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Passenger Oxygen Mask Design Study

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16. Abstract In response to Section 536 of Public Law 115-254, the Federal Aviation Administration (FAA) Reauthorization Act of 2018, the FAA conducted a review of the design, use, and effectiveness of commercial aircraft passenger oxygen masks. The intent was to determine whether the current design of passenger oxygen masks is adequate and whether changes to the design could increase correct passenger use of the masks. The yellow "Dixie-Cup" mask has changed little since the late 1950s, but its deceptively simple appearance belies a well-thought-out design. The round shape allows for quick and easy donning regardless of mask orientation. The mask also conforms to a wide range of face sizes and shapes, and one mask shape performs well for infants, children, and adults. Oxygen masks located throughout the passenger cabin typically meet minimum design, construction, and performance requirements using the FAA Technical Standard Order approval process and associated industry consensus standards. Following the completion of our review, we determined that the current passenger oxygen mask design is adequate and significant changes to the size and shape of the mask facepiece are not necessary. Although we determined that the general design and effectiveness of the mask facepiece is adequate, we made recommendations that may increase the correct use of the passenger mask. We made recommendations related to mask measurement, as well as increased comprehension of preflight briefing materials by passengers. We also made a recommendation to explore a cost-effective means to add text or symbology that would specify that the mask should be worn over the nose and mouth.					
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Executive Summary

In response to Section 536 of Public Law 115-254, the Federal Aviation Administration (FAA) Reauthorization Act of 2018, the FAA conducted a review of the design, use, and effectiveness of commercial aircraft passenger oxygen masks. The intent was to determine whether the current design of passenger oxygen masks is adequate and whether changes to the design could increase correct passenger use of the masks. The yellow “Dixie-Cup” mask has changed little since the late 1950s, but its deceptively simple appearance belies a well-thought-out design. The round shape allows for quick and easy donning regardless of mask orientation. The mask also conforms to a wide range of face sizes and shapes, and one mask shape performs well for infants, children, and adults. Oxygen masks located throughout the passenger cabin typically meet minimum design, construction, and performance requirements using the FAA Technical Standard Order approval process and associated industry consensus standards.

In the event of a sudden loss of cabin pressure at high altitudes, passenger cabin occupants must be able to don the oxygen mask quickly and breathe high concentrations of oxygen to prevent the onset of hypoxia (i.e., an insufficient supply of oxygen to the tissues). Once a high concentration of oxygen is administered, recovery usually begins in a matter of seconds. Once the oxygen mask is donned, it is important to breathe as normally as possible to prevent hyperventilation, which may exacerbate an already present hypoxic condition.

Knowledge is an important factor in the effective use of passenger oxygen masks. Studies show that an alert, knowledgeable individual has a much better chance of surviving a dangerous or life-threatening situation that could occur during passenger-carrying flight operations. Therefore, FAA operating regulations require air carriers and commercial operators to develop oral briefings and passenger safety information briefing cards.

Following the completion of our review, we determined that the current passenger oxygen mask design is adequate and significant changes to the size and shape of the mask facepiece are not necessary. Although we determined that the general design and effectiveness of the mask facepiece is adequate, we made recommendations that may increase the correct use of the passenger mask. We made recommendations related to mask measurement, as well as increased comprehension of preflight briefing materials by passengers. We also made a recommendation to explore a cost-effective means to add text or symbology that would specify that the mask should be worn over the nose and mouth.

Introduction

This report is provided in response to the legislative requirements established in the Federal Aviation Administration (FAA) Reauthorization Act of 2018 (Public Law 115-254), Section 536, Oxygen Mask Design Study.

Multiple data sources and references were used, including but not limited to FAA regulations and advisory circulars, aerospace industry consensus standards, recommended practices and information reports, proprietary design information from oxygen mask manufacturers, aerospace medicine technical reports, peer-reviewed academic research, and National Transportation Safety Board (NTSB) accident/incident reports.

This literature review presents a description of the current passenger cabin occupant oxygen mask design and function, followed by information on mask design, materials and performance testing standards, and passenger education. Appendices contain a historical overview of aviation oxygen masks, information on oxygen systems and mask assemblies, and flight physiology. We present evidence that the current mask design is adequate, and we provide recommendations that may increase passenger understanding and correct use of the mask.

Legislative Mandate

The FAA Reauthorization Act of 2018 (Public Law 115-254), Section 536; Oxygen Mask Design Study, specified:

Not later than 180 days after the date of enactment of this Act, the Administrator shall conduct a study to review and evaluate the design and effectiveness of commercial aircraft oxygen masks. In conducting the study, the Administrator shall determine whether the current design of oxygen masks is adequate, and whether changes to the design could increase correct passenger usage of the masks.

Background

Passenger Cabin Occupant Oxygen Mask Design and Function

This section describes the general design and function of the continuous flow, phase-dilution oxygen mask (i.e., yellow “Dixie Cup”) currently used throughout the passenger cabin onboard commercial transport aircraft. Specific design details are not provided in this report because oxygen mask suppliers and oxygen system installers consider such detailed information proprietary. Therefore, we provide only general or publicly available information.

Transport category airplane oxygen systems meet minimum performance requirements described

in Title 14 Code of Federal Regulations (14 CFR), Part 25. For oxygen masks located throughout the passenger cabin, the most common compliance method is to meet the minimum performance requirements stipulated in FAA Technical Standard Order (TSO)-C64, *Passenger Oxygen Mask Assembly, Continuous Flow*. The most current version at the time of this writing is TSO-C64b (FAA, 2008). TSO-C64b refers to the SAE International Aerospace Standard AS8025A, *Passenger Oxygen Mask*, an industry consensus standard that establishes the minimum requirements for the design, construction, and performance of the continuous flow, phase-dilution oxygen mask for passenger cabin occupants in civil commercial aircraft (SAE International, 2016a)

Mask Components

The continuous flow, phase-dilution oxygen mask consists of oxygen tubing with an in-line oxygen flow indicator, a reservoir bag to accumulate/hold highly concentrated oxygen, and a face piece with three valves (Figure 1).

