Document Title: Environmental Control and Life Support Systems for Flight Crew and Space Flight Participants in Suborbital Space Flight

Originating Office: AST-200
AC Number: 460.11-1-A

Summary:

This Advisory Circular (AC) provides guidance for a launch operator proposing to conduct suborbital human space flights authorized under a license or experimental permit issued by the Federal Aviation Administration. This AC reviews some, but not all, of the many technical means of monitoring and controlling atmospheric conditions. This AC also describes technical means that an applicant may employ to provide an equivalent level of safety to monitoring and controlling some atmospheric conditions.

How to Comment:

This draft AC is open for public comments and recommendations until February 16, 2009. Comments should be submitted to the Federal Docket Management System at http://www.regulations.gov. The originating office (AST-200) then reviews the comments and recommendations to determine if the text should be updated.

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U.S.
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Advisory Circular

Subject: ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR FLIGHT CREW AND SPACE FLIGHT PARTICIPANTS IN SUBORBITAL SPACE FLIGHT

Date: December 16, 2008
Originated by: AST-200

AC No.: 460.11-1-A

1.0 PURPOSE

a. This Advisory Circular (AC) provides guidance for a launch operator proposing to conduct suborbital human space flights authorized under a license or experimental permit issued by the Federal Aviation Administration (FAA). Title 14 Code of Federal Regulations section 460.11 (14 CFR § 460.11) requires an operator to provide atmospheric conditions adequate to sustain life and consciousness for all inhabited areas within a vehicle. This AC reviews some, but not all, of the many technical means of monitoring and controlling atmospheric conditions. This AC also describes technical means that an applicant may employ to provide an equivalent level of safety to monitoring and controlling some atmospheric conditions. We provide guidance on operational considerations that the FAA has identified for an applicant proposing an environmental control system and life support system that ensures flight crew can perform safety-critical tasks for a suborbital space flight, as required by 14 CFR § 460.15. Addressing these considerations, or other considerations that are vehicle-specific but of similar scope or consequence for launch vehicle system safety, may assist an applicant with demonstrating that it can satisfy the regulatory requirements described above.

b. This AC provides an acceptable means of complying with the regulations; however, it is not the only means of compliance. The provisions in this AC are not mandatory and do not constitute a regulation. When this AC uses mandatory language (e.g., “must” or “may not”) it is paraphrasing a regulatory requirement or prohibition. When this AC uses permissive language (e.g., “should” or “may”), it describes acceptable means, but not the only means, of complying with regulations. However, if you use the means described to comply with a regulatory requirement, you must follow it in all respects.

c. This draft AC is open for public comments and recommendations until February 16, 2009. Comments should be submitted to the Federal Docket Management System at http://www.regulations.gov. The originating office (AST-200) then reviews the comments and recommendations to determine if the text should be updated.

2.0 APPLICABLE REGULATIONS AND RELATED DOCUMENTS

a. Regulations
- Title 14 Code of Federal Regulations (14 CFR) parts 401, 415, 431, 435, 440, and 460 - Human Space Flight Requirements for Crew and Space Flight Participants; Final Rule (Dec. 15, 2006)
  Subpart A – Launch and Reentry with Crew, § 460.11 Environmental control and life support systems
- 40 FR 29114, FAA’s Role with Respect to Occupational Safety and Health Conditions Affecting Aircraft Crewmembers on Aircraft in Operation (Jul. 10, 1975).

b. Other Documents

- Memorandum of Understanding between the Federal Aviation Administration, U.S. Department of Labor, and the Occupational Safety and Health Administration, U.S. Department of Labor, to enhance safety and health in the aviation industry (Aug. 7, 2000).

3.0 DEFINITIONS

a. Closed-Loop System. A closed-loop system of control is a system that has an active feedback loop that compares the measured value for an atmospheric parameter to the corresponding predetermined set point, and then autonomously adjusts the control system operation to reduce any difference between the measured value and the set point.

b. Control. The functions of components, subsystems, or systems; or the methods of design, fabrication, or maintenance, constraining each of the individual atmospheric conditions of the inhabited area of a launch or reentry vehicle within a predetermined range that determines a nominal, or safe, condition to sustain life and consciousness.

c. Decompression sickness. A variety of symptoms suffered by a person exposed to a reduction in the pressure surrounding the body.

d. Degraded. In reference to launch vehicle performance, trajectory, or stage impact point, a launch vehicle flight where some vehicle aerodynamic parameters are not as expected, or vehicle internal or external systems do not perform exactly as planned, but all safety-critical systems perform as planned. An example is a malfunctioning temperature control system that causes temperatures to be above or below the nominal temperature range of the vehicle, but the pilot and vehicle systems are still able to perform all safety-critical functions.

e. Ebullism. Formation of gas bubbles in bodily fluids at reduced environmental pressure.

f. Emergency. In reference to launch vehicle performance, trajectory, or stage impact point, a launch vehicle flight where some vehicle aerodynamic parameters are not as expected, or vehicle internal or external systems do not perform exactly as planned, resulting in a human space flight incident, reentry incident, or reentry accident.

g. Flight Crew. Crew that is on board a vehicle during a launch or reentry.

h. Mishap. A launch or reentry accident, launch or reentry incident, launch site accident, failure to complete a launch or reentry as planned, or an unplanned event or series of events resulting in a fatality or serious injury (as defined in 49 CFR 830.2), or resulting in greater than $25,000 worth of damage to a payload, a launch or reentry vehicle, a launch or reentry support facility, or government property located on the launch or reentry site.

i. Mission Duration. The time starting when the vehicle is first boarded by a flight crew member, preparatory to flight, to when the last flight crew member leaves the vehicle after completion of the flight. The duration includes both the pre-flight time and the post-flight time.

j. Monitoring. Observing the measured value for each of the individual atmospheric conditions of the inhabited area of a launch vehicle or a reentry vehicle.

k. Nominal. In reference to launch performance, trajectory, or stage impact point, a vehicle flight where all vehicle aerodynamic parameters are as expected, all vehicle internal and external systems perform exactly as planned, and there are no unexpected external perturbing influences.

l. Open-Loop System. An open-loop system of control is a system that does not autonomously adjust the control system operation to reduce any difference between the measured value for an atmospheric parameter and the corresponding predetermined set point.

m. Safety Critical. Essential to safe performance or operation. A safety critical system, subsystem, component, condition, event, operation, process, or item is one whose proper recognition, control, performance, or tolerance is essential to ensuring public safety. A safety critical item creates a safety hazard or provides protection from a safety hazard.

n. Space Flight Participant. An individual, who is not crew, carried onboard a launch vehicle or reentry vehicle.

o. Suborbital Rocket. A vehicle, rocket-propelled in whole or in part, intended for flight on a suborbital trajectory, and the thrust of which is greater than its lift for the majority of the rocket-powered portion of its ascent.

p. Suborbital Trajectory. The intentional flight path of a launch vehicle, reentry vehicle, or any portion thereof, whose vacuum instantaneous impact point does not leave the surface of the Earth.

4.0 BACKGROUND

The FAA Office of Commercial Space Transportation (AST) regulates commercial space transportation operations to ensure protection of the public, property, and the national security and foreign policy interests of the United States under authority of the Commercial Space Launch Act of 1984 as codified and amended at 49 U.S.C. Subtitle IX (Chapter 701). On December 23, 2004, Congress passed the Commercial Space Launch Amendments Act (CSLAA), which made the Department of Transportation responsible for regulating the operations and safety of the emerging commercial human space flight industry. The FAA has the authority to promulgate regulations to protect the crew when they are part of the flight safety system that protects the general public.

In response to the CSLAA, the FAA established the requirements of 14 CFR § 460.11, which included requirements for governing environmental control and life support systems to ensure atmospheric conditions adequate to sustain life and consciousness for all inhabited areas within a vehicle. Section 460.11 requires an operator or flight crew to monitor and control specific atmospheric conditions in inhabited areas, or to demonstrate through the license or permit process that an alternative means of compliance provides an equivalent level of safety. This section states:

> ***§ 460.11 Environmental control and life support systems.***
> (a) An operator must provide atmospheric conditions adequate to sustain life and consciousness for all inhabited areas within a vehicle. The operator or flight crew must monitor and control the following atmospheric conditions in the inhabited areas or demonstrate through the license or permit process that an alternate means provides an equivalent level of safety—
> (1) Composition of the atmosphere, which includes oxygen and carbon dioxide, and any revitalization;
> (2) Pressure, temperature and humidity;
> (3) Contaminants that include particulates and any harmful or hazardous concentrations of gases, or vapors; and
> (4) Ventilation and circulation.
> (b) An operator must provide an adequate redundant or secondary oxygen supply for the flight crew.
> (c) An operator must
> (1) Provide a redundant means of preventing cabin depressurization; or
> (2) Prevent incapacitation of any of the flight crew in the event of loss of cabin pressure.

5.0 DISCUSSION

One objective of this AC is to provide general information about the factors affecting monitoring and control of atmospheric conditions and ECLSS design considerations for suborbital vehicles. The environmental control and life support system (ECLSS) requirements are performance based rather than design based (the requirements do not contain prescriptive design solutions). The design considerations provided are based on case histories of aircraft, space craft, or the use of similar ECLSS components for other industrial applications on Earth. Depending on an applicant's vehicle design and mission profile, these design considerations may or may not be relevant for all ECLSS designs. Addressing these considerations may assist an applicant in demonstrating that an alternate means provides an equivalent level of safety, as described in 14 CFR § 460.11(a).

