Federal Aviation Administration

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

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RECORD OF CHANGES

CHANGE	DATE	OPTIONAL INFORMATION

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1.0 PURPOSE

a. This document provides guidance for design and development of environmental control and life support systems 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 guide reviews some, but not all, of the many technical means of monitoring and controlling atmospheric conditions within the cockpit and cabin of a suborbital launch vehicle.

b. This guide provides an acceptable means of complying with the regulations; however, it is not the only means of compliance. The provisions in this guide are not mandatory and do not constitute a regulation. When this guide uses mandatory language (e.g., “must” or “may not”) it is paraphrasing a regulatory requirement or prohibition. When this guide 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.

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. The condition arises from the precipitation of dissolved gasses into bubbles inside the body.

d. **Degraded.** Means a reduction in capability, performance or a loss of a non-critical system. 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.** The formation of gas bubbles within the body caused by the vaporization of body fluids at very low environmental pressures, generally less than 0.9 psia (or, alternatively, greater than 63,000 feet altitude).

f. **Emergency**. Means a sudden unforeseen event where vehicle internal or external systems do not perform as planned, which may lead to or cause distress or an urgent condition.

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**. For the purposes of this document, the time starting when humans on board the vehicle begin to use the ECLSS system, until the time when humans on board the vehicle no longer use the ECLSS system.

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.** Means when all vehicle internal and external systems perform exactly as planned.

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 the safety of persons or property. 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

The CFR § 460.11 environmental control and life support system (ECLSS) requirements are performance based rather than design specific (the requirements do not contain prescriptive design solutions). The design considerations provided in this Guide 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.

One objective of this guide is to provide information about the factors affecting monitoring and control of atmospheric conditions and ECLSS design considerations for suborbital launch vehicles. This guide addresses two areas of difficulty in complying with § 460.11 expressed during the public comment period for the 2005 Notice of Proposed Rulemaking (NPRM) containing proposed ECLSS requirements:

1) 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.
2) Whether control may be achieved with open-loop systems rather than closed-loop systems.

Monitoring provides insight into atmospheric conditions so that adjustments can be made to maintain a nominal, safe atmospheric 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. In some cases, control may be achieved using open-loop systems. These options may be used to assist designers or developers with their design solutions in an effort to comply with the requirements of 14 CFR § 460.11(a).

Another objective is to provide guidance on ECLSS design where control alone, or control with open-loop systems, may be sufficient to meet the requirements of CFR part 460. An operator must demonstrate an equivalent level of safety for a system that does not incorporate both monitoring and control of the atmospheric conditions in question. 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?

6.0 FACTORS AFFECTING MONITORING AND CONTROL OF ATMOSPHERIC CONDITIONS

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

The atmospheric conditions covered will be described in the areas of:

a. Hazards and characteristics. The guide describes the hazards presented to humans as a consequence of exposure for each atmospheric condition. The guide describes the potential for rapid changes or for changes of large magnitude for each atmospheric condition.

b. Operational considerations for suborbital launch vehicles. The guide 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.

c. Related FAA regulations for aircraft. Designers and developers may give consideration to ECLSS design based on FAA regulations for aircraft. While they are not requirements for suborbital space flight, they may be insightful.

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

e. Available control techniques. The guide 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, could 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 total cabin pressure loss, the pressure would decay below levels necessary for human life.

The maximum cabin pressure altitude the agency would find acceptable for a period not to exceed 30 minutes is 14,000 feet, unless the cabin ppO_2 composition is increased above standard or the flight crew is provided with and uses supplemental oxygen for that part of the flight at those altitudes. An applicant selecting a higher cabin pressure altitude and ppO_2 different from standard will be evaluated on a case-by-case basis. Cabin pressure altitudes between sea level and 12,500 feet would be acceptable for all suborbital flights as long as an effective ppO_2 composition is maintained.

The FAA may also accept higher cabin pressure altitudes on a case-by-case basis if appropriate denitrogenation or transition procedures are followed for the flight crew before flight. Transition procedures for lower operating pressures can help 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).

b. Operational considerations for suborbital launch vehicles

Cabin depressurization can be one of the most rapidly developing, human performance-compromising emergency conditions within an aircraft 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[1], Helios Airways Flight 522[2], Japan Airlines Flight 123[3], and China Airlines Flight 611[4]. 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. 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 tends to be self-sealing 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 when internal cabin pressure exceeds ambient pressure. 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[5], Aloha Flight 243[6], Japan Airlines Flight 123[3], and China Airlines Flight 611[4].