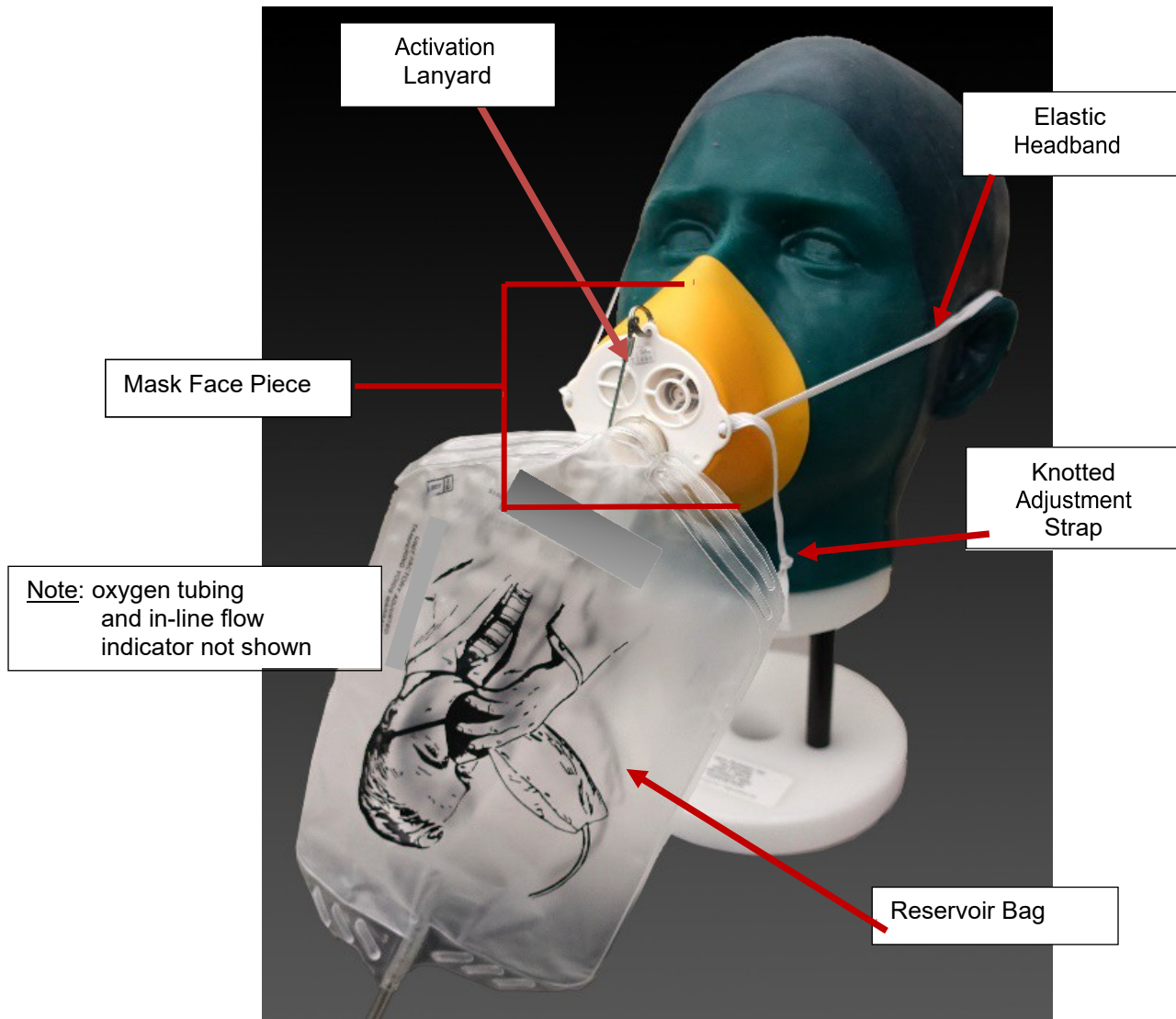


Figure 1: *Passenger Cabin Occupant Mask*

The three valves include an inhalation valve located between the bag and face piece that allows for the inhalation of highly concentrated oxygen from the bag, an ambient inhalation valve that allows for the intake of ambient air, and an exhalation valve that releases exhaled gases to the ambient air (Figure 2). An elastic band goes over and behind the head to secure the mask to the face over the nose and mouth, with knotted adjustment straps to tighten the mask.

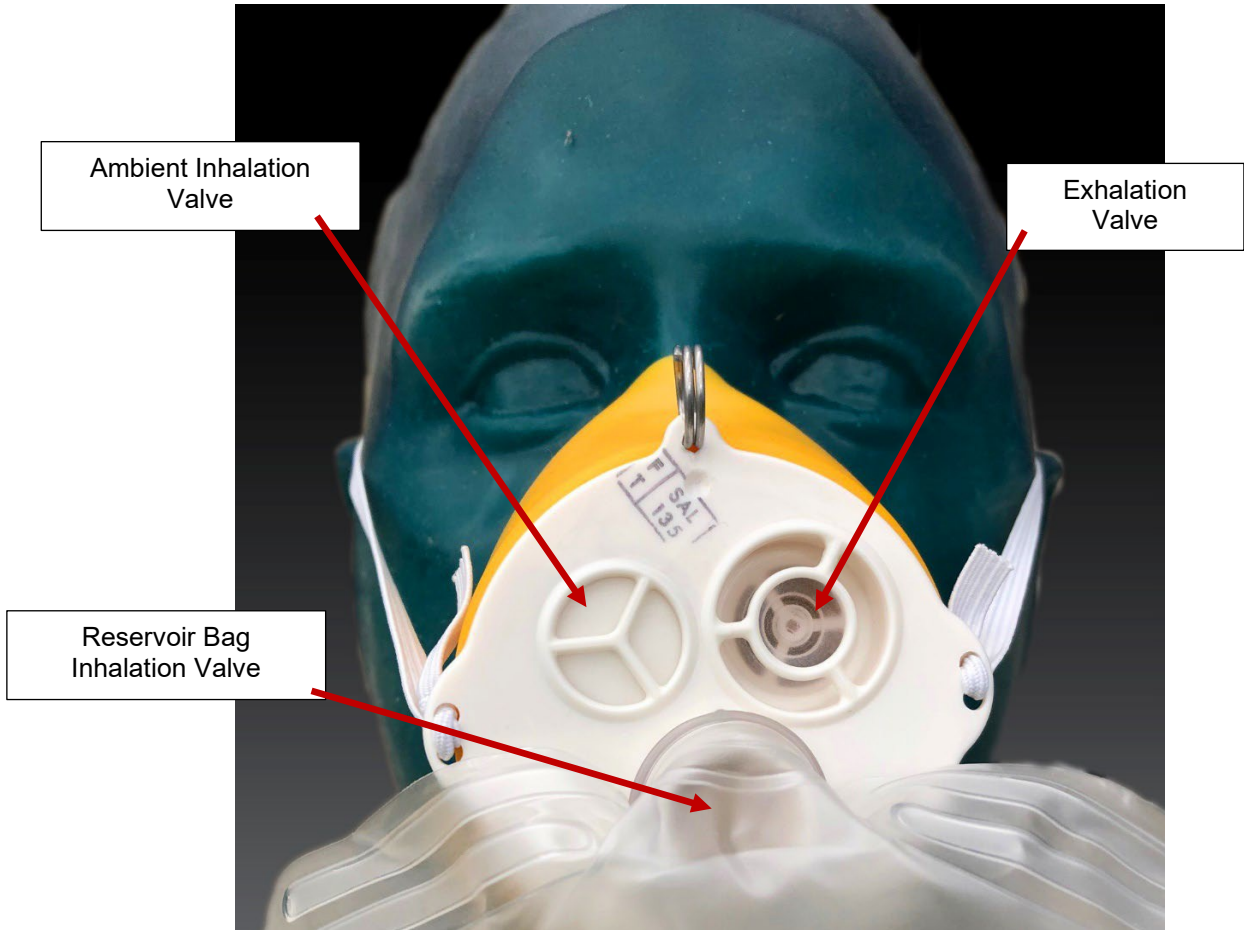


Figure 2: *Mask Face Piece with Valves*

Mask Deployment and Oxygen Flow Activation

Airplane oxygen masks do not contain their own oxygen supply source. Phase-dilution oxygen masks require a constant flow of oxygen from either a small, single-use oxygen source located in the overhead passenger service unit (PSU) with the masks or from a remote location with a plumbing system to transfer oxygen to the PSU. For airplanes certified for operation above 30,000 ft (9,144 m), 14 CFR § 25.1447(c) requires that oxygen masks providing the required oxygen flow must automatically deploy before the cabin pressure altitude reaches 15,000 ft (4,572 m). Individual oxygen masks are suspended from the PSU by a lanyard to prevent the masks from being donned without activating the flow of oxygen. Several oxygen masks are deployed from each PSU (e.g., four masks for a row of three seats; Figure 3). Extra masks

may be used by lap children or the flight attendants and are required per 14 CFR § 25.1447(c), which stipulates that the total number of oxygen masks must exceed the number of seats by at least 10% and be as uniformly distributed throughout the cabin as practicable.



Figure 3: *Deployed But Not Yet Activated Oxygen Masks*

To activate the flow of oxygen, the user pulls the mask down and to the face. It is important to pull the mask (i.e., the yellow Dixie cup facepiece), not the oxygen tubing; pulling on the tubing may pull it free from the oxygen dispensing unit. Pulling on the mask places tension on the lanyard, and the pull force releases a mechanism to start the flow of oxygen. Once activated, oxygen flows to the mask. For some system designs, every mask in a seat row will drop when one mask is pulled, and oxygen flows to all the masks suspended from the PSU. An indication of oxygen flow is required for oxygen mask approval to the FAA TSO, and many systems use an in-

line flow indicator in the oxygen tubing that turns GREEN to indicate oxygen flow to the reservoir bag (Figure 4).