This AC addresses two fundamental issues concerning compliance with § 460.11 raised in comments by the public to a 2005 Notice of Proposed Rulemaking (NPRM) containing proposed ECLSS requirements:

a. Whether both monitoring and control were always required for every atmospheric parameter, under every condition, or alternatively, whether control alone (without monitoring) might be adequate to satisfy the safety requirements.

b. Whether control may be achieved with open-loop systems rather than closed-loop systems.

Monitoring ensures that an atmospheric condition falls within a predetermined range that determines a nominal or safe condition to sustain life and consciousness. The measured values may either be continuously refreshed or periodically updated, depending on the hazard that an unmonitored atmospheric condition would present to the vehicle occupants. Monitoring may be primarily the responsibility of the on-board crew, an on-board computer system, or of a ground-based remote operator who can alert the on-board crew of an unsafe condition. Control without monitoring of certain atmospheric conditions might be sufficient in some cases. In some cases, control may be achieved using open-loop systems. The above criteria may be used to assist operators with their initial consideration of acceptable solutions to meet the requirements of 14 CFR § 460.11(a), but an operator must demonstrate an equivalent level of safety for a system that does not incorporate monitoring or closed-loop control of the atmospheric conditions in question.

Another objective of this advisory circular is to provide guidance on ECLSS configuration where control alone, or control with open-loop systems, might demonstrate an equivalent level of safety as both monitoring and control of some ECLSS atmospheric conditions. The FAA will address the following questions when determining if both monitoring and control of an atmospheric parameter are required, or whether an open-loop or closed-loop system control is sufficient to meet the requirements:

1) What is the severity of the hazard presented to humans in the event the atmospheric condition is uncontrolled during nominal, degraded, or emergency operating conditions within the vehicle?
2) Does the uncontrolled atmospheric condition create a noticeable, non-debilitating, physiologic effect upon the flight crew at the onset of exposure under plausible flight conditions, such that a flight crew could identify a flight hazard at the onset of exposure before flight safety is compromised?
3) Is the uncontrolled atmospheric condition unlikely to change rapidly or in large magnitude, such that a flight crew could identify a flight hazard at the onset of exposure before flight safety is compromised?
4) Following the onset of exposure to uncontrolled atmospheric conditions stemming from a failed component, what corrective actions are possible?
5) What is the maximum period of time between onset of exposure to the uncontrolled atmospheric condition and the completion of corrective actions?

5.1 Regulation Roadmap

There are FAA regulations other than 14 CFR § 460.11 that apply to ECLSS systems, and this section will outline the relationship of 14 CFR § 460.11 to these other regulations.

5.1.1 14 CFR Part 401 – Organization and Definitions

14 CFR part 401 establishes definitions that apply across all parts of the Commercial Space Transportation Statute and Regulations, including the ECLSS requirements of 14 CFR part 460.

5.1.2 14 CFR Part 413 – License Application Procedures

14 CFR part 413 explains how to apply for a license or experimental permit. These procedures apply to all applications for issuing a license or permit, transferring a license, and renewing a license or permit. These procedures apply whether an applicant intends to operate an expendable or reusable suborbital launch vehicle. These procedures also apply to the section of the application showing compliance with ECLSS requirements as part of a license or experimental permit application.

5.1.3 14 CFR Part 414 – Safety Approvals

14 CFR part 414 establishes procedures for obtaining a safety approval, and for renewing and transferring an existing safety approval. Safety approvals issued under this part may be used to support the application review for one or more launch or reentry license requests, or experimental permits. A safety approval is an FAA document containing the FAA determination that one or more safety elements, when used or employed within a defined envelope, parameter, or situation, will not jeopardize public health and safety or safety of property. It may be issued independently of a license, and may be granted for a launch vehicle, reentry vehicle, safety system, process, service, or any identified component thereof. A safety approval may also be issued for qualified and trained personnel, performing a process or function related to licensed launch activities or vehicles.

A safety approval certifies that the FAA has agreed to accept the approved safety element, within the conditions described in the approval, regardless of the particular mission or vehicle for which the safety element is flown. For example, an operator seeking multiple permits or licenses with numerous vehicle propulsion system configurations, each employing common ECLSS safety elements, may seek a safety approval for those common safety elements that will be included in future permit or license applications.

5.1.4 14 CFR Part 415 – Launch License

14 CFR part 415 describes the process for obtaining a license to launch a launch vehicle other than a reusable launch vehicle. It is the license granted for expendable launch vehicles, including those that may carry humans on board. When the pilot or flight crew perform safety-critical activities on board a launch vehicle, the ECLSS is considered a safety-critical system that falls under 14 CFR § 415.35(c) and (d). Under 14 CFR § 415.35(c), an applicant must complete a system safety analysis that identifies and assesses the probability and consequences of reasonably foreseeable ECLSS failures during launch that could result in risk to the public. 14 CFR § 415.8 references the requirements of 14 CFR part 460 as part of the launch license process; therefore, submittal requirements are addressed in 14 CFR part 415. Safety-critical systems that are dependent upon but not comprising any part of the ECLSS (such as avionics cooled by cabin air) are addressed in 14 CFR § 415.35.

5.1.5 14 CFR Part 431 – Launch and Reentry of a Reusable Launch Vehicle (RLV)

14 CFR part 431 describes requirements for obtaining a reusable launch vehicle (RLV) mission license. When the pilot or flight crew perform safety-critical activities on board an RLV, the ECLSS is considered a safety-critical system that falls under 14 CFR § 431.35(c) and (d). Under 14 CFR § 431.35(c), an applicant must complete a system safety analysis that identifies and assesses the probability and consequences of reasonably foreseeable ECLSS failures during launch, flight and reentry that could result in a casualty to the public. 14 CFR § 431.8 references the requirements of 14 CFR part 460 as part of the RLV license process; therefore, submittal requirements are addressed in 14 CFR part 431. Safety-critical systems that are dependent upon but not comprising any part of the ECLSS (such as avionics cooled by cabin air) are addressed in 14 CFR § 431.35.

5.1.6 14 CFR Part 437 – Experimental Permits

This part prescribes requirements for obtaining an experimental permit. 14 CFR § 437.21(b)(3) requires an applicant proposing launch or reentry with flight crew or a space flight participant on board a reusable suborbital rocket to demonstrate compliance with 14 CFR §§ 460.5, 460.7, 460.11, 460.13, 460.15, 460.17, 460.51, and 460.53. These sections include ECLSS and ECLSS-related components and training described in this AC.

For a permit, the required information is used to construct a hazard analysis to evaluate the ability of the safety systems on the vehicle to protect the public. This hazard analysis and verification data of components, subsystems, or systems form the basis of evaluating a permit application, whereas a full system safety process and in-flight verification data forms the basis of evaluating a license application. Therefore, information about ECLSS failures, mitigation measures, and crew training that are relevant for constructing a hazard analysis for the suborbital vehicle must be provided to the FAA during the permit evaluation process.

5.1.7 14 CFR Part 460 – Human Space Flight Requirements

This part establishes requirements for licensed or permitted launch vehicles carrying humans on board. In addition to the ECLSS requirements of 14 CFR §460.11, part 460 describes requirements for: crew qualifications and training (14 CFR § 460.5), operator training of crew (14 CFR § 460.7), smoke detection and fire suppression (14 CFR § 460.13), human factors (14 CFR § 460.15), and verification program (14 CFR § 460.17). Hazardous gases or vapors may be a by-product of fire suppression in the cabin environment, and smoke may be associated with particulate contaminants in the vehicle cabin, but fire suppression and smoke detection techniques will not be discussed in depth in this AC.

Crew operations involving manipulation or control of ECLSS components during flight are considered safety-critical operations, therefore crew training relevant to the operation of ECLSS components is required for both permitted and licensed activities, per 14 CFR § 460.5(a). 14 CFR § 460.7 requires that the ECLSS training systems are implemented with defined standards of successful completion, the ECLSS training devices are comparable in function to the systems on board the suborbital vehicle, the training records are maintained, and that the operator establish and maintain a recurrent training schedule.

14 CFR §460.11 and 14 CFR §460.15 describe the level of performance required of the ECLSS system. 14 CFR §460.11(a) states that an operator must provide atmospheric conditions adequate to sustain life and consciousness for all inhabited areas within a vehicle. 14 CFR §460.15 states that an operator must take the precautions necessary to account for human factors that can affect a crew's ability to perform safety-critical roles. Physiologically, the range of conditions under which a human can be living and conscious is broader than the range of conditions under which a human can be capable of performing a safety-critical role. In addition to physiological performance limits, other concerns may include communications, visibility, reach, tactile sensitivity, applied force, and hand-eye coordination while operating in the flight environment and dependent upon primary or redundant systems.