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, equal make-up air input, and pressure difference between the cabin and the exterior. Rapid decompression may be accompanied by a sudden drop in cabin temperature, fogging in the cabin, windblast and noise. In addition to the threat of hypoxia, these factors may lead to confusion, impairment of situational awareness and increased 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.

Total loss of cabin pressure at altitudes above 40,000 feet altitude without the protection of a pressure suit will most likely result in a fatal accident, however, 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.[7] 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. Unless human factors and design are considered for both the suit and the aircraft, pressure suits may adversely affect the ability of flight crew to perform certain safety-critical functions by limiting range of motion, response time, communications, visibility, reach, tactile sensitivity, applied force, or hand-eye coordination. 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.[12]

Finally, a unique consideration for suborbital vehicles is the relatively greater possibility of explosive fragments from a rocket engine or motor failure contributing to a cabin hull puncture. Commercial aircraft engines do not normally stress engine materials on each flight as much as rocket engines. 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.[8,9] 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 or limitations on flight duration for crew or passengers.[10]

The FAA airworthiness regulations for the cabin environment for transport category airplanes 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.[8,9] The FAA would find that these are acceptable design specifications to meet 14 CFR § 460.11(a)(2) pressure monitoring requirements.

d. Available monitoring techniques

Direct-reading 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. For example, one suitable design would include a caution and warning signal that includes a warning light within direct view of the flight crew as well as an audible warning to the flight crew in the event the monitoring system detects a rapidly decaying 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. 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.

There are two general approaches for sustaining environmental control: cabin and garment (or suit) containment. Either control approach is acceptable as a redundant means of preventing cabin depressurization.

Cabin control approaches are the standard for pressurized transport category aircraft. Barometric pressure in the pressure hull of commercial aircraft is measured continuously and is under precise control of an automatic system. The aircraft cabin is supplied with turbine engine ‘bleed air’ to the environmental control system and released through outflow valves to automatically maintain the set cabin pressure altitude.[13]

Submarine and some space vehicle applications control gases separately, usually because there is a source of O_2 gas that is external to the storage capacity and initial consumable endowment of the ECLSS system (deionization and hydrolysis of water for submarines, propulsion or fuel cell oxygen gas for space vehicles).[12]

An autonomous, compressed gas release system that activates when pressure drops below a nominal pressure value would be an acceptable means of preventing cabin depressurization, as long as the partial pressure of O_2 is maintained within acceptable limits throughout the cabin. The use of nitrogen or mixed gas for pressure maintenance may be required to avoid excessive oxygen partial pressure with attendant flammability concerns.

Historically, various combinations of pressure suits have been used in both high altitude aircraft and spacecraft 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. Partial pressure suits maintain a pressure environment adequate to provide protection from hypoxia and ebullism, and with adequate denitrogenation such suits may provide 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 14 CFR § 460.11(b). An adequate redundant or secondary oxygen supply the FAA would find acceptable is one that can provide the necessary breathing and pressurant supply to the flight crew member for the duration the launch vehicle cabin pressure is above 15,000 feet pressure altitude. A flight crew pressure suit that incorporates a supply of oxygen as described may be used as an acceptable redundant system to prevent crew incapacitation.

6.2 Atmospheric Temperature

a. Hazards and characteristics

Although humans can survive in a relatively wide range of temperatures, proper temperature control can help ensure the flight crew will be capable of performing safety-critical tasks, 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.[12] The FAA finds that 25 to 70 percent relative humidity and 65 to 80 °F are acceptable humidity and temperature ranges for satisfying the temperature and humidity requirement of 14 CFR §

460.11(a)(2). Other limits may be proposed along with specific design and operational considerations to justify their use.