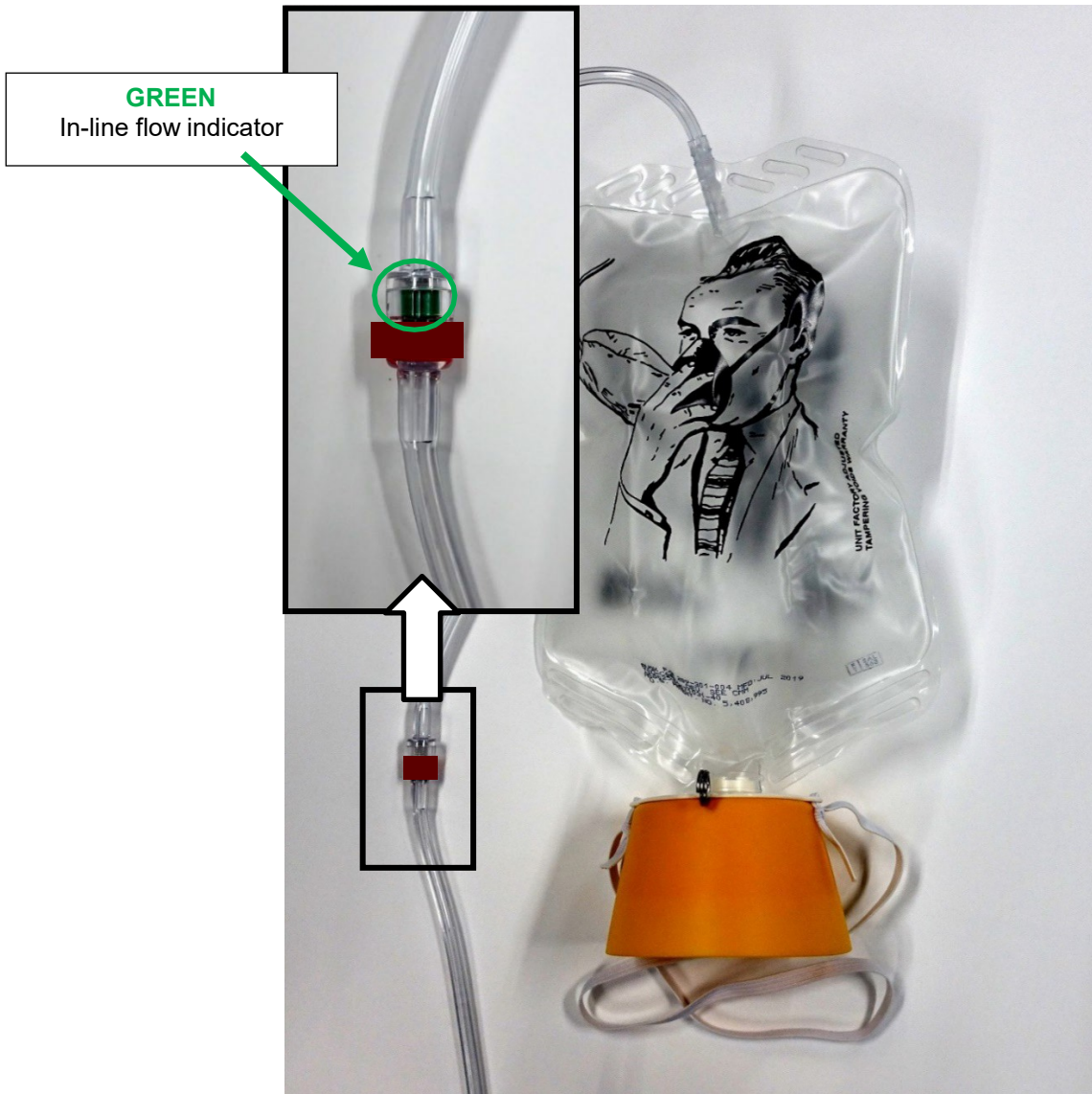


Figure 4: *Oxygen Tubing and In-Line Flow Indicator*

Mask Function

Oxygen from the supply source flows into the reservoir bag, interposed between the delivery tubing and the mask facepiece. The continuous flow of oxygen fills the reservoir bag throughout the breathing cycle—*inhalation, exhalation, and the pauses in between*. The reservoir bag is separated from the mask facepiece by a sensitive, one-way check valve. During *inhalation*, highly concentrated oxygen drawn from the bag flows deep into the lungs. If the reservoir bag empties before *inhalation* is complete, the second *inhalation* valve opens to permit the flow of ambient air, allowing a full breath intake without feeling suffocated.

Highly concentrated oxygen is provided at the most advantageous point in the breathing cycle—at the beginning of inspiration—and flows deep into the lungs where it is most needed. Any ambient air (with <100% oxygen) inhaled at the end of breath intake flows no farther than the upper respiratory tract (i.e., mouth cavity, trachea, and bronchi—the anatomical “dead space” where no pulmonary gas exchange occurs).

During exhalation, oxygen diluted with ambient air is swept from the mask (last in, first out), along with expired air from the lungs. The expired air vents “overboard,” out of the mask via the exhalation valve; expired air is not returned to the reservoir bag. The next inhalation starts with highly concentrated oxygen drawn from the reservoir bag.

Mask Not for Use as Protective Breathing Equipment

There is a general lack of understanding among the flying public of how passenger oxygen masks work and when they should be deployed. The passenger cabin occupant mask is for use only in the event of a loss of cabin pressurization to provide hypoxia protection from the increase in cabin pressure altitude. The mask is not intended to provide fire/smoke/fume protection due to the inhalation valve that permits the flow of ambient air, including potential smoke and fumes. In the event of a cabin fire with spreading flames, if oxygen masks are deployed, oxygen flowing from the supply source may increase the intensity of a fire.

There are several recent incidents in which the passenger oxygen masks were incorrectly deployed, or the passengers demanded that the masks be deployed during a fire/smoke/fume event. JetBlue Airways Flight 1416 (September 18, 2014; Long Beach, CA) experienced several right engine fire indications shortly after takeoff. The flight crew deployed the engine fire extinguishers and initiated an air turnback for Long Beach. During descent, the cabin filled with smoke. The oxygen masks did not deploy (the airplane leveled off at approximately 9,400 ft [2,865 m]), but the flight attendants manually deployed the masks. The airplane made a successful, uneventful single-engine landing at Long Beach, and the passengers evacuated via slides (NTSB, 2016).

British Airways Flight 2276 (September 8, 2015; Las Vegas, NV) and American Airlines Flight 383 (October 28, 2016; Chicago O’Hare) both experienced uncontained engine failures during takeoff and aborted flight on the runway. In both incidents, while the flight crew and flight attendants assessed the situation (e.g., engine shut down, fire location to avoid evacuation slide deployment into the fire) billowing smoke filled the cabin. Passengers became aggressive and combative when flight attendants did not deploy the oxygen masks, causing confusion and slowing the emergency evacuation once initiated (NTSB, 2017a; NTSB, 2017b). Emirates Flight 521 (Dubai International Airport, August 3, 2016) experienced significant wind shear during the

approach, made a hard landing, and skidded down the runway. As the plane came to rest, several fires broke out under the fuselage. The oxygen masks deployed due to the hard landing, and confused passengers attempted to don the masks instead of heeding the flight attendants' urgent orders to evacuate (General Civil Aviation Authority, 2016).

Per FAA regulations, oxygen systems for flight crew on flight deck duty include minimum performance requirements for supplemental oxygen and are meant to serve as protective breathing equipment (PBE; e.g., full-face visor, mask plus smoke goggles) against fire, smoke, or fumes in the flight deck. FAA regulations do not require passenger PBE for fire, smoke, or fumes in the cabin.