6.0 FACTORS AFFECTING MONITORING AND CONTROL OF ATMOSPHERIC CONDITIONS

The FAA will assess "atmospheric conditions" on a case-by-case basis. The major atmospheric conditions addressed herein are:

- 6.1 Total pressure in the cabin
- 6.2 Atmospheric temperature
- 6.3 Atmospheric humidity
- 6.4 Concentration of oxygen
- 6.5 Concentration of carbon dioxide
- 6.6 Concentration of hazardous gases or vapors
- 6.7 Particulate contaminants
- 6.8 Ventilation and air circulation

Relevant factors to consider in determining if both monitoring and control are needed, and whether a closed-loop control system is necessary are:

a. Hazards and characteristics. The AC describes the hazards presented to humans as a consequence of exposure for each atmospheric condition. The AC describes the potential for rapid changes or for changes of large magnitude for each atmospheric condition. The discussion is important for addressing the physiological and human factors needs of an ECLSS design, and it describes acceptable NASA design standards that control the atmospheric condition.

b. Operational considerations for suborbital launch vehicles. The AC describes considerations that the FAA has identified regarding monitoring and control of ECLSS conditions for suborbital flight. These considerations are based on air and space flight history or operation of similar ECLSS components on Earth, and the likelihood of mishaps occurring due to undesirable atmospheric conditions. Depending on the planned flight profile, number of human occupants, ECLSS component layout, habitable volume, or other design elements of a vehicle's design, these considerations may or may not apply to all applicants. However, these considerations may assist applicants with demonstrating an equivalent level of safety for systems or components that the FAA has not yet evaluated.

c. Related FAA regulations for aircraft. While FAA regulations for aircraft are not binding for suborbital space flight, they may be instructive for some applicants.

d. Available monitoring techniques. The AC describes in-flight measurement techniques and devices.

e. Available control techniques. The AC describes in-flight control techniques and devices and assesses the availability and effectiveness of closed- and open loop systems.

6.1 Total pressure in the cabin

a. Hazards and characteristics

Although the probability may be low during suborbital flight, a puncture of the vehicle's pressure shell by space debris or micrometeoroids, or failure in the pressure shell or in the seals at shell penetrations, would result in a loss of cabin air. An uncontrolled decrease in cabin total pressure might be rapid, depending upon the volume of the cabin and the size of the breach in the shell. In the event of cabin pressure loss, the pressure would decay below levels necessary for human life.

The nominal internal pressure for both NASA's Space Shuttle Orbiter and the International Space Station is the Earth-normal 101.0 kPa (14.7 psia). NASA selected this nominal internal pressure to provide an effective baseline comparison for human ground studies on the physiological effects of space flight and microgravity conditions, and to keep fire hazards to a minimum. Crew reduce pressure to 70.3 kPa (10.2 psia) when preparing for extra-vehicular activities (EVAs) to ease the transition to the space suit pressure.[13] NASA's plans for the Constellation Program propose a variable internal pressure for a Crew Exploration Vehicle (CEV, also called Orion) of 101.0 kPa (14.7 psia) for ISS-docking missions, or down to 65.5kPa (9.5 psia), with 30 percent oxygen concentration for lunar missions. NASA proposes an operating pressure of 65.5kPa (9.5 psia), with 30 percent oxygen concentration for a Lunar Surface Acquisition Module (LSAM, also called Altair).[1] These are examples of acceptable total pressures for meeting 14 CFR § 460.11, when appropriate pre-breathing or transition procedures are followed for the flight crew before flight for operating conditions transitioning to a lower total atmospheric pressure. Transition procedures for lower operating pressures are required to ensure the health and situational awareness of the flight crew, so that they may withstand any physical stress factors associated with vehicle operation as required by 14 CFR § 460.15(d).

Provided that requirements for oxygen partial pressures are met, humans can survive in a range of atmospheric pressure from many times greater than the pressure at sea level to approximately 40,000 ft. altitude (2.73 psia). However, oxygen partial pressure is not the only concern relative to reduced total pressures. Regardless of the adequacy of oxygen pressure, physiological aspects of reduced environmental pressure include decompression sickness and ebullism. In addition to decreased pressure, rapid pressure change, as in a decompression from normal cabin altitudes to 40,000 ft., can result in pain from gas expansion in the gastrointestinal system and other areas of the body that contain gas. The pain can compromise safety-critical performance of the flight crew.

b. Operational considerations for suborbital launch vehicles

Cabin depressurization can be one of the most rapid and performance-compromising emergency conditions within an air or space vehicle. It was the cause of the deaths of three cosmonauts during reentry of Soyuz 11. Depressurization has been a cause or contributing factor of numerous fatalities aboard commercial aircraft, notably Turkish Airlines Flight 981[2], Helios Airways Flight 522[3], Japan Airlines Flight 123[4], and China Airlines Flight 611[5]. In the case of the Helios Airways Flight 522, depressurization occurred slowly enough that the flight crew did not notice anything out of the ordinary upon reaching cruising altitude. The slow onset of hypoxia impaired crew's judgment due to low partial pressures of oxygen, and as a result they were unable to interpret and correct the problem. Accident investigators concluded that unclear labeling of the warning system indicators was a contributing factor. With appropriate warning devices, small leaks can be detected quickly enough for corrective action to be successful.

Depressurization events for aircraft have been associated with the failure of doors, bulkheads, or faulty hull repairs. An inward-opening door is inherently fail-safe since the pressure difference between the cabin and the exterior prevents the door from opening, even if it is not securely latched. However, an inward-opening door can be difficult or impossible to open if it is to be used for emergency egress at higher altitudes, which in some cases may require the use of pyrotechnics. Outward-opening doors must be locked shut to prevent unwanted opening, usually requiring a complex latching mechanism and an independent means of visually verifying that the door has been shut. Failure of the structure surrounding a depressurization site can also disrupt the electronic, hydraulic, or control cables near that site, leading to loss of control of the vehicle. If a bulkhead or hull is improperly designed, constructed, or repaired, repeated pressurization/depressurization cycles during normal use of the vehicle can cause structural fatigue, as in the case of BOAC Flight 781[6], Aloha Flight 243[7], Japan Airlines Flight 123[4], and China Airlines Flight 611[5].

The reaction time of the flight crew or automated system to initiate mitigating measures is an important design consideration for this system. In the case of a mitigation system that releases replacement gases into the cabin such as nitrogen, the maximum release rate of the gas regulator system may limit the usefulness of the depressurization prevention technique for large hull failures. Commercial aircraft are able to descend to lower altitudes when necessary in the event of depressurization. By contrast, most suborbital vehicles are committed to a ballistic trajectory after a rocket burn is terminated, with little or no recourse for shortening the time to return to lower altitudes.

In addition to the systems designed to replenish lost atmospheric gases within the vehicle, the design of the cabin pressure containment components are also relevant design considerations of the total cabin pressurization system. Dual pressure containment components (i.e., dual pane windows, dual seals at mated surfaces, dual hull shells, or isolation bulkheads) may decrease hazards associated with depressurization events in exchange for a small increase of mass and complexity of the vehicle, depending on vehicle design.

Depressurization of small cabins occurs much more quickly than large cabins with equal puncture size and pressure difference between the cabin and the exterior. Rapid decompression may be accompanied by a sudden drop in cabin temperature, fogging in the aircraft, windblast and noise. In addition to the threat of hypoxia, these factors may lead to confusion, impairment of situational awareness and decreased response times. Unless the environmental control system can compensate for the decreased temperature, occupants could suffer frostbite and other cold related problems. Cabins with lower total pressure may have lower leak rates, but require a higher partial pressure of oxygen, increasing the risk of cabin fire or lung irritation. If compressed air is used that contains a significant amount of water vapor, icing within or near the regulator or gas release plumbing may cause plugging problems, depending on the flow rate and regulator aperture.

Regular use of pressure suits in a low-pressure operating environment brings a unique set of operational concerns that applicants may consider. A survey of more than 400 U-2 pilots found that 75% reported in-flight symptoms of decompression sickness throughout their careers that resolved upon descent to lower altitudes, and about 13% of them reported that they altered or aborted their missions as a result. [8] Regular use of suits may entail a complex maintenance regimen such that suits may be a liability for an operator if they are not regularly tested and maintained. Pressure suits may adversely affect the ability of flight crew to perform certain safety-critical functions by limiting range of motion, response time, or communication ability. Heat dissipation may also be an operating concern with partial-pressure suits, depending on the design, operating environment, user workload, and degree of user control.[13]

Finally, a unique consideration for suborbital vehicles is the possibility of explosive fragments from a rocket engine or motor failure contributing to a cabin hull puncture. Commercial aircraft operations do not normally stress engine materials as much as rocket engines and motors. This is partially reflected by the higher historical rate of catastrophic failure of rocket engines and motors than aircraft engines. Even if mitigating measures are in place to ensure fail-safe operation of a suborbital vehicle in the event of catastrophic engine failure, a chamber explosion may still expel debris that can puncture the cabin pressure vessel.

c. Related FAA regulations for aircraft

The FAA airworthiness regulations for transport category aircraft require that they be equipped to provide a cabin pressure altitude of not more than 8,000 feet (equivalent to a cabin pressure of not less than 10.9 psia). Transport aircraft are normally pressurized to an equivalent altitude of 5,000 to 8,000 feet (12.2 to 10.9 psia). The comparable regulations for normal, utility, acrobatic, and commuter category airplanes require that for certification for operation over 25,000 feet, the airplane must be able to maintain a cabin pressure altitude of not more that 15,000 feet (greater than 8.29 psia) in event of any probable failure or malfunction in the pressurization system.[9,10] For general operation of unpressurized civil aircraft, cabin pressure altitudes of less than 12,500 feet with a partial pressure of oxygen corresponding to outside air do not require any supplemental oxygen provisions for crew or passengers.[11] These are acceptable pressure ranges for meeting 14 CFR § 460.11. The primary purpose of minimum cabin pressure regulation is to maintain the partial pressure of oxygen at acceptable levels.[12]