An enclosed environment containing humans receives metabolic heat, 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.[12] 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 may also receive sensible heat from avionics and other electrical equipment located in the habitable areas of the vehicle. Additional sensible heat may be transferred to or from the cabin air through the vehicle's pressure shell, depending on the flight profile and vehicle design..[11]

b. Operational considerations for suborbital launch vehicles

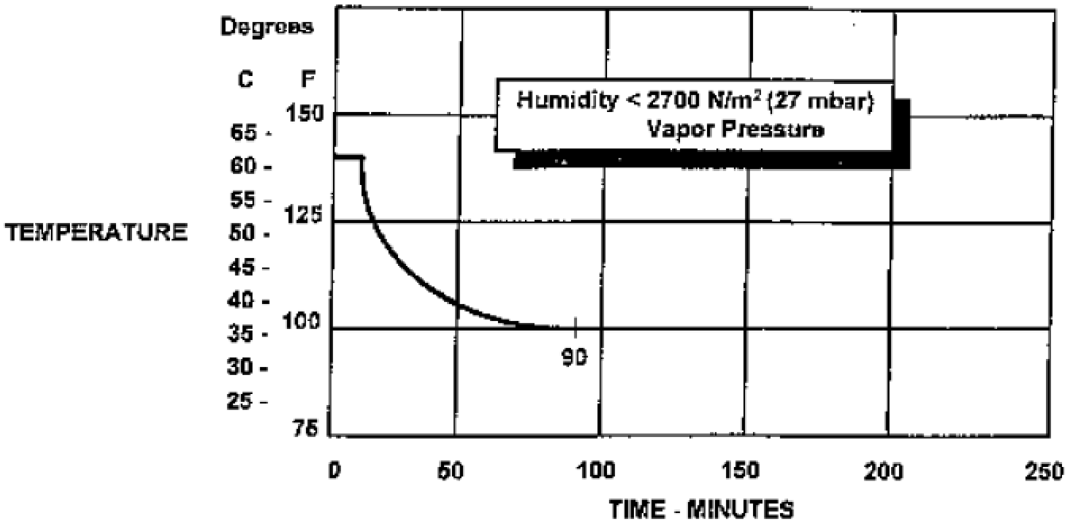
Suborbital vehicles are unique (compared to aircraft and orbital vehicles) in that there are almost no external conditions that are constant or steady-state throughout a typical suborbital flight profile. Pressure, temperature, and vehicle speed may change significantly throughout all phases of flight, which may complicate thermal management of inhabited spaces.

High-altitude subsonic aircraft flight usually requires a net addition of heat to the cabin because the exterior air is much colder than standard sea level conditions. A suborbital launch vehicle using compressed gases may also have to overcome cold external temperatures as well as internal cabin cooling due to the pressurized gas released into the cabin which cools upon adiabatic 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.

c. Related FAA regulations for aircraft

14 CFR § 25.831 requires that means must be provided in transport category airplanes 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, except if the compartments are sized, ventilated, and controlled as described in 14 CFR § 25.831(f).[18]

14 CFR § 25.831(g) requires that the exposure time at any given temperature must not exceed the values shown in the following graph after any improbable failure condition. This is an example of an acceptable envelope of upper temperature limits and exposure times for meeting 14 CFR § 460.11(a)(2).



TIME - TEMPERATURE RELATIONSHIP

d. Available monitoring techniques

Many different temperature monitoring systems have been qualified and proven for aerospace applications through test, demonstration, and flight operations. Many of these systems would be acceptable to the FAA if the operator successfully verifies 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 is between the range of 40 to 90 °F, a temperature monitoring device designed to operate within this range would be acceptable for complying with 14 CFR § 460.11(a)(2).

e. Available control techniques

Active automatic and manual temperature control systems have been used successfully in both aircraft and spacecraft.

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.[12]

Some vehicles are designed to simplify load demands by compartmentalizing a temperature-controlled volume into areas with similar demand requirements. For example, air temperature is measured and controlled in some aircraft for the comfort of passengers and crew, for the safe transport of luggage and cargo, and for cooling electronic and mechanical equipment. Because thermal loads are not the same in all parts of the aircraft, it may be separated into "control zones." Each zone has an independent temperature sensor and adjustable supply of conditioned air. Thermal conditioning in the cockpit is controlled separately from that in the passenger cabin or the luggage and cargo compartment. The passenger cabin may be further divided into two or more control zones, and may also include passenger control of air flow rates to individual seats.[11]

Passive control design techniques can use load matching as a means of controlling temperature by matching a heat sink with a heat source. An example of this is matching heat loss from a cabin to a cold exterior with heat production from electronic or mechanical equipment inside the cabin. Another passive control technique is to use the thermal capacitance of a material to absorb or emit heat energy in response to thermal loads.