The FAA's Civil Aeromedical Institute conducted a series of studies from 1965 to 1989 to evaluate the feasibility of providing smoke/fume passenger PBE by modifying the passenger oxygen mask for dual-use (i.e., hypoxia protection and fire/smoke/fume protection) or developing completely separate passenger PBE (e.g., smoke hoods). The researchers also investigated what effect PBE had on passengers' ability to initiate and complete an emergency evacuation (McFadden et al., 1967; DeSteiguer et al., 1978; DeSteiguer & Saldivar, 1983; Higgins et al., 1985; McLean et al., 1989).

Ultimately, the FAA determined not to require PBE for passenger cabin occupants. Even if the passenger oxygen mask could be adapted for dual-use as PBE, that would be undesirable due to concern that the PBE might cause a delay in evacuation (Higgins, 1987).

Mask Design, Materials, and Performance Testing Standards

Oxygen masks located throughout the passenger cabin typically meet FAA TSO-64b, which refers to SAE AS8025A and contains details of minimum design, construction, and performance requirements. The most pertinent standards related to the Congressional tasking are summarized below.

Mask Design/Presentation

The mask assembly application (i.e., how to don the mask) shall be obvious. The mask "shall be capable of quick and easy donning regardless of any special orientation requirements" (SAE International, 2016a). This general presentation requirement has been in effect for 60 years. First introduced in the original industry consensus standard (National Aerospace Safety [NAS] 1179) in 1959, it has been included in all SAE AS8025 revisions since 1988.

Mask Materials

All mask materials must be of a type, grade, and quality (demonstrated by test, experience, or both) to be suitable for the intended purpose. Materials that contaminate oxygen or are affected

adversely by continuous service with oxygen must not be used. The facepiece must be free of objectionable odors. Materials in contact with the skin must be nonallergenic and nonirritating. The mask must be made of materials that permit cleaning and sterilization without adverse effects and without disassembly. Per TSO requirements, oxygen mask suppliers provide a component maintenance manual that provides detailed inspection, cleaning, and replacement criteria to equipment installers.

Mask Face Piece

The facepiece shall be of sufficient resilience, size, and shape to conform readily to extreme facial contours using no more pressure than that supplied by the mask suspension device. The facepiece shall cover the airways of the nose and mouth. The main body of the mask shall be stiff enough to minimize deformation due to incorrect handling, which may result in reduced operating performance. The chamber formed between the face and the mask shall be of a minimum volume at all times to prevent the build-up of carbon dioxide during exhalation. SAE AS8025A also prescribes the color of the facepiece - No. 13538 yellow of Federal Standard No. 595.

Mask Performance Testing Standards

FAA regulation 14 CFR § 25.1443 prescribes minimum tracheal oxygen partial pressures. To demonstrate compliance with the FAA regulation, passenger oxygen masks are tested using procedures described in SAE AS8025A to determine the minimum oxygen flow required to the mask as a function of cabin pressure altitude. Once the minimum oxygen flow to the mask is determined, oxygen mask installers use the data to ensure that the oxygen system supply source provides sufficient flow rates to the oxygen mask for each airplane installation.

Determining the minimum oxygen flow required to an oxygen mask design is a three-step testing process:

- (1) Determine the typical fit leakage value (i.e., how much oxygen/air leakage occurs between the mask and the user's face) by fitting the mask to human test participants of various ages and facial contours.
- (2) Test the oxygen mask on a breathing machine to determine the minimum oxygen flow needed to the mask at various cabin pressure altitudes. The breathing machine simulates breathing rate, tidal volumes (i.e., the volume of air inspired and expired with each normal breath), and the tracheal oxygen partial pressures described in FAA regulation § 25.1443.
- (3) Validate the breathing machine results using human participants in an altitude chamber.

Passenger Education and Situational Awareness

Passenger Behavior

Regardless of oxygen mask design, minimum performance requirements, and applicable regulations, passengers must still understand how to don and use the equipment correctly. Assuming that the social media pictures from Southwest Flight 1380 (April 17, 2018; diverted to Philadelphia, PA) were taken during the emergency descent (Figure 5 [p. 14]; Shapiro, 2018), not all passengers on that particular flight understood how to use the oxygen masks. Conversely, in the course of our historical review of similar oxygen mask deployments, no data suggest that the social media pictures from the Southwest Flight 1380 event and Jet Airways Flight 9W697 (September 20, 2018, Mumbai), where the flight crew failed to activate the cabin pressurization system (Figure 6 [p. 15]; The Hindu, 2018) are indicative of how the flying public typically uses passenger oxygen masks.



Figure 5: *Southwest Flight 1380*



Figure 6: *Jet Airways Flight 9W697*

Oxygen Mask Deployments

In a notice of proposed rulemaking (NPRM) issued January 9, 2013 (FAA, 2014), the FAA provides statistics related to the probability of in-service decompression events and related oxygen mask deployments. As discussed in the NPRM, the FAA identified 2,800 instances over 40 years when supplemental oxygen was needed, and there was no reported loss of life due to lack of oxygen.

It is easy for passengers to become complacent because the instances are so rare; however, knowing how to use the oxygen equipment correctly, when needed, reduces the probability of injury should a high-altitude decompression occur. Information in the history and flight physiology appendices (Appendices B and D, respectively) describes how, as technological advances led to high-altitude flight, it became imperative that passengers don their oxygen equipment quickly and correctly to prevent rapid-onset hypoxia (insufficient supply of oxygen to the tissues).

Passenger Apathy

In 1996, the European Transport Safety Council (ETSC) estimated that 90% of commercial aircraft accidents were survivable (ETSC, 1996). In 2001, the NTSB performed a comprehensive

review of national aviation accidents (Part 121 carrier operations) from 1983 through 2000 and found that 95.7% of passengers survived accidents. The NTSB also examined the proportion of occupants who survived each accident from 1983 to 2000 and found that, in 528 of the 568 accidents (93%), more than 80% of the passengers survived (NTSB, 2001). Although these statistics are dated, commercial air travel has, if anything, become safer due to improvements in impact protection (e.g., 16 G-force passenger seats, updated brace position instructions), fire survivability (e.g., fire retardant materials), and evacuation procedures.

However, despite the survival statistics, passengers continue to display a dangerous level of apathy towards the preflight safety briefing. The average airline passenger does not think that an emergency such as a loss of cabin pressure will happen to them. Very few people, except perhaps airline crews or military personnel, have been exposed to or trained for the details of an inflight emergency. Appropriate training for an inflight emergency brings required, time-sensitive action steps to mind immediately during a crisis event. Studies show that an alert, knowledgeable individual has a much better chance of surviving any life-threatening or dangerous situation that could occur during passenger-carrying flight operations (FAA, 2019a). Therefore, FAA operating regulations (14 CFR § 121.571, § 125.327, and § 135.117) require air carriers and commercial operators to develop oral briefings and passenger safety information briefing cards.

Passenger Briefings

Regardless of the delivery method of the oral (including video) safety briefing, passengers often do not pay attention and do not review the safety information cards. As with other forms of transportation, the level of passenger distraction has increased dramatically with the expanded use of portable electronic devices (FAA, 2019b).

Air carriers continually evaluate passenger briefings. Guidance to air carriers to encourage effective passenger briefings is found primarily in the sources below which provide minimum safety content and presentation guidelines:

- (1) Federal Aviation Administration (FAA) Advisory Circular (AC) 121-24D, *Passenger Safety Information Briefing and Briefing Cards* (FAA, 2019a)
- (2) SAE Aerospace Recommended Practice ARP1384, *Passenger Safety Information Cards* (SAE International, 2006)

Flight attendants prepare passengers for critical flight phases, irregular activities, and potential inflight emergencies by using scripted oral announcements, video briefings (where available), and by pointing to safety information card pictorials. Per 14 CFR § 121.333(f), a passenger briefing is required for flights conducted above flight level 250 during which "...a crewmember shall instruct the passengers on the necessity of using oxygen in the event of cabin depressurization and shall point out to them the location and demonstrate the use of the oxygen-dispensing equipment." Advisory Circular (AC) 121-24D guidance cautions air carriers about passenger

distractions during the safety briefing, where it states,

Consideration should be given to the content and assessment of the passenger safety information system delivery methods, taking into account passenger behavior and strategies to mitigate distractions during safety briefings. Every passenger should be motivated to focus on the safety information in the required passenger safety briefing; however, motivating people, even when their own personal safety is involved, is not easy. One way to increase passenger motivation is to make the safety information briefings and safety information cards as interesting, entertaining, and attractive as possible.