The FAA airworthiness regulations for the airplane cabin environment require the presence of instruments that indicate to the pilot the pressure differential, the cabin pressure altitude, and the rate of change of cabin pressure altitude. In addition, the regulations require a warning at the pilot station to indicate when the safe or preset pressure differential is exceeded and when a cabin pressure altitude of 10,000 feet (equivalent to a cabin pressure of 10.1 psia) is exceeded.[9,10] These are acceptable design specifications for monitoring total pressure for meeting 14 CFR § 460.11(a)(2).

d. Available monitoring techniques

Direct-reading total pressure monitoring devices (e.g. mechanical, piezoelectric, etc.) have been qualified and proven for aerospace applications through test, demonstration, and flight operations. These total pressure monitoring devices are acceptable to the FAA, provided that these devices meet the needs of the applicant's risk elimination and mitigation measures pertaining to depressurization hazards as required by 14 CFR § 431.35(d)(7) for licenses, and 14 CFR § 437.55(a)(5) for permits. Some of these needs may include pressure sample measurement rate, display refresh rate, caution and warning signals, and time to recognize the situation and complete corrective actions that control the vehicle's instantaneous impact point. The operator must successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight. The operational flight environment includes the total range of pressures for which the pressure monitoring device is expected to operate. For example, if the design pressure (with margins) for the launch vehicle cabin is not to exceed 15 psia, a total pressure monitoring device designed to operate between 0 and 15 psia would be acceptable for meeting 14 CFR § 460.11(a)(2). A caution and warning signal that warns the flight crew in the event monitoring detects a rapid decrease in total pressure or a low total pressure so that the pilot or crew can take corrective action in the very brief time available before consciousness is lost would be acceptable to the FAA.

e. Available control techniques

Section 460.11(c) requires (1) a redundant means of preventing cabin depressurization; or (2) preventing incapacitation of any of the flight crew in the event of loss of cabin pressure. For most ECLSS applications, there are two general approaches for environmental control: cabin and garment (or suit) containment. Either control approach is acceptable as a redundant means of preventing cabin depressurization, but an operator must successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment before allowing any space flight participant on board during a flight, as required by 14 CFR § 460.17.

Cabin control approaches are the most common. Barometric pressure in the pressure hull of commercial aircraft is measured continuously and is under precise control of an automatic system. The supply of compressed air from an environmental control system and release of air through an exhaust valve are balanced automatically to maintain cabin pressure.[12] For typical submarine and some space vehicle applications, O_2 and N_2 gases are controlled separately, usually because there is a source of O_2 gas that is external to the ECLSS system (deionization and hydrolysis of water for submarines, propulsion or fuel cell oxygen gas for space vehicles).[28]

For example, an autonomous, compressed nitrogen gas release system that releases nitrogen gas when pressure drops below 14.0 psia within a cabin of nominal operating pressure at 14.7 psia is an acceptable means of preventing cabin depressurization, as long as an operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment before any space flight participant may be allowed on board during a flight, as required by 14 CFR § 460.17. The integrated system must also include a redundant or secondary oxygen supply for the flight crew, as required by 14 CFR § 460.11(b).

Various combinations of pressure suits have been used to provide high altitude protection and to prevent pilot incapacitation caused by a loss of cabin pressure. Altitude protection garments may use gas pressure, direct mechanical pressure or a combination of gas and mechanical pressure to apply pressure to the body while oxygen is supplied via a pressurized helmet or full face mask. Full pressure suits, similar to the Extra Vehicular Activity (EVA) suits used in space, use compressed gas to provide a pressure environment around the entire body. Partial pressure suits use a mechanical system of pneumatic levers or capstans to apply pressure around the circumference of the user's limbs and torso. This mechanical pressure system is combined with a pressure helmet and torso bladders to provide the required partial pressure of oxygen and support breathing. In either system, 100% oxygen or an oxygen mix is supplied to the user to maintain an oxygen partial pressure of 2.83 psia or greater. These suits maintain a pressure environment adequate to provide protection from hypoxia and ebullism; however, the pressure generated by the suits is generally not adequate to ensure protection from decompression sickness. A pressure suit used as a redundant safety system to prevent incapacitation of the flight crew must also include an adequate redundant or secondary oxygen supply for the flight crew as required by 14CFR 460.11(b). A pressure suit that meets the minimum oxygen requirement may be used as an acceptable redundant system to prevent crew incapacitation; however, consideration must be given to requirements for denitrogenation to prevent decompression sickness.

6.2 Atmospheric Temperature

a. Hazards and characteristics

Although humans can survive in a relatively wide range of temperatures, proper temperature control would ensure the flight crew maintained a degree of situational awareness to perform a safety-critical role, as required by 14 CFR § 460.15. A NASA-developed "comfort box" is bounded by 25 to 70 percent relative humidity and by 65 to 80 °F.[13] This is an example of an acceptable temperature range for meeting 14 CFR § 460.11.

Cabin air receives metabolic heat from the humans on board, which includes the latent heat of exhaled water vapor, and evaporated perspiration. The average metabolic heat generation rate per person is 136.7 watts (467 Btu per hour or 11,200 Btu per day) for normal activity.[13] This average rate is comparable to the instantaneous nominal metabolic heat generation rates for light to medium workloads, 450 to 550 Btu per hour per person. The average heat generation by a comfortable, sedentary person is about 70 watts (240 Btu per hour).[12] Cabin air receives sensible heat from avionics and other electrical equipment in the habitable areas of the vehicle. Additional sensible heat can be transferred to or from the cabin air through the vehicle's pressure shell, depending on the flight profile and vehicle design. In the cabin of commercial airplanes, a supply of about 1.4 pounds per minute per person of conditioned air is necessary to maintain a comfortable temperature.[12]

b. Operational considerations for suborbital launch vehicles

Temperature control systems are relatively simple, but the contributions from numerous sources, sinks, and the thermal transfer mechanisms that connect them are very complex. Suborbital vehicles are unique (compared to aircraft and even orbital vehicles) in that there are almost no external conditions that are constant or steady-state throughout flight. Pressure, temperature, speed, propulsive forces, and g-load are changing constantly.

High-altitude flight usually requires a net addition of heat to the cabin because the exterior air is colder than standard sea level conditions, and because any pressurized gas being released into the cabin cools upon expansion from the tank. However, operating an enclosed cabin during low-altitude flight or during ground taxi may cause a net addition of thermal energy, requiring removal of heat from the cabin. Other vehicle systems interfaced within the cabin (e.g., avionics) may have a significant thermal contribution to the ECLSS temperature management systems as well.

For some vehicle designs, temperature and humidity control may be inter-dependent or dual-function systems. Care may be taken to ensure that high demand for either conditioning system does not overburden the other. The location of significant sources and sinks may also imply special design considerations that are wholly dependent upon vehicle arrangement and flight profile. For example, locating a heating element near a chemical oxygen generator, or a condensation cooler adjacent to critical avionics, may pose additional in-flight hazards that can be easily avoided by judicious design decisions.

c. Related FAA regulations for aircraft
14 CFR § 25.831 requires that means must be provided to enable the flight crew and crewmembers to control the temperature and quantity of air within their respective compartments, independently of the temperature and quantity of air supplied to other compartments and areas.[25]

d. Available monitoring techniques
Direct-reading temperature monitoring devices (e.g., thermocouple, thermochemical, etc.) have been qualified and proven for aerospace applications through test, demonstration, and flight operations. These temperature monitoring techniques are acceptable to the FAA if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17 before any space flight participant may be allowed on board during a flight. The operational flight environment includes the total temperature range for which the monitoring device is expected to operate. For example, if the nominal, degraded, and emergency design temperature ranges for a vehicle fall between 40 to 90 °F, a temperature monitoring device designed to operate within this range is acceptable for meeting 14 CFR § 460.11(a)(2).

e. Available control techniques
Automatic and manual temperature controls are flight-proven technologies. Temperature control in manned spacecraft is typically achieved by removing heat from the circulating cabin air, with forced continuous circulation of the cabin air through one or more heat exchangers. Chilled water, ethylene glycol / water, or Freon serves as the coolant in these heat exchangers. For space habitats with continuous recirculating air flow, the temperature control method may be to bypass a variable portion of the air flow around the heat exchanger. Resistive heating is a common approach for adding heat.[13] These control techniques are acceptable to the FAA if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17 before any space flight participant may be allowed on board during a flight. The operator must also take the precautions necessary to account for human factors that can affect a crew's ability to perform safety-critical roles, as required by 14 CFR § 460.15. Some human factors may include the design and layout of the monitoring and control interfaces, the presence of sharp, hot, or cold surfaces within the cabin, or appropriate access to critical systems for troubleshooting or repair.

There are also design choices that act as passive control techniques. Air temperature is measured and controlled in all commercial aircraft for the comfort of passengers and crew and to help provide cooling capacity to maintain appropriate operating temperatures for electronic and mechanical equipment. Because thermal loads are not the same in all parts of an aircraft, it is separated into "control zones." Each zone has an independent temperature sensor and adjustable supply of conditioned air. For example, thermal conditioning in the cockpit is controlled separately from that in the passenger cabin. The passenger cabin may be further divided into two or more control zones, and may also include direct passenger control of air flow rates to individual seats.[12]

6.3 Atmospheric Humidity

a. Hazards and characteristics
Hazards to humans associated with humidity are related to maintaining situational awareness by the pilot and flight crew. Relative humidity and temperature are inversely related. Cold air has a lower humidity capacity than warm air. At higher temperatures, the relative humidity may be higher to reduce evaporative heat loss for maintaining optimal situational awareness, but very high humidity inhibits the body's natural body temperature regulation processes (i.e., sweating). A NASA-developed "comfort box" is bounded by 25% to 70% relative humidity and by 65 to 80 °F.[13] This is equivalent to an operational dew point range of 40 to 60 °F. This is an example of an acceptable humidity range for meeting 14 CFR § 460.11, as long as other safety-critical systems

present within the cabin or cockpit (e.g., window surfaces or avionics) can withstand this humidity range without failure or without impairing the situational awareness of the crew or pilot.