These temperature control system designs would be acceptable to the FAA if the developer successfully verifies the integrated performance of a vehicle's hardware and any software in an operational flight environment, as required by 14 CFR § 460.17 before allowing any space flight participants on board during a flight.

The FAA notes that a design and operation must take 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.

6.3 Atmospheric Humidity

a. Hazards and characteristics

Excessive humidity or a lack of humidity does not pose an immediate health risk to flight crew for short periods of suborbital spaceflight. However, both a high humidity and very low humidity can impact the flight crew's physical comfort. High temperature and high humidity decreases the body's natural body temperature regulation processes (i.e., sweating). Low humidity has a 'drying effect' on the human body and is quickly noticed in areas such as eyes, lips, nose, and mouth causing discomfort. Thus, humidity may be interrelated with a flight crew's ability to successfully perform safety critical functions.

Spacecraft 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).[12] Stressed or excited individuals will produce water vapor at higher-than-average rates, which will vary. Design considerations should consider the rate of moisture generation over the mission duration to determine how the cabin humidity will change during the mission.

Relative humidity in commercial aircraft cabins is typically below 20 percent[11] because air is continuously compressed from the engine, conditioned by the air-cycle machine for the cabin and then dumped overboard via the outflow valves thus preventing any significant accumulation of humidity in the cabin. 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.[13] The NASA-developed "comfort box" is bounded by 25% to 70% relative humidity and by 65 to 80 °F.[12] Therefore, a range of humidity from 20-

70% is acceptable for meeting 14 CFR § 460.11. Other limits may be proposed along with specific design and operational considerations to justify their use.

However, it is also noted by the Agency that other safety-critical systems present within the cabin or cockpit (e.g., window surfaces or avionics) must retain their capability to operate within this humidity range without failure or without impairing the situational awareness of the crew or pilot.

b. Operational considerations for suborbital launch vehicles

Humidity management is important for maintaining crew comfort so that flight crew can perform safety-critical tasks as well as ensuring proper function of flight critical systems present within the cabin that have limited humidity exposure specifications.

Suborbital flight launch vehicle cabin volume(s) are expected to be small. 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.[12] Therefore, thermal management or other considerations may be appropriate to prevent condensation on or within safety critical components or systems. For example, on Skylab heaters were located to prevent excess moisture from forming on and damaging sensitive electronics.[14,15]

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 condensate or disaggregated solids (e.g., silica adsorption granules) associated with humidity control may impact the pilot’s ability to perform safety critical tasks.

c. Related FAA regulations for aircraft

None.

d. Available monitoring techniques

Commercially available portable as well as fixed sensors for monitoring relative humidity or dew point temperature have been shown to have acceptable accuracy (+/- 5%) for monitoring relative humidity. These systems 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.[12] 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 remove the moisture. Air flow-through or 'flushing' is an approach that can maintain appropriate humidity. Dry make-up gases are injected continuously, automatically, or on demand into an enclosed volume, while a separate valve system vents excess gases to maintain a nominal pressure range, removing excess humidity. In some cases, atmospheric capacity may be sufficient for short duration missions.

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.[14]

Each of 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 FAA notes that humidity control techniques that require direct attention or action on the part of the flight crew (e.g., wiping off windows obscured by condensation) may be 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

Very low oxygen partial pressure constitutes a severe hazard, and results in impaired judgment, ability to concentrate, night vision acuity, and shortness of breath, nausea, and fatigue. The result of low oxygen ppO_2 affects the proper functioning of the crew and can be the cause of a mishap.[12]

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).[12] 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 significant magnitude during the mission.