The NTSB conducted a Safety Study of passenger safety briefing methods titled, *Airline Passenger Safety Education: A Review of Methods Used to Present Safety Information* (NTSB, 1985). The rationale for the study was “a long-standing concern that some passengers onboard air carrier airplanes contributed to their own injuries or deaths because they were not prepared to respond appropriately to emergencies.” The NTSB concluded that many safety card depictions were confusing and ambiguous, and provided three recommendations to improve safety briefing cards:

- (1) Develop tests and minimum comprehension standards to assure proper passenger actions based on the safety information presented.
- (2) Revise air carrier Operations Handbooks and Bulletins and FAA inspector training programs to provide better guidance based on results of passenger comprehension testing.
- (3) Revise FAA AC 121-24 to include updated information on emergency procedures.

Further, the NTSB called for greater standardization of safety briefing materials based on qualitative and quantitative research into the best content and manner to convey safety information to passengers. The FAA published multiple revisions to the guidance in AC 121-24, and in the current revision (AC 121-24D, dated March 05, 2019), Appendix 6 provides guidance to improve safety briefings and specifically encourages the collection, evaluation, and continuous improvement of safety briefings using survey data (FAA, 2019a). Appendix A of this report provides industry representative examples of a briefing card and script related to passenger education on oxygen mask use (Figure 7 [p. 19] and Figure 8 [p. 20]).

Conclusions

Historically, the current design of the passenger cabin occupant oxygen mask has effectively provided protection from hypoxia during typical decompression events. As such, we determined that the current oxygen mask design is adequate, and significant changes to the size and shape of the mask facepiece are not necessary.

All the early phase-dilution masks retained the most important design feature—a round, symmetrical facepiece, which eliminates confusion in having to orient the mask into a single position or putting the mask on upside down. The general presentation requirement of “the mask shall be capable of quick and easy donning regardless of any special orientation requirements” has been in effect for 60 years. First introduced in the original industry consensus standard in 1959, the presentation requirement has been included in all revisions of the mask design standards (SAE AS8025) since 1988. The round, symmetrical facepiece is essential not just for quick mask donning regardless of orientation—a round shape conforms to the broadest range of face shapes and sizes, and one mask shape fits infants, children, and adults.

Based on the review conducted, we determined that the general design and effectiveness of the oxygen mask facepiece is adequate.

To address the concern of correct passenger use of the mask, efforts should be directed to passenger education versus a mask redesign. Passengers should have a better understanding of how the passenger oxygen mask works, the situations in which the mask is deployed, and why it is important to don the mask over *both* the nose and mouth.

Appendices

Appendix A: Sample Briefing Cards and Safety Briefing Script



Figure 7: Excerpts from Industry Representative Examples of Passenger Briefing Cards – Passenger Oxygen Mask Use

Remove the vest only if told to do so. Pull the red strap to open the container and remove the pouch. *Place the vest over your head. Wrap the strap around your waist, buckle it in the front, and pull to tighten.*

Once outside, *pull down on the red tab* to inflate the vest. To manually inflate, *blow into the tube* at your shoulder.

We are coming by to check that your seatbelt is fastened, your seatback and tray table are in the full-upright and locked position, and your carryon items are completely under the seat in front of you or in an overhead bin, leaving the area around your feet clear.

Smoking, including use of electronic cigarettes, is not allowed onboard, including the lavatories. Federal law prohibits tampering with, disabling, or destroying any smoke detector in an aircraft lavatory.

Federal Aviation Regulations require Passenger compliance with the lighted passenger information signs, posted placards, and Crew Member instructions including information on seatbelts and smoking.

If needed, *four oxygen masks will drop* from the compartment overhead. To activate the flow of oxygen, *pull down on the mask* until the plastic tubing is fully extended. *Place the mask over your nose and mouth* and breathe normally. *Secure the mask with the elastic strap.* Although oxygen will be flowing, the plastic bag may not inflate. Continue wearing the mask until otherwise notified by a Crew Member. If you are traveling with children or anyone needing special assistance, put on **your** mask first.

Thank you for your attention. Please sit back, relax, and enjoy

your _____ (hour-and-minute) flight to _____. Welcome aboard
_____ Airlines.

9.6.0 Reading Lights

Revised: 06/01/2014

We will dim the cabin lights for departure. If you need a reading light, press the button above you with the figure of a light bulb on it.

Note: Announcement made when conditions warrant.

9.7.0 Cleared for Departure

Revised: 06/01/2014

Ladies and gentlemen, we have been cleared for departure.

9.8.0 Service

Revised: 02/04/2019

Ladies and gentlemen, in a few moments we will begin our inflight service. A menu that lists our complimentary beverages and selections for purchase is available in your seatback pocket.

Please remain seated while the FASTEN SEAT BELT sign is on. We have lavatories in the front and back of the aircraft. The sign on the ceiling indicates the lavatory is occupied. Please do not form a line at the forward lavatory.

Figure 8: Industry Representative Example of a Safety Briefing Script

Appendix B: Aviation Oxygen Masks - Historical Overview

World War I: The Pipe Stem

The pipe stem was the first aviation oxygen delivery system. Developed by the Germans for dirigible aircrew, the pipe stem delivered compressed oxygen from heavy iron flasks through a mouthpiece clenched between the teeth. By the war's end, both German and Allied pilots carried small, "personal" oxygen supplies using an early liquid oxygen-generating system (Kalei, 2008). Inefficient and difficult to use—most of the constant flow oxygen vented into ambient air, cold temperatures and altitude made it difficult to hold the pipe stem for long periods, and water vapor froze in the line blocking oxygen flow—the pipe stem did however provide a measure of protection against hypoxia (Boothby & Lovelace, 1938; Kalei, 2008).

The 1930s–1940s: The BLB Mask and the K-S Disposable Oxygen Mask

By the 1930s, unpressurized commercial transport airplanes routinely flew between 10,000 ft (3,048 m) and 14,000 ft (4,267 m), avoiding most terrain and flying above the weather for a smoother, less turbulent flight (Boothby & Lovelace, 1938). However, airline executives were increasingly concerned with the rising number of airplane crashes, and the medical community suspected that pilot impairment from hypoxia was a significant underlying factor in many accidents initially attributed to "pilot error" (Barach, 1937).

Most individuals begin to exhibit mild symptoms of hypoxia (e.g., headache, fatigue) around 10,000 ft (3,048 m), although more subtle impairments may go unrecognized at lower altitudes (e.g., night vision degradation at 5,000 ft [1,524 m]) (Pickard & Gradwell, 2008). In the absence of any standardized aviation oxygen rules, some airlines instituted their own. United Airlines required oxygen use above 10,000 ft (3,048 m) regardless if pilots felt it necessary (Boothby & Lovelace, 1938).

In the late 1930s, the pipe stem was still the most common method to deliver aviation oxygen, and although the anticipated introduction of a pressurized airplane¹ was expected to render oxygen use unnecessary, the flight crew still needed a reliable oxygen mask system in the event of a depressurization (Miller, 1995; Nelson, 1995).

¹ The first flight of a fully pressurized airplane, an Army Lockheed XC-35, occurred May 7, 1937. The Boeing 307 Stratoliner, the first commercial transport airplane with a pressurized cabin, launched December 3, 1938. Commercially unsuccessful, the Stratoliner was surpassed by the Lockheed Constellation. Developed in 1937, the "Connie" was the first pressurized cabin civilian airliner in widespread use (Grant, 2002; FAA, 2017a).