Relative humidity in commercial aircraft cabins is typically below 20 percent.[12] A study of airliner cabin environment by the National Research Council found no conclusive evidence of extensive or serious health effects of low relative humidity, and therefore did not recommend supplemental humidification of cabin air.[14]

Cabin air receives moisture as exhaled water vapor and evaporated perspiration from the humans on board the vehicle. The average metabolic rate (normal activity) is 5.02 pounds of respiration and perspiration water generated per person per day (0.21 pounds per hour).[13] Stressed or excited individuals will likely produce water vapor at higher-than-average rates, which vary from person to person. The rate of moisture generation, integrated over the mission duration, would determine whether the cabin humidity change would be rapid or would be of large magnitude during the mission.

b. <u>Operational considerations for suborbital launch vehicles</u>
Humidity management is important for maintaining the situational awareness of the flight crew such that they are able to perform safety-critical tasks, and may be important for the proper functioning of avionics present within the cabin. An explosion during the Apollo 13 mission required that the ECLSS humidity control components be powered down to conserve electrical energy. During this shutdown period, the temperature drop and the water vapor exhalation of the crew generated condensation that accumulated on command module windows and the interior surfaces of the cabin. This condensation obscured vision through windows and raised concerns about whether the electronics systems would function properly when reactivated. However, the humidity did not reach levels which were uncomfortable for the crew.[15]

For a suborbital flight, the time duration will be much shorter than for Apollo 13, but the cabin volume may be smaller with more people present. If the flight crew or space flight participants are physically active or stressed, the rate of water vapor production can be expected to exceed average rates. ECLSS components such as carbon dioxide scrubbing agents may contribute to the water vapor content within the cabin.[13] The sensitivity of a suborbital launch vehicle's safety-critical avionics is an important safety consideration if the humidity is expected to jump rapidly should the humidity management system fail. On Skylab, heaters were located to prevent excess moisture from forming on and damaging sensitive electronics.[16,17]

If the temperature of viewing windows of suborbital launch vehicles is sufficiently low, condensation may accumulate as liquid or ice on windows even if the relative humidity in the cabin does not approach 100% and the humidity system is functioning properly. Condensation may also contribute over the lifetime of the vehicle to increased corrosion of the vehicle shell, or to biological growth that could affect cabin air quality.

Gravity is an external environmental factor that greatly simplifies an ECLSS design, and may create special design considerations for humidity management systems in particular. Although the microgravity condition is expected to be relatively short for suborbital flights, the movement, storage, or stowage of condensation or disaggregated solids (e.g., silica adsorption granules) associated with humidity control may be important for maintaining the pilot's situational awareness within the vehicle.

c. <u>Related FAA regulations for aircraft</u>
None.

d. <u>Available monitoring techniques</u>
Portable instruments for monitoring relative humidity or dew point temperature have sufficient accuracy and precision for monitoring relative humidity between 2.5% and 80%. The most commonly used methods incorporate a thin hygroscopic polymer film whose electrical capacitance varies with relative humidity or an electrolyte solution whose electrical impedance varies with relative humidity. These instruments have an accuracy of approximately ±2.5% if calibrated periodically.[12] These humidity monitoring techniques are acceptable to the FAA if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight. The operational flight environment includes the total range of humidity for which the monitoring device is expected to operate. For example, if the nominal, degraded, and

emergency design humidity ranges for a vehicle using this technique fall between 10% and 70%, a humidity monitoring device designed to operate within this range would be acceptable for meeting 14 CFR § 460.11(a)(2)

e. Available control techniques
Humidity control for limited duration missions may be achieved by the adsorption of airborne moisture using silica gel, activated alumina, or molecular sieve materials.[28] Commercially available desiccants may contain color coding to indicate when the materials have been saturated with moisture. Canisters containing these materials may be regenerated between missions, using heat or vacuum to drive off the moisture.
Humidity control for longer duration missions may be achieved simultaneously with temperature control, by removing heat from the circulating cabin air, with forced continuous circulation of the cabin air through condensing heat exchanger(s). Chilled water, ethylene glycol / water, or Freon serves as the coolant in these condensing heat exchangers. Under reduced gravity conditions, the condensed liquid water is separated from the circulating air with a hydrophilic "slurper" bar, and is collected using a centrifugal separator.[16] These control techniques are acceptable to the FAA if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight.

Humidity control techniques that imply direct attention or action on the part of the flight crew (e.g., wiping off windows obscured by condensation) are acceptable to the FAA, but an operator must take the precautions necessary to account for human factors that can affect a crew's ability to perform safety-critical roles, as required by 14 CFR § 460.15. Some of these human factors may include consideration of the impact on the flight crew's communications, visibility, reach, tactile sensitivity, applied force, and hand-eye coordination. This may also include cockpit management problems such as increased workload and decreased attention during activities that can reduce situational awareness.

6.4 Concentration of Oxygen

a. Hazards and characteristics
The normal sea level atmospheric partial pressure of oxygen is 160 mm Hg (3.09 psia). NASA defines the operational range of oxygen partial pressure for proper respiration on long-duration missions from about 2.76 to 3.35 psia.[13,16] NASA's accepted limit of oxygen partial pressure for alertness is 137 mmHg (2.7 psia). According to another statement in the same document, however, oxygen partial pressure should be maintained above 152 mm Hg (2.94 psia) for normal functioning of average crewmembers.[16] NASA's plans for the new Constellation Program call for a nominal internal pressure, for both the Orion and the Altair on lunar missions, as low as 65.5kPa (9.5 psia), with 30 per cent oxygen concentration, with an equivalent oxygen partial pressure of 2.85 psia.[1] NASA plans to use the 9.5 psia cabin pressure and 30% oxygen concentration to reduce the denitrogenation times normally required to protect astronauts from decompression sickness during EVA activities. These are examples of acceptable minimum oxygen partial pressure ranges for meeting 14 CFR § 460.11 and 14 CFR § 460.15, when appropriate pre-breathing or transition activities are planned for the flight crew and pilot before flight for operating conditions that may involve some risk of decompression sickness.

Very low oxygen partial pressure constitutes a severe hazard, and results in impaired judgment and ability to concentrate, shortness of breath, nausea, and fatigue. The result affects the proper functioning of the crew and so potentially results in mishap.[13] The central nervous system, including the brain and eyes are particularly sensitive to oxygen deficiency, and cannot function without oxygen. Acute impairment of brain function occurs within 13 seconds whenever the alveolar oxygen tension drops below about 33 mm Hg (4.4 kPa). The effects of falling oxygen partial pressure are insidious, as it dulls the brain and prevents realization of danger. The total atmospheric pressure and the duration of exposure affect the minimum allowable oxygen partial pressure, as some detrimental effects of hypoxia are time dependent.[16]

High oxygen partial pressure increases material flammability hazards. The autoignition temperature decreases with increasing oxygen partial pressure, such that materials that are benign in the standard Earth atmosphere can become a source of a conflagration. Replenishment oxygen gas released into an unmixed or unventilated part of a cabin in a microgravity environment can accumulate and produce an autoignition hazard. High oxygen partial pressures may also result in lung irritation and oxygen toxicity (hyperoxia).[13,16]

With no controls or supplemental oxygen, the potential rate of decrease in oxygen partial pressure would depend upon the habitable volume (i.e., the size of the cabin oxygen reservoir) and upon the number of crew and space flight participants aboard. The metabolic consumption rate (for normal activity) is 1.84 pounds of O_2 consumed per person per day (0.077 pounds per person per hour).[13] Over reasonable ranges of these two variables, changes of sufficient magnitude to cause deleterious health effects might occur, especially for flights of extended duration. The rate of oxygen consumption, integrated over the mission duration, would determine whether the oxygen partial pressure change would be rapid or would be of large magnitude during the mission.

b. Operational considerations for suborbital launch vehicles

The potential for rapid changes in conditions, disruption of decision-making abilities, flammability risks, and lack of detection by natural human senses (e.g., smell) make effective control of oxygen levels an important safety-critical function for piloted suborbital launch vehicles. In the case of the Helios Airways Flight 522,[3] depressurization of the cabin and cockpit decreased the partial pressures of oxygen, and as a result the flight crew was unable to interpret and correct the problem. Accident investigators concluded that unclear labeling of the warning system indicators was a contributing factor, since the warnings indicated that there was an avionics cooling problem, not a depressurization event. With appropriate monitoring and warning devices the time required to complete corrective actions may be reduced.

If a lower total pressure is selected for cabin or pressure suits, the partial pressure of oxygen must be raised to maintain the ability of the space flight crew to remain conscious, which increases the total fraction of oxygen in the controlled atmosphere. Increased oxygen fractions of an atmosphere increase fire risks dramatically. Astronauts Gus Grissom, Ed White, and Roger Chaffee died during a capsule fire in 1967 when the oxygen-pressurized Apollo 1 command module, being used for test and training exercises, burst into flames that were ignited by a wiring failure. Valentin Bondarenko, a Soviet cosmonaut trainee, died in 1961 during a routine medical screening activity in an oxygen-filled isolation chamber.