The human 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). Rapid decreases in oxygen partial pressure result in loss of consciousness within a few seconds. The effects of gradually 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.[14]

High oxygen partial pressures (starting at 4.7 psia) are also a hazard which can result in lung irritation and oxygen toxicity (hyperoxia).[12,14] Oxygen concentration above ambient increases material flammability hazards. The autoignition temperature decreases with increasing oxygen concentration, such that materials that are benign in the standard Earth atmosphere can become a source of a conflagration. The FAA emphasizes that replenishment oxygen gas released into an unmixed or unventilated part of a cabin in a microgravity environment can accumulate and produce an autoignition hazard.

The normal sea level atmospheric partial pressure of oxygen is 160 mm Hg (3.09 psia). Oxygen partial pressure should be maintained above 143 mm Hg (2.76 psia) for normal respiration to occur.[12,14] This is an example of an acceptable minimum oxygen partial pressure range for meeting 14 CFR § 460.11 and 14 CFR § 460.15. Other ppO_2 levels may be found acceptable to the FAA and will be evaluated on a case-by-case basis.

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.

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.[16]

Chemical oxygen generators may entail special operational considerations that complicate their use aboard suborbital launch vehicles. Co-location of exothermic oxygen gas 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.[17] 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.

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 and supplemental oxygen 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 (21%) of the total pressure. For this reason, the oxygen partial pressure in the cabin of commercial aircraft is not measured routinely.

Supplemental oxygen requirements for civil aircraft are described in 14 CFR § 91.211, which requires that at the minimum, flight crew be provided with and use supplemental oxygen after 30 minutes of exposure to cabin pressure altitudes between 12,500 and 14,000 feet and immediately on exposure to cabin pressure altitudes above 14,000 feet. Every occupant of the aircraft must be provided with supplemental oxygen at cabin pressure altitudes above 15,000 feet. Chapter 8, section 8-1-2(a)(6) of the Aeronautical Information Manual encourages pilots to use supplemental oxygen at cabin pressure altitudes above 10,000 feet during the day, and above 5,000 feet at night. With an oxygen gas fraction of 21%, this is an acceptable combination of exposure times, flight conditions, and operating limitations for nominal cabin conditions meeting 14 CFR § 460.11(a)(1) and 14 CFR § 460.15. Other ppO_2 levels may be found acceptable to the FAA and will be evaluated on a case-by-case basis.

d. Available monitoring techniques

Some commercially available oxygen partial pressure monitoring devices would be acceptable to the FAA, provided that these devices meet the design requirements 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.

Relevant operational design requirements 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

There are many techniques for controlling the oxygen content of the cabin 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), chemical, or liquid oxygen supply. Chemical oxygen generators are non-regenerable systems that produce O_2 and, for some generator materials, simultaneously remove CO_2. These types of systems 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.

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. After acute exposure to CO_2 concentrations ranging from about 3-7% at 1 atm, crewmembers will typically begin to exhibit symptoms that may affect the ability of crewmembers to perform safety critical functions, such as dyspnea, fatigue, impaired concentration, dizziness, faintness, flushing and sweating of the face, visual disturbances, and headache.[14] Exposure to 10% or greater concentrations at 1 atm can cause nausea, vomiting, chills, visual and auditory hallucinations, burning of the eyes, extreme dyspnea, and loss of consciousness.[14]

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).[12] 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.

The FAA would find an acceptable, acute exposure level of maximum carbon dioxide partial pressure for meeting 14 CFR § 460.11 is equivalent to 0.5 percent at one atmosphere total pressure. Other $ppCO_2$ levels may be acceptable for short-term exposure durations, but will be reviewed on a case-by-case basis.

b. Operational considerations for suborbital launch vehicles

Pellet-based control systems such as calcium hydroxide, lithium hydroxide, zeolites, or Carbon-dioxide and moisture removal Amine Swing-bed (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 or broken down 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. 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 lead to adverse physiological effects for vehicle occupants, causing potential degraded performance or injury to the flight crew.

Exothermic chemical oxygen generators that also scrub CO_2, or other exothermic CO_2 removal materials, may imply special operational considerations that complicate their use aboard suborbital launch vehicles. For example, exothermic chemical oxygen generators and CO_2 scrubbers may produce a tremendous amount of heat as oxygen is produced. Co-location of exothermic generators with combustible materials can be extremely dangerous.