The BLB mask was the first successful, widely used aviation oxygen mask. Developed by the Mayo Clinic and named for its designers, Dr. Walter M. Boothby (surgeon/anesthesiologist), Dr. W. Randolph Lovelace II (surgeon/flight surgeon), and Dr. Arthur H. Bulbulian (dentist/orthodontist, an expert in facial prosthetics), the mask was introduced for aviation use in 1939. The Mayo Clinic physicians originally developed the BLB oronasal mask to deliver patient oxygen more efficiently than using an oxygen tent (Miller, 1995). A rebreather-dilution mask design, the BLB mask consisted of a molded, soft rubber nasal mask and connecting tubes, an oxygen inlet and regulator, and a rebreather bag (Figure 9) (Cooper & Street, 2017). Gaseous oxygen passed through a reducing valve and flowmeter calibrated for altitude, then flowed into the rebreather bag via the oxygen inlet. On inhalation, oxygen was drawn up through the connecting tubes to the nasal cavity. Expired air flowed down the connecting tubes, a portion of which passed into the rebreather bag to be mixed with ambient air and incoming oxygen, the remaining vented via an exhalation port (Boothby & Lovelace, 1938).

May 13, 1941. W. M. BOOTHBY ET AL. 2,241,535
 APPARATUS FOR DELIVERING AND PERMITTING NORMAL
 BREATHING OF MIXTURES OF GASES
 Filed July 28, 1939 4 Sheets-Sheet 1

May 13, 1941. W. M. BOOTHBY ET AL. 2,241,535
 APPARATUS FOR DELIVERING AND PERMITTING NORMAL
 BREATHING OF MIXTURES OF GASES
 Filed July 28, 1939 4 Sheets-Sheet 2

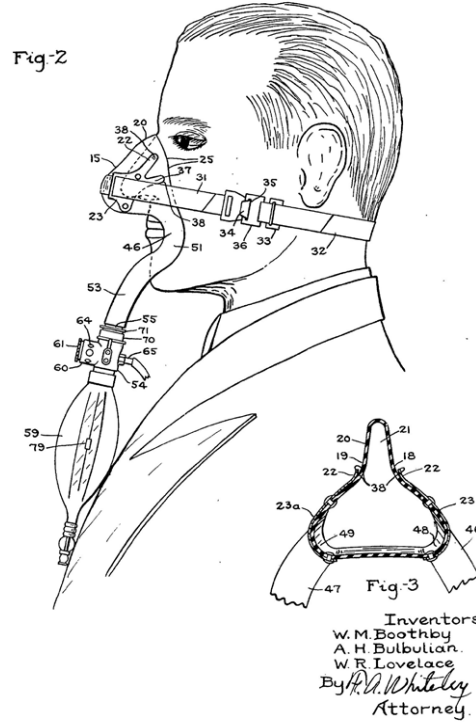
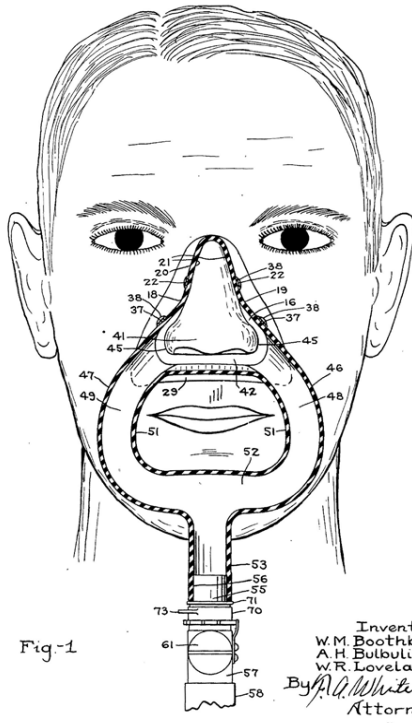


Figure 9: Patent Diagrams of the BLB Mask (Lovelace et al., 1941)

The mask was tested extensively in the laboratory, in altitude chambers, and in-flight—the first of which occurred March 10, 1939, on board a Northwest Airlines Lockheed 14H twin motor airplane. The 1,150-mile (1,851-km) flight from Minneapolis to Boston was completed in 4.5

hours, flying 270 mph at an average altitude of 23,000 ft (7,010 m). The pilot, copilot, and nine passengers (the mask designers and Northwest Airlines executives) all wore BLB masks throughout the flight with no discomfort or ill effects from hypoxia (Figure 10) (Whitemule, 2019).



Figure 10: *Passengers Wearing the BLB Mask During the First Operational Test Flight, On Board a Northwest Airlines Lockheed 14H Twin Motor Airplane, March 10, 1939*

Additional test flights demonstrated that the BLB mask could successfully maintain lung partial pressures and arterial blood saturation levels to meet the physiological demands of high-altitude flight and protect flight crew and passengers from hypoxia (Boothby & Lovelace, 1938; Cooper & Street, 2017).

The BLB mask had numerous advantages over the clenched-in-the-mouth pipe stem, the most important being efficiency. Mixing supply source oxygen with exhaled air (16% oxygen) and ambient air (21% oxygen) substantially decreased the number of large, gaseous oxygen bottles required onboard the flight, thus saving airplane weight and space. The mask was comfortable and could be worn for long periods, the mouth was free and unobstructed for talking over the radio or to other crew members, and the mask was mechanically simple and easy to use (Cooper & Street, 2017; Boothby & Lovelace, 1938). Widely used in commercial transport airplanes for

flight crew and passengers alike, the BLB mask was also used by American and Allied pilots during World War II and became the prototype for today's military tactical jet oxygen masks (Cooper & Street; 2017).

Post-World War II airplanes capable of flying at higher altitudes prompted revisions to the Civil Air Regulations oxygen use rules for both flight crew and passengers. The 1947 regulation recommended that oxygen and an oronasal mask be provided for each passenger for flight above 12,000 ft (3,658 m) (Tuttle et al., 1951). Before this, masks were not required for all passengers and were hung in the cabin as a convenience for passengers suffering from airsickness or used to "refresh" themselves during flight.

The 1947 regulation prompted United Airlines to design and introduce the K-S Disposable Oxygen Mask.² Designed for passenger use only, the K-S disposable mask was a constant flow, rebreather-dilution mask consisting of a double bag (i.e., a bag within a bag) of lightweight plastic. The inner bag fitted over the nose and mouth with air exchange occurring via two holes with the outer (rebreather) bag into which oxygen flowed. Two additional, smaller holes in the inner bag permitted ambient air exchange. An adjustable elastic band secured the mask around the head, and a pliable metal strip in the upper rim of the facepiece could be molded to fit over the nose and cheeks (Figure 11).

Designed to meet oxygen requirements in pressurized airplanes from sea level to 14,000 feet (4,267 m), and up to 25,000 feet (7,620 m) in the event of depressurization, passengers easily donned the mask without the need for complicated instructions, and one mask shape/design could be used for children and adults (Tuttle et al., 1951). The K-S disposable mask was quickly adopted for use onboard commercial airplanes—its lightweight and compact size made it an attractive alternative to the bulky BLB mask.

Despite performing well in experimental altitude chamber flights from 10,000 ft (3,048 m) to 25,000 ft (7,620 m), meeting or exceeding all material and physiological performance test criteria and comparing favorably to BLB mask performance, a rapid loss of cabin pressure (i.e., rapid decompression) to 25,000 ft (7,620 m) pushed the K-S mask to its performance limits.