If oxygen is being released from a nearly-pure oxygen tank into a cabin, circulation duct, or face mask, simple systems such as in-line flame or flashback arrestors may help to prevent flame propagation from the oxygen-rich gas release area back to the tank. Rapid mixing of the oxygen gas with the cabin air decreases the risk of producing an oxygen-rich region of the cabin. Materials generally considered benign, such as petroleum-based lip balms or hair oils, can induce irritating or hazardous effects in combination with some face mask oxygen delivery systems. It has been noted that facial hair can interfere where facial hair is present along the face mask sealing surface of some crew oxygen masks, which may decrease the performance of the system. This decrease is proportional to the amount of facial hair present, the type of mask worn, the suspension system associated with the mask, and the exercise level to which the individual is subjected.[18]

Chemical oxygen generators may entail special operational considerations that complicate their use aboard suborbital launch vehicles. Chemical oxygen generators use materials that produce exothermic heat and oxygen, so co-location of generators with combustible materials can be extremely dangerous. Chemical oxygen generators using potassium superoxide use water vapor to initiate the exothermic reaction, and must be used carefully because potassium superoxide canisters can ignite or explode on contact with water or moist air.[19] The arrangement of the humidity control system or condensation surfaces should be carefully considered so that moisture does not come into direct contact with the oxygen generators. Improper stowage of chemical generators in the vicinity of combustible materials (airplane tires) was associated with the crash of ValuJet Flight 592,[20] and improper stowage and labeling of hydrogen peroxide, a powerful oxidant, caused an accident aboard American Airlines Flight 132.[21]

c. Related FAA regulations for aircraft

There are no FAA regulations for oxygen partial pressure in aircraft cabin air. Regulations for airplane cabin total pressure cover the requirements for oxygen partial pressure. The replenishment of oxygen consumed by metabolism with outside makeup air in commercial aircraft results in oxygen remaining a relatively fixed fraction of the total pressure. For this reason, the oxygen partial pressure in the cabin of commercial aircraft is not measured routinely. Operating in the vacuum of space necessitates that the air composition requirements for suborbital launch vehicles differ significantly from those of aircraft.

d. Available monitoring techniques

Oxygen-measuring devices can include coulometric and fluorescence measurement, paramagnetic analysis, and polarographic methods.[22] OSHA requires their use for entry into confined spaces.[23] These oxygen partial pressure monitoring devices are acceptable to the FAA, provided that these devices meet the needs of the applicant's risk elimination and mitigation measures pertaining to oxygen level control as required by 14 CFR § 431.35(d)(7) for licenses, and 14 CFR § 437.55(a)(5) for permits. Some of these needs may include pressure sample measurement rate, display refresh rate, caution and warning signals, and time to recognize the situation and complete corrective actions that control the vehicle's instantaneous impact point. The operator must successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight. The operational flight environment includes the time required to display updated oxygen partial pressure measurements that would prevent undetected or uncorrected oxygen depletion to hazardous levels in the cabin. The operational flight environment also includes the total range of oxygen for which the monitoring device is expected to operate. For example, if the nominal, degraded, and emergency design oxygen ranges for a vehicle fall between 2.85 and 3.30 psia, an oxygen monitoring device designed to operate within this range would be acceptable for meeting 14 CFR § 460.11(a)(1).

e. Available control techniques

For most cases of suborbital human space flight, no outside air is expected to be introduced into the cabin, so supplemental oxygen must be used to maintain a constant oxygen concentration.

There are many techniques for controlling the oxygen content of the atmosphere. Oxygen consumed by occupants can be readily replaced by adding oxygen to the habitable atmosphere from a stored gas (pure oxygen or compressed air) or liquid oxygen supply. Chemical oxygen generators are non-regenerable systems that produce O_2 and, for some generator materials, simultaneously remove CO_2. They have been successfully used for spacesuits and Soyuz spacecraft by the Russian Space Agency, and for rebreathing canisters for fire fighting and mine rescue work. When properly designed and used, chemical oxygen generators can be simple to use, compact in design, and dependable.[13,24] Section 460.11(b) of 14 CFR also requires an adequate redundant or secondary oxygen supply for the flight crew. These techniques are acceptable to the FAA as primary and redundant sources of oxygen if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17 before any space flight participant may be allowed on board during a flight. An operator must also take the precautions necessary to account for human factors that can affect a crew's ability to perform safety-critical roles, as required by 14 CFR § 460.15.

Whether used as primary or redundant sources of oxygen, an operator choosing to employ these control techniques must provide atmospheric conditions adequate to sustain life and consciousness for all inhabited areas within the vehicle, as required by 14 CFR § 460.11(a). For example, if the nominal, degraded, and emergency design partial pressure of oxygen ranges for a vehicle fall between 2.83 and 3.35 psia, an oxygen control device that operates within this range would be acceptable for meeting 14 CFR § 460.11(a)(1).

6.5 Concentration of Carbon Dioxide

a. Hazards and characteristics

Humans can survive and function effectively in a wide range of atmospheric carbon dioxide concentrations. The carbon dioxide concentration in the standard sea-level atmosphere is 0.039 per cent, equivalent to a partial pressure of 0.0058 psia. Long-term exposures to carbon dioxide (CO_2) concentrations in the range of 1 to 1.5 percent will generally not produce significant changes in blood pressure, pulse, or temperature (chronic CO_2 toxicity). Such exposures, however, have been noted to produce chronic physiological changes such as respiratory acidosis, increased carbonate retention in bone tissue, increased cortical adrenal activity, and decreased cardiovascular function. No outward apparent symptoms would be expected at this concentration. Greater CO_2 concentrations may be tolerated in short flights as the detrimental effects are time dependent. Carbon dioxide withdrawal symptoms (e.g., headaches of varying severity) may be experienced after the cessation of certain exposures to CO_2 and may result in even greater functional impairment than the exposure itself. At CO_2 concentrations of about 3 per cent, crewmembers will typically exhibit increased motor activity, excitement, euphoria, mental acuity and sleeplessness for about a day. These symptoms will be followed by headache, mental depression and cloudiness, decreased memory and attentiveness, and decreased appetite.[16] At concentrations above 3 per cent, acute CO_2 toxicity symptoms include dyspnea, fatigue, impaired concentration, dizziness, faintness, flushing and sweating of face, visual disturbances, and headache. Exposure to 10 per cent or greater concentrations can cause nausea, vomiting, chills, visual and auditory hallucinations, burning of the eyes, extreme dyspnea, and loss of consciousness.[16]

Without controls, carbon dioxide from respiration of the crew and the space flight participants would accumulate in the cabin atmosphere. The metabolic rate (normal activity) is 2.2 pounds of CO_2 generated per person per day (0.092 pounds per person per hour).[13] The resulting increment in the atmospheric concentration of CO_2 would depend upon the habitable volume, the number of crew and space flight participants aboard, and the overall mission duration. With no control mechanism, the rate of carbon dioxide generation, integrated over the mission duration, would determine whether the carbon dioxide partial pressure change would be rapid or would be of large magnitude during the mission.

NASA defines the required operational maximum carbon dioxide partial pressure as 3.0 mm Hg (0.06 psia), equivalent to 0.4 percent at one atmosphere total pressure, with a 90-day degraded maximum of 7.6 mm Hg (0.15 psia, or 1.0 percent).[16] These are acceptable examples of maximum carbon dioxide partial pressure for meeting 14 CFR § 460.11.

b. Operational considerations for suborbital launch vehicles

Pellet-based control systems such as calcium hydroxide, lithium hydroxide, zeolites, or CAMRAS systems may have special concerns for operation in a microgravity environment. Although the microgravity condition is expected to be relatively short for suborbital flights, the stowage of disaggregated solids (especially if an applicant's system uses off-the-shelf components not specifically designed for use in space) may release particulate matter into the cabin environment and become an irritant to the occupants. For example, it was suspected that lithium hydroxide (a common CO_2 scrubbing agent) dust contributed to nasal irritation aboard Skylab, although this was never proven conclusively and never posed any significant problem. Further, when lithium hydroxide elements were stored unbagged on Skylab, they swelled unexpectedly, with the result that they would not fit properly in the environmental control system interface.[13,17] This may be relevant to operators who consider storing back-up lithium hydroxide canisters on board as an emergency mitigation measure, or for operators who anticipate a reasonably probable scenario involving high cabin humidity adversely affecting lithium hydroxide canisters.

Carbon dioxide monitoring systems may require periodic recalibration to produce reliable results. An inaccurate CO_2 monitoring system may produce adverse physiological effects for vehicle occupants, leading to a loss of situational awareness for the flight crew.