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 (sea level equivalent) in compartments normally occupied by passengers or crew members.[18,19] This FAA limit is the same as the OSHA Permissible Exposure Limit (PEL).[20]

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 commercially available CO_2 monitoring techniques would be 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. The operational flight environment includes the total range of CO_2 for which the monitoring device is expected to operate.

e. Available control techniques

Both non-regenerable and regenerable devices have been used successfully in spaceflight applications.

CO2 can 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.12 Canisters are replaced on a schedule depending upon use.

Chemical oxygen generators are non-regenerable systems that produce O2 and, for some generator materials, remove CO2. They have been successfully used for spaceflight fire fighting and mine rescue operations. Chemical oxygen generators can be simple to use, compact in design, and dependable.12

Air flow-through or ‘flushing’ is an approach that can remove carbon dioxide. Fresh or make-up gases are injected continuously, automatically, or on demand into an enclosed volume, while a separate valve system vents excess gases to maintain a nominal pressure range. For some vehicles, atmospheric capacity may be sufficient for short missions.

Each of these system design concepts would be 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. 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

In an enclosed space, most materials have the potential to produce gas or vapor contaminants. 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.

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.[21,22] 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.[21]

The FAA will require an applicant to mitigate or eliminate the effects of those contaminants that are expected to be present within the applicant’s vehicle. 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 internal vehicle systems or other process sources may be sources of harmful substances.

Selecting materials to minimize outgassing and locating tanks and processing equipment where contaminant generation will be minimal are design considerations for controlling and preventing contaminants in the cabin environment.

The American National Standards Institute has published a standard test method for contamination outgassing characteristics of spacecraft materials.[23] 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.[24,25] At the time of writing this guide, 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.[27] 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.[26] 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.[14] 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.[27]

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.[28]

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.

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.[29] 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 or face masks are incorporated into emergency procedures, then egress procedures and structures may be affected by reduced sight abilities within the cabin.[30,31]

6.7 Particulate Contaminants

a. Hazards and characteristics

Airborne particulates such as dust may contain minerals (i.e., sand), metals, textile, paper and insulation fibers, nonvolatile organics, and various materials of biological origin (e.g., hair, skin flakes, dander, vomitus, and bacteria and fungi).[11] 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.[32]

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. NASA's operational limit for airborne microorganisms is 500 Colony Forming Units (CFU) per cubic meter.[14] 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 the flight crew's ability to perform safety critical tasks.

c. Related FAA regulations for aircraft

None.

d. Available monitoring techniques

The following information on commercially 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.

e. Available control techniques

An operator would be expected to develop a system for addressing particulates, whether it includes vacuuming the cabin preflight, periodic ground checks, material selection, flight suit cleanliness, or 'white-room' procedures such that the operator can maintain a specific level of cleanliness in the cabin so that contaminates will not cause a health hazard to the flight crew that would prevent them from performing their safety critical functions.

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.[12]

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, regularly maintained or replaced filters effectively control concentrations of particulate contaminants in the atmosphere for extended times, with neither rapid nor large changes during space flight operation. 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%.[11] HEPA filters also effectively trap bacteria and fungi.[33]

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.

6.8 Ventilation and Air Circulation

a. Hazards and characteristics

In microgravity, convection is reduced or non-existent and air stagnancy may be a risk in a microgravity environment where natural convection does not occur. Therefore, ventilation, i.e., effective circulation of the cabin atmosphere, is recommended to avoid crew discomfort in stagnant air and air pockets which could contain unmixed gases. Qualitative or quantitative assessment of flow paths and speed can be made during ground testing using a small source of smoke. The direction and speed of a smoke trail is observed as the smoke particles are emitted from the smoke source. A smoke source is also useful for identifying regions of stagnant air associated with flow obstructions such as seats, stowage compartments, and display panels.

NASA has determined that the minimum linear air velocity for maintaining crew comfort is 10-15 feet per minute.[14] 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.[11]

b. Operational considerations for suborbital launch vehicles

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.

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.

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.[11]

d. Available monitoring techniques

Measurement of the volumetric flow may be accomplished using a variety of different flow-meters or through the direct monitoring of fan speed or related current.

e. Available control techniques

Circulation fans that are commercially available which have been designed for aerospace and general industrial applications would be an acceptable means 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. 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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