² Named for mask designers Mr. Koza and Mr. Stockam



Figure 11: *The K-S Disposable Oxygen Mask*

Researchers evaluated the K-S disposable mask in a series of experimental altitude chamber flights, exposing test participants to simulated rapid decompressions from 6,000 ft (1,823 m) to 20,000 ft (6,096 m), 25,000 ft (7,620 m), and up to 27,000 ft (8,230 m). Test participants successfully donned the K-S disposable mask within 38 seconds on average (range, 15 to 70 seconds), well within the time of useful consciousness (TUC)³ at these altitudes which is 10 minutes at 20,000 ft (6,096 m) to approximately 1.5 minutes at 27,000 ft (8,230 m) (FAA, 2015; Pickard & Gradwell, 2008). However, the participants' arterial blood oxygen saturation took longer than 1 minute to reach a minimum of 90% with the K-S disposable mask, in contrast to

³ Time from interruption of the oxygen supply, or exposure to an oxygen-poor environment, to the time when an individual is no longer capable of reacting and taking effective corrective actions (i.e., donning oxygen mask); TUC it is **not** the time to total unconsciousness; a rapid decompression reduces the TUC by 50% (FAA, 2015).

10 to 15 seconds using a flight crew “on-demand” oxygen mask. The delay was due to increased dilution of mask air with ambient air at higher altitudes, and although not serious enough to endanger healthy individuals, it demonstrated the performance limits of the K-S disposable mask. The researchers recommended that for altitudes above 25,000 ft (7,620 m), passenger masks should provide 100% oxygen using a non-diluting oronasal mask (Luft, 1951; Tuttle et al., 1951).

The 1950s–1960s: New Oxygen Mask Designs for Jet Airplanes

Flight in pressurized commercial airplanes of the 1940s and early 1950s was generally limited to 20,000 ft (6,096 m); the Lockheed Constellation had a service ceiling of 24,000 ft (7,315 m) and the Boeing’s Stratoliner was limited to 23,000 ft (7,010 m). The first commercial jet airliner, the British de Havilland Comet, entered service in 1952. The Comet’s ability to fly up to 40,000 ft (12,192 m), and similar jet aircraft designs by American manufacturers Boeing, Douglas Aircraft, and Convair, prompted the need to develop oxygen systems that could provide hypoxia protection at much higher altitudes. The need was even more apparent when the Comet experienced a series of fatal explosive decompressions that grounded the airplane in 1954. Realizing that cabin pressure decompressions could be a recurring hazard, an industry standard was needed for an extremely lightweight, “get me down” passenger oxygen mask for use from 40,000 ft (12,192 m) until the airplane reached a lower safe flying altitude.

In the early 1950s, the Society of Automotive Engineers (SAE) started to scrutinize aircraft oxygen systems within an environmental control systems working group. By 1957, the SAE formally established a separate, independent A-10 Aircraft Oxygen Equipment Committee.

The SAE A-10 committee also developed equipment and performance specifications for a new type of passenger oxygen mask to provide short-term hypoxia protection up to 40,000 ft (12,192 m). These specifications were the basis for National Aerospace Standard (NAS) 1179 (published in 1959) that established minimum standards for materials, testing, and performance of the “phase-dilution” mask. In 1961, NAS 1179 standards were incorporated into and became the basis for the FAA TSO-C64 - *Passenger Oxygen Mask Assembly, Continuous Flow*⁴ (SAE International, 2016b; Garner, 1996).

⁴ In 1988, NAS 1179 was superseded by a revised SAE A-10 standard, AS8025. The current FAA TSO-C64b (effective 2008) refers manufacturers to SAE Aerospace Standard AS8025A - *Passenger Oxygen Mask* (reaffirmed, 2016) for minimum design, construction, and performance requirements of continuous flow passenger oxygen masks.

In the 1940s and early 1950s, unpressurized and pressurized airplanes typically cruised below 20,000 ft (6,096 m), and Civil Air Regulations limited cabin pressure altitude to no more than 8,000 ft (2,438 m). Below 10,000 ft (3,049 m), most healthy individuals exhibit no overt signs of hypoxia. Between 10,000 ft (3,049 m) to 15,000 ft (4,572 m), the cardiopulmonary system compensates for the lack of oxygen by increasing heart rate and the rate and depth of breathing.

At 25,000 ft (7,620 m), most individuals become severely hypoxic and lose consciousness within 3 to 5 minutes, and supplemental oxygen must be administered within 3 to 4 minutes before irreversible brain cell damage and death begins (Guyton & Hall, 2006). Above 40,000 ft (12,192 m), 100% oxygen must be administered under positive pressure (Pickard & Gradwell, 2008).

The BLB oronasal and K-S disposable masks provided adequate hypoxia protection from sea level to 14,000 ft (4,267 m), and up to 25,000 ft (7,620 m) in the event of a rapid decompression if the airplane descended quickly to a lower altitude. However, the rebreather-dilution design limited the physiological effectiveness of these masks at higher altitudes. Expired air forced back into the rebreather bag mixes with ambient air and supply source oxygen, and although this saves airplane weight and space (less oxygen needs to be carried), the oxygen within the bag is diluted and never reaches the 100% concentration needed for hypoxia protection at cabin pressure altitudes above 25,000 ft (7,620 m).

In addition to physiological performance limitations, the shape of the BLB and K-S masks raised concerns about a passenger's ability to don the mask quickly following a rapid decompression. Most aircraft depressurizations are slow and gradual, and at the 20,000 ft (6,096 m) cruising altitude of the 1940s and early 1950s, a passenger had approximately 15 minutes of TUC to don the mask. However, the TUC for a slow decompression at 30,000 ft (9,144 m) is 1 to 2 minutes, and only 15 to 20 seconds at 40,000 ft (12,192 m) (Pickard & Gradwell, 2008; FAA, 2015). A rapid decompression at any altitude reduces the TUC by 50% (FAA, 2015). Thus, a rapid decompression at 40,000 ft (12,192 m) provides occupants approximately ≤ 10 seconds in which to don the mask and obtain a good seal.

In the mid-1950s, researchers at the FAA's Civil Aeromedical Research Institute (CARI) conducted a series of studies focused specifically on mask shape, ease of donning, and the design of a new shape/type of passenger oxygen mask. Over 150 naïve participants of different ages and facial configurations practiced donning the BLB and K-S oxygen masks following rapid decompressions to simulated altitudes of 35,000 to 40,000 ft (10,668 to 12,192 m). Donning the K-S disposable mask was more difficult; over half of the participants (58%) donned the K-S mask correctly within the approximately 20-second TUC compared to 85% who donned the BLB mask correctly (McFadden, 1955). A follow-up study included the evaluation of a new cup-like, adhesive oxygen mask. In this study, all participants (100%) successfully donned and sealed the

adhesive mask within 10 seconds, compared to 29% who correctly donned the BLB mask and only 6% who correctly donned the K-S mask within the same 10-second period (McFadden, 1955; Swearingen, 1957).

Results and observations from these studies illustrated the need for a radically new oxygen mask design and mask presentation system to provide passengers short-term hypoxia protection up to 40,000 ft (12,192 m). Recommendations from the study included the following:

- (1) Mask presentation must be automatic, turning on the oxygen and deploying the mask instantaneously into passenger view at a predetermined cabin pressure altitude.⁵
- (2) The mask should be extremely simple and possess radial symmetry to eliminate passenger confusion orienting the mask into a single position or putting the mask on upside down.
- (3) The mask should be quickly attached to the passenger's face without the need for elastic bands or tangled straps.
- (4) The mask should fit infants, children, and adults.
- (5) The mask should be lightweight and comfortable to wear over long periods (Swearingen, 1957).

The CARI researchers (Swearingen and McFadden) ultimately designed and developed an adhesive-type oxygen mask assembly composed of a light plastic, cup-shaped mask with an oxygen hose attachment and an exhalation valve, surrounded by a disposable adhesive cone (Figure 12 [p. 28]) (Swearingen, 1957). The mask presentation system consisted of spring-loaded doors in the overhead luggage compartment that opened when the cabin pressure altitude increased to a predetermined altitude (ideally 12,000 to 14,000 ft [3,658 to 4,267 m]). The passenger needed only to reach up and pull the mask loose from its package, place the mask over the nose and mouth, and press the adhesive to the face (Figure 13 [p.28]) (Swearingen, 1957; Mohler & Collins, 2005).