Chemical oxygen generators may imply special operational considerations that complicate their use aboard suborbital launch vehicles. Chemical oxygen generators use materials that produce a tremendous amount of heat as oxygen is produced, and co-location of generators with combustible materials can be extremely dangerous. Improper stowage of chemical generators in the vicinity of combustible materials (airplane tires) was associated with the crash of ValuJet Flight 592,[20] and an accident aboard American Airlines Flight 132.[21] Chemical oxygen generators with potassium superoxide use water vapor to initiate the exothermic reaction, and must be used carefully because potassium superoxide canisters can ignite or explode on contact with water or moist air. The arrangement of the humidity control system or condensation surfaces should be carefully considered so that moisture does not come into direct contact with the oxygen generators.[19]

c. Related FAA regulations for aircraft

The FAA regulations for transport aircraft cabin environment require that carbon dioxide concentrations during flight must not exceed 0.5 percent (5,000 parts per million) by volume in compartments normally occupied by passengers or crew members.[25,26] This FAA limit is the same as the OSHA Permissible Exposure Limit (PEL).[27] These are acceptable examples of maximum carbon dioxide partial pressure for meeting 14 CFR § 460.11.

d. Available monitoring techniques

Carbon dioxide monitoring instruments of a size suitable for use in continuous monitoring on aircraft have been developed, such as nondispersive infrared photometers that use light-emitting diodes as the infrared sources. Such instruments have acceptable accuracy for CO_2 concentrations of 100–50,000 ppm (0.01–5 percent by volume). These CO_2 monitoring techniques are acceptable to the FAA if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight. The operational flight environment includes the total range of CO_2 for which the monitoring device is expected to operate. For example, if the nominal, degraded, and emergency design CO_2 ranges for the launch vehicle are from 0 psia up to NASA's 90-day degraded maximum of 1.0 percent at 14.7 psia total pressure, a CO_2 monitoring device designed to operate within this range would be acceptable for meeting 14 CFR § 460.11(a)(1).

e. Available control techniques

Both non-regenerable and regenerable devices have been developed, verified, and successfully used by NASA.[28] Subsystems implementing Sorbent-Based Atmosphere Revitalization (SBAR) have been flight proven in Skylab (171 days without a significant anomaly) and International Space Station applications. The CAMRAS (CO_2 and Moisture Removal Amine Swing Bed) is a regenerative technology that absorbs or removes CO_2 and moisture from the crew cabin and then desorbs or releases the CO_2 and moisture through exposure to space vacuum. The CAMRAS contains two canisters packed with pellets that have amine on a solid support, and a valve that cycles between the two beds. The two beds are thermally linked, with one bed absorbing from the crew cabin while the other is venting CO_2 to space vacuum.[1]

CO_2 may be effectively removed by flowing cabin air through non-regenerable beds of hydrated calcium hydroxide or lithium hydroxide. Commercially available hydrated calcium hydroxide may contain small amounts of sodium hydroxide and an indicator dye to signify saturation, and has been in widespread use for carbon dioxide removal in medical, marine, industrial, and rescue operations.[13] Canisters are replaced on a schedule depending upon use. For extended-duration or rapid-turnaround missions, the operator might choose to provide regenerable CO_2 devices, using molecular sieves, an amine-base adsorbent, or metal oxides.

Chemical oxygen generators are non-regenerable systems that produce O_2 and, for some generator materials, remove CO_2. They have been successfully used for spacesuits and Soyuz spacecraft by the Russian Space Agency, and for rebreathing canisters for fire fighting and mine rescue work. When properly designed and used, chemical oxygen generators can be simple to use, compact in design, and dependable.[13]

All of the aforementioned control techniques are acceptable to the FAA if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight. An operator choosing to employ these control techniques must provide atmospheric conditions adequate to sustain life and consciousness for all inhabited areas within the vehicle, as required by 14 CFR § 460.11(a). For example, if the nominal, degraded, and emergency design partial pressure of CO_2 ranges for a vehicle using a CO_2 control device fall between 0.0 and 1.0 percent at 14.7 psia total pressure, this technique would be acceptable for meeting 14 CFR § 460.11(a)(1).

6.6 Concentration of Hazardous Gases or Vapors

a. Hazards and Characteristics

Due to the relatively closed environment inherent to suborbital launch vehicles, gas or vapor contaminants could create hazardous environmental conditions. The accumulation of harmful gases or vapors in the cabin atmosphere, and the resulting increment in their atmospheric concentrations, can occur at varying rates depending on the source and type of contaminant. Consequently, possible health effects upon the crew from trace concentrations might be chronic rather than acute, and may or may not adversely affect the ability of the flight crew to perform their safety critical roles during a mission. The contaminants covered in this AC may or may not be relevant for all suborbital vehicles. They are covered here to assist applicants with unique vehicle designs, or for return-to-flight efforts following non-nominal mission events such as cabin fires, hull punctures, or extreme reentry conditions.

NASA toxicologists, in collaboration with the National Research Council's Committee on Toxicology, have established guidelines known as spacecraft maximum allowable concentrations (SMACs) for many airborne contaminants.[29,30] Exposure limits have been defined for short-term (1-24 hour) emergency exposures to high levels of chemical contaminants, and long-term continuous exposure of astronauts for up to 180 days. Short-term SMACs refer to concentrations of airborne substances that will not compromise the performance of specific tasks by astronauts during emergency conditions or cause serious or permanent toxic effects. Such exposures might cause reversible effects, such as mild skin or eye irritation, but they are not expected to impair judgment or interfere with responses to emergencies. The SMACs take into account factors unique to NASA's human space program, such as the stresses of space flight, good astronaut health, and subjects that are not pregnant or very young. Note that SMACs do not explicitly consider mixtures of contaminants, and human subjects with allergies or unusual sensitivity to trace pollutants may not be afforded complete protection, even when long-term SMACs are not exceeded.[29]

SMACs contain guidelines for dozens of contaminants, however, the FAA only expects an applicant to mitigate or eliminate the effects of those contaminants that are expected to be present within the applicant's vehicle. The FAA anticipates that commercial human space flight operations may deviate from the factors taken into account for the development of SMACs. Therefore, the FAA will evaluate hazardous gases and vapors on a case-by-case basis according to what contaminants are expected to be present within inhabited areas of the vehicle, as well as the expected effects on flight crew and space flight participant physiology.

b. Operational considerations for suborbital launch vehicles

Outgassing from materials used in the inhabited areas, or leaks of fluids or vapors from propulsion systems, thermal control systems, hydraulic actuators, or other process sources may be sources of harmful substances. The internal surface of the fuselage may be coated with anticorrosive or antimicrobial materials. Materials in thermal contact with the vehicle skin during reentry may experience elevated temperatures that produce outgassing.[13]

Selecting materials to minimize outgassing and locating tanks and processing equipment where contaminant generation will be minimal are the first steps to controlling and preventing trace contaminant introduction in the cabin environment. The American National Standards Institute has published a standard test method for contamination outgassing characteristics of spacecraft materials.[31] Databases containing outgassing properties of aerospace materials have been constructed by the NASA Space Environments and Effects (SEE) Program. The resources are alternately referred to as the Spacecraft Contamination and Materials Outgassing Effects Knowledgebase (SCMOEK) or the Satellite Contamination and Materials Outgassing Knowledgebase.[32,33] At the time of writing this AC, these resources were available by contacting NASA via the SEE website. However, some SEE products might have export restrictions and be subject to International Traffic in Arms (ITAR) regulations.

Carbon monoxide (CO) is odorless and colorless and symptoms of toxicity are not readily noticeable. CO is produced by incomplete combustion and materials outgassing.[35] A NASA survey of outgassed products from nonmetallic materials under consideration for use in the Apollo capsule reported that approximately 90% of materials tested produced significant amounts of carbon monoxide when heated to 68 °C for prolonged periods.[34] Carbon monoxide concentrations from 120 to 180 ppm result in a throbbing headache and breathlessness from any exertion. Loss of consciousness results from CO concentrations above 300 ppm.[16] Humans are more susceptible to CO poisoning under conditions where the body is oxygen-deficient, such as when the partial pressure of oxygen in the cabin atmosphere is low.[35]

The decomposition of fire suppressants during a cabin fire may produce significant quantities of hazardous contaminants. For example, Halon is one of the most effective fire suppression agents in use. Even though it is often considered to have low toxicity, safety and health problems can occur from its release in confined or poorly ventilated spaces comparable to those expected on suborbital launch vehicles. Decomposition of halogenated agents occurs upon exposure to flame or surface temperatures above approximately 900 °F, and may include hydrogen fluoride, hydrogen bromide, hydrogen chloride, bromine, or chlorine.[36]

Volatile organic compounds (VOCs) include a variety of chemicals, some of which may have short- and long-term adverse health effects. The ability of organic chemicals to cause health effects varies greatly from those that are highly toxic to those with no known health effect. As with other pollutants, the extent and nature of the health effect will depend on many factors including level of exposure and length of time exposed. Health effects include eye, nose, and throat irritation; headaches, loss of coordination, nausea; damage to liver, kidney, and central nervous system. Some organics can cause cancer in animals; some are suspected or known to cause cancer in humans. Key signs or symptoms associated with exposure to VOCs include conjunctival irritation, nose and throat discomfort, headache, allergic skin reaction, dyspnea (labored breathing), nausea, emesis (vomiting), epistaxis (nosebleed), fatigue, dizziness.[37] Eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment are among the immediate symptoms that some people have experienced soon after exposure to some organics. VOCs can reach hazardous levels within the cabin as the result of burning, abnormally high temperatures, or chemical reactions occurring with carbon composites, plastics, or other carbon-based polymer materials. If VOC countermeasures such as goggles are incorporated into emergency procedures, then egress procedures and structures may be affected by reduced sight abilities within the cabin.[38,39]

