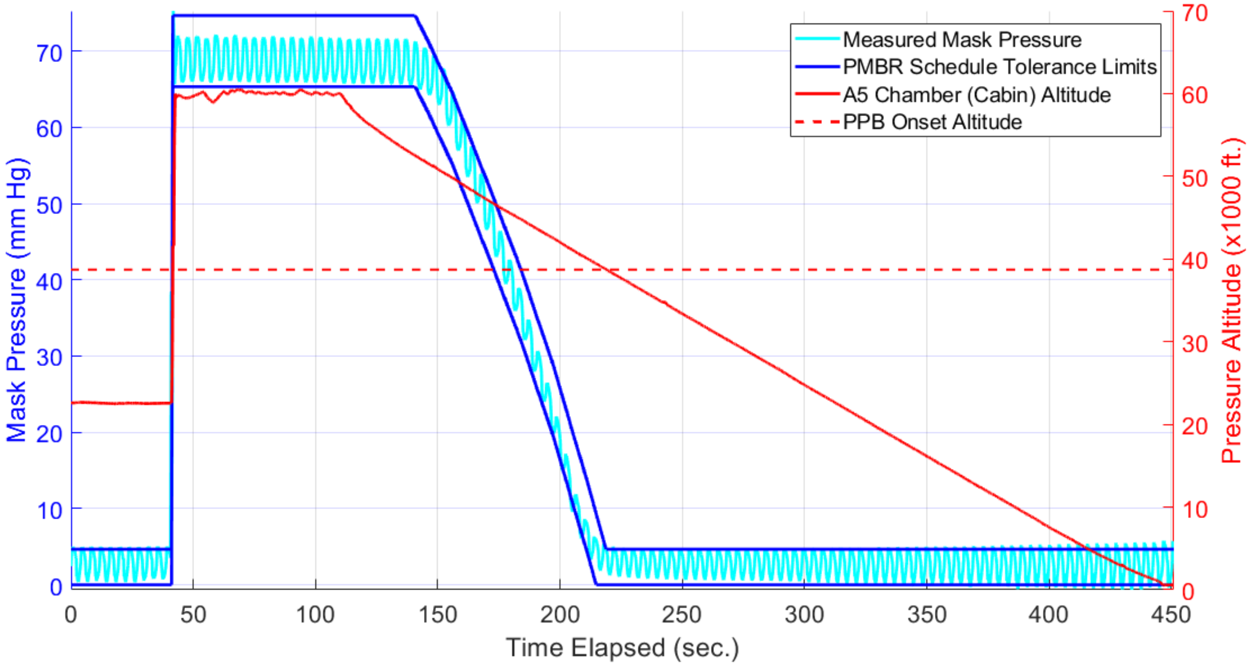


Fig. 7. Sample unmanned primary oxygen system rapid decompression test data.

One task remains to be performed at KBR to complete certification tests: a manned rapid decompression test series with an ejection seat outfitted with an actual EOS bottle mounted in its final configuration. This test would be a cumulative evaluation to demonstrate the system performance as realistically as possible along an ejection profile, which is the absolute worst-case scenario for the LSS.

VII. Conclusion

A novel life support system (LSS) was designed and tested for application in the X-59 airplane, consisting of a primary oxygen system and independent emergency oxygen system. Both systems are composed of legacy flight-rated components. Beyond proof-of-concept testing and preliminary fluid mechanics modelling, both systems successfully underwent rigorous qualification testing in hypobaric chambers to demonstrate their functionality along realistic mission pressure altitude profiles. Formal completion of the qualification test program is pending final mechanical design of the emergency system for installation onto the ejection seat. Acquired data indicate that the LSS fully meets the requirements of acceptable breathing impedance, adherence to pressure supply schedules, and sufficient emergency oxygen supply duration.

The successful design and testing of the X-59 life support system is a critical milestone in the approval process for this airplane to take flight on its quest to revolutionize commercial aviation.

Acknowledgments

The author is indebted to Low Boom Flight Demonstrator managers Brian Griffin, Brett Pauer, and Catherine Bahm; engineers Kurtis Long and Matthew Zu; and life support technicians Mathew Sechler and Ron Shepherd for providing opportunities to learn about, work on, and contribute to the X-59 life support system (LSS) operation. Fellow interns Chris Antony, Noah Edwards, and Anna Gardner and their parallel work in flow analysis, LSS computer modelling, and operations coordination are also greatly appreciated.

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