Ozone is a concern for commercial aircraft cabin atmospheres because outside air at higher altitude contains ozone at elevated concentrations. Cabin air for commercial aircraft is usually a mixture of re-circulated air and outside air, supplied to the cabin by a compressor on the engine. Consequently, ozone should not be a significant hazardous contaminant of suborbital spacecraft atmospheres that are well-sealed from the high-altitude environment. Should a suborbital launch vehicle be designed to use outside air for some phases of flight at high altitudes, ozone control measures similar in effectiveness to those employed in commercial aircraft may be required. When inhaled, even at very low levels, ozone can cause acute respiratory problems, headaches, significant temporary decreases in lung capacity of 15 to 20% in some healthy adults, and inflammation of the eyes and lungs. Further, it can impair the body's immune system defenses, making people more susceptible to respiratory illnesses, including bronchitis and pneumonia.[40]

6.7 Particulate Contaminants

a. Hazards and characteristics

Airborne particulates such as dust may contain minerals, metals, textile, paper and insulation fibers, nonvolatile organics, and various materials of biological origin (e.g., hair, skin flakes, dander, and bacteria and fungi).[12] Dense smoke and soot can impair situational awareness by obscuring vision, or causing intense bouts of coughing, choking, and extreme eye irritation. In a microgravity environment, metal or plastic shavings from machining of the onboard materials can become ingested or cause significant eye injury after becoming dislodged during launch. Fine particles (less than 2.5 micrometers) are of health concern because they easily reach the deepest recesses of the lungs, and have been linked to a series of significant health problems, including aggravated asthma, acute respiratory symptoms, aggravated coughing and difficult or painful breathing, chronic bronchitis, and decreased lung function that can be experienced as shortness of breath.[41]

The NASA operational requirement limiting particulate contaminants in respirable air is 3,500,000 particles per cubic meter (100,000 particles per cubic foot), for particles greater than 0.5 microns.[12] NASA's operational limit for airborne microorganisms is 500 Colony Forming Units (CFU) per cubic meter.[16] These are examples of acceptable maximum particulate contaminant levels for meeting 14 CFR § 460.11.

b. Operational considerations for suborbital launch vehicles

Smoke and particulates can immediately affect the eyes, nose, throat, and lungs if caused by a fire within the cockpit, impairing situational awareness of the pilot or flight crew.

The pressure differential across the filter increases with use as pores become plugged with particulate matter. The blower motor that drives cabin air across the filter should be appropriately sized to function over the expected lifetime of a filter in service aboard the launch vehicle, not just at the initial time of filter use. If the filter is in-line with other airborne control systems (i.e., humidity or carbon dioxide absorbents) a plugged air filter may inhibit the proper functioning of these other systems.

c. Related FAA regulations for aircraft
None.

d. Available monitoring techniques
Suborbital launch vehicles will likely experience rapid cycling of internal air because the average mission duration will be short compared to the expected useable lifetime of such vehicles. A vehicle operator may choose to demonstrate an equivalent level of safety to in-flight particulate monitoring is achieved by an alternate means. For example, an operator may demonstrate that the pilot can monitor the operation of the ventilation system during flight, which circulates cabin air through an appropriate filter to control particulate levels. The following information on available particulate monitoring techniques may be useful to operators who choose to develop a regimen for testing the vehicle air quality during ground maintenance, to employ monitoring devices throughout flight, or to verify completion of clean-up efforts for vehicle return-to-flight in the aftermath of unplanned events that release particulates into the cabin (e.g., cabin fires).

A nephelometer (a continuous monitor of light scattered by suspended fine particles) can be used to monitor cabin air for particulates during recirculation. A nephelometer would provide a continuous indication and recording of the mass concentration of fine particles. Although coarse particles (particles with diameters greater than 2 µm) from resuspended dust on carpets, seats, luggage, and occupants' clothing may also be present in the cabin air, they are less efficient in scattering light and will contribute less than the fine particles, per unit mass, to the measured light scattering. Portable nephelometers that could be used to monitor fine-particle concentrations in spacecraft cabins use light-emitting diodes as light sources and solid-state photodetectors to collect the scattered light from particles passing through the sensing zone.

Direct-reading instruments based on the behavior of electrically charged particles include commercial smoke detectors as well as more technically sophisticated electrical aerosol analyzers. Smoke detectors employ an ionizing radiation source to generate electric charges on particles. The resulting change in electric current is used to sense the presence of particles in air. These devices respond within seconds to relatively high concentrations of fine particles (e.g., combustion aerosols), but may not be suitable for continuous monitoring of lower levels aboard aircraft or launch vehicles.

These particulate monitoring techniques are acceptable to the FAA if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight.

e. Available control techniques
Passive contamination control such as careful selection of materials to minimize particle generation may be a critical first step in the design process. Preventative measures such as Foreign Object Damage (FOD) programs seek to prevent the circumstances that place foreign objects within functioning systems or occupied areas before hazards can occur.[13]

An active control method commonly employed is to provide filters (usually HEPA filters) for the cabin air return duct inlets. With a recirculation fan operating, filters effectively maintain low concentrations of particulate contaminants in the atmosphere for extended times, with neither rapid nor large changes during space flight operation.[42,43] Most recently manufactured aircraft use HEPA filters for recirculated cabin air. HEPA filters remove 0.3-micron particles with a minimal efficiency of 99.97%.[12] HEPA filters also effectively trap bacteria and fungi.[44]

Smoke goggles, enclosed flight suits with an independent source of breathable air, face masks, or other protective eye coverings may be effective short- or long-duration countermeasures to smoke and particulates from a cabin or cockpit fire and, combined with proper training, may enable the flight crew to aggressively combat in-flight fires.[45]

6.8 Ventilation and Air Circulation

a. Hazards and characteristics
Ventilation, i.e., effective circulation of the cabin atmosphere, is recommended to avoid crew discomfort in stagnant air. In microgravity, diffusion slows and convection stops altogether. Forced ventilation, with the aid of a powered fan or fans, is recommended to achieve the minimum volumetric air movement rate to avoid stagnant air pockets that could contain high levels of carbon dioxide or low oxygen levels. Failure of the ventilation system may induce failure of safety-critical systems that require the movement of air through processing components, such as carbon dioxide scrubbers.

NASA has determined that the minimum linear air velocity for maintaining crew comfort from a thermal flux perspective is 10-15 feet per minute.[16] The amount of air required in any region of the cabin depends on the number of crew present and on their work activity. In terms of volumetric air movement, the NASA-recommended amount of air for adults engaged in moderate physical activity ranges from 5-30 ft^3 per minute per person.[16] In commercial aircraft, the supply of cabin air to remove heat from the cabin, and to provide adequate circulation, ranges from about 15 to 25 cabin air exchanges per hour. Higher air exchange rates are provided for the cockpit.[12] Acceptable exchange rates for sealed suborbital launch vehicles will depend upon the number of people and total enclosed volume of an applicant's vehicle, to ensure that transient levels of contaminants (e.g., carbon dioxide) do not pose a threat to the pilot or flight crew's ability to perform safety-critical tasks.

b. Operational considerations for suborbital launch vehicles
Commercially available circulation fan(s) components may not have been tested for the unique rigors of launch vehicle applications, such as g-loading and vibration. An applicant must demonstrate that any monitor or control technique depended upon to fulfill a safety-critical function has been verified to perform in its operational flight environment before allowing any space flight participant on board during a flight, as required by 14 CFR § 460.17.

If a single circulation fan is relied upon for all air processing, the arrangement of individual processes within that circulation loop may imply consideration to reduce or mitigate hazards, such as temperature control system failure affecting humidity control, or humidity control failure affecting chemical oxygen production.

c. Related FAA regulations for aircraft
The FAA regulations for transport aircraft require that the ventilation system be designed to provide each occupant with an airflow containing at least 0.55 pounds of fresh air per minute.[12]

d. Available monitoring techniques
Techniques and devices for measuring volumetric flow rate of air, or linear air velocity across the inhabited areas, have limited applicability for in-flight use. Measurement of the volumetric flow may be accomplished using a variety of flowmeters, and measurement of the linear velocity profile may require an array of pitot tubes (or equivalent devices) across the cabin cross-section. Calculations based on the rated performance of the ventilation unit and the dimensions of the occupied areas of the vehicle may be just as effective for demonstrating adequate ventilation flow rates. An operator may choose to demonstrate that if the flow rate for adequate ventilation and circulation is contingent upon the operation of the circulation fan, then monitoring operation of the circulation fan is equivalent to monitoring the ventilation and circulation.

Qualitative assessment of flow paths and speed can be made using a small source of smoke. The direction and speed of the smoke trail is observed as the smoke particles are emitted from the smoke source. A smoke source is useful for identifying regions of stagnant air associated with flow obstructions such as seats, stowage compartments, and display panels. However, most suborbital flights will likely be of relatively short duration, with air stagnancy mostly a risk in a microgravity environment where natural convection does not occur.

e. Available control techniques
Circulation fan(s) are available that have been designed for aerospace and general industrial applications. Control may be accomplished by automated or human input by the pilot or flight crew. NASA and FAA regulations for aircraft are provided for guidance purposes, but adequate ventilation and circulation will

ultimately depend on the specifics of cabin layout, volume, circulation system design, and number of people on board a suborbital launch vehicle since there are no ventilation rates intrinsic to human physiological concerns, provided atmospheric composition requirements have been met. Circulation fans are acceptable to the FAA for providing adequate ventilation and circulation if the operator can successfully verify the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17, before any space flight participant may be allowed on board during a flight. An operator must also take the precautions necessary to account for human factors that can affect a crew's ability to perform safety-critical roles, as required by 14 CFR § 460.15.

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