⁵ A drop in cabin pressure results in an increase in *cabin pressure altitude*.



Figure 12: *The Adhesive Oxygen Mask Assembled*

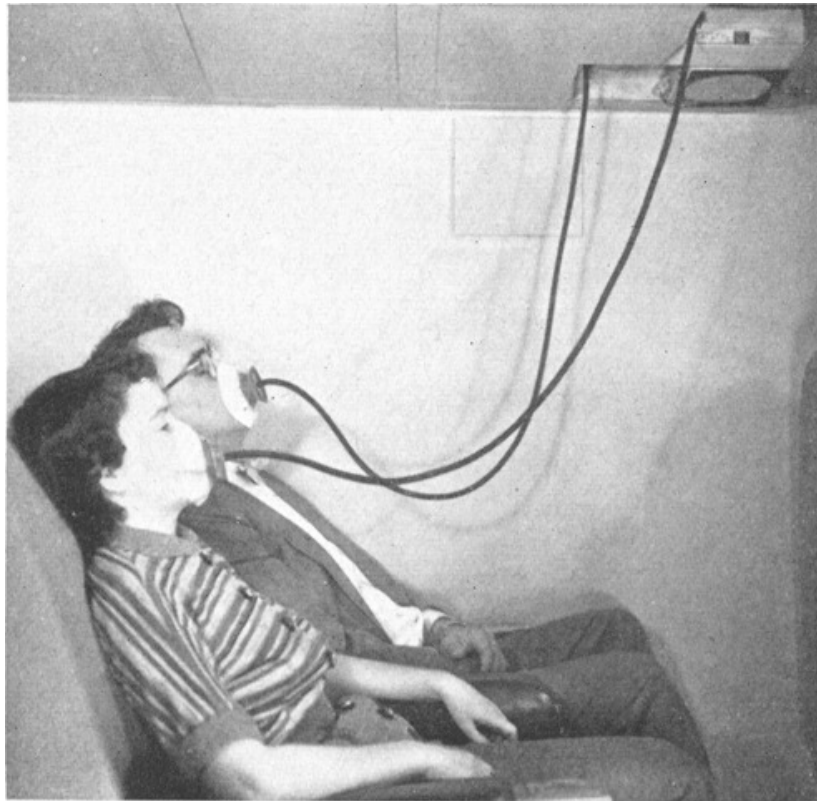


Figure 13: *Experimental Study Participants Wearing the Adhesive Oxygen Mask*

In 1957, Swearingen and McFadden patented their “adhesive-type oxygen mask” and automatic drop-down mechanism. The adhesive mask provided a superior seal compared to other masks, but concern about the shelf life of the then-available adhesive material precluded introduction and widespread use. Future passenger oxygen mask designs adopted the cup-like design and radial mask shape, and a drop-down mask presentation system was widely used onboard the first generation of American passenger jets such as the Boeing 707, Douglas DC-8, and Convair 880 (Mohler & Collins, 2005).

Throughout the 1950s and into the 1960s, numerous aircraft companies (Boeing, Douglas Aircraft, Lockheed), commercial airlines (United Airlines, British European Airways, Scandinavian Airlines Systems), and engineering companies (Aero Equipment Company, Bendix Corporation, Scott Aviation, Sierra Engineering, Puritan Equipment, Puritan Bennet Company) developed and manufactured passenger oxygen masks of varying shapes and configurations. All retained a round shape because it allowed for quick donning regardless of any particular orientation and because a round mask conforms to the broadest range of face shapes and sizes. Numerous anthropometric studies provided valuable information on adult facial features and anthropometric landmarks (Emanuel et al., 1959; Seeler, 1961), and special attention was paid to anthropometric measurements of infants and young children (Young, 1966).

The basic design of the new continuous flow, phase-dilution mask came from the NAS 1179 standards. A reservoir bag replaced the rebreather bag, and two valves on the mask face piece work sequentially to support inhalation and exhalation. Mask design has changed little since the mid-1950s, although small modifications and gradual refinement have led to the phase-dilution mask in use today. More robust, lightweight plastic valves replaced flap seals. The large cylindrical face piece evolved into a smaller, tapered, conical shape to reduce the build-up of carbon dioxide. A sharp edge seal produced a better fit/face seal than the original rounded inner lip design.

The 1970s to the Present: Mask Presentation and Passenger Preflight Briefing

The continuous flow, phase-dilution mask design of the 1950s meets the minimum FAA requirements for an emergency, “get me down” passenger oxygen mask to provide hypoxia protection for altitudes up to 40,000 ft (12,192 m). Since the 1970s, few changes have been made to the mask itself; however, significant changes were made to how the mask is presented and to the passenger preflight briefing

In the mid-1970s, several rapid decompression incidents and accidents involving Douglas DC-10 and Lockheed L-1011 aircraft, in which passengers failed to use the supplemental oxygen system correctly, prompted the National Transportation Safety Board (NTSB) to issue a special study and

several safety recommendations (NTSB, 1976a; NTSB, 1976b).

Problems arose from mask presentation systems that were confusing or required excessive passenger involvement. The L-1011 incorporated the automatic drop-down design; however, some passengers failed to pull the mask down to their face (required to activate oxygen flow); instead, they leaned forward and attempted to breathe from the mask. The DC-10 supplemental oxygen system was contained in the seatback in front of the passenger. The compartment door opened automatically, but the mask remained stowed, and oxygen flow did not activate unless the passenger removed the mask and pulled it toward him/her. Passenger life vests were installed in an adjacent compartment, leading to additional confusion, and passengers were hesitant to disturb a neatly packed system. The entire presentation of the DC-10 system—the exposed oxygen generator, linkages, piping, and connections—tended to frighten passengers who ignored the oxygen system rather than use it (NTSB, 1976a).

The NTSB also noted that the passenger preflight briefing contained little information on system activation and lacked a demonstration on how to don and adjust the mask properly. In several incidents, passengers and flight attendants believed the equipment malfunctioned because the reservoir bag did not fully inflate, and there was no oxygen flow indicator. Many were unaware that 10 to 15 seconds must elapse after generator activation for sufficient oxygen flow to fill the bag. Passengers did not use the elastic headband or could not find the adjustment straps used to tighten the mask (NTSB, 1976a).

The NTSB's findings prompted revisions to FAA regulations, as well as changes to mask presentation standards (which are in effect today) and led to a more informative/detailed passenger preflight briefing.

For flights operating above 30,000 ft (9,144 m), oxygen masks providing the required oxygen flow must automatically deploy before the cabin pressure altitude exceeds 15,000 ft (4,572 m). The mask must be within reach of a seated, belted passenger with a reach arc in front, to the sides, and above based on a seated passenger ranging in size from a 5th percentile female to a 95th percentile male. The mask must not reach the face of a seated, belted passenger without activating the flow of oxygen. Mask stowage under or around the seat is discouraged due to confusion and possible delays in accessing the mask (SAE International, 2016c; SAE International, 2017a). Although not required by regulation, most airlines use a drop-down system from an overhead PSU. An in-line flow indicator, which turns green when oxygen flows towards the reservoir bag, was added to the oxygen tubing. Located at approximately eye-level for a standing flight attendant, the oxygen flow indicator is easy to see and provides an additional indication of oxygen flow compared to bag inflation alone (SAE International, 2019).

The FAA revised Advisory Circulars to provide guidelines for improved passenger briefings and printed instruction cards on the use of supplemental oxygen systems and ordered a review of the passenger preflight briefing to ensure the use of factual, unambiguous information. Airlines provided enhanced training to flight attendants on chemical oxygen generating systems, which became common oxygen supply sources, and included a mask-donning demonstration to the passenger preflight briefing.

The passenger oxygen mask has evolved from the pipe stem, through the early rebreather mask designs of the BLB and K-S oxygen masks, to the current continuous flow, phase-dilution mask that provides short-term hypoxia protection up to 40,000 ft (12,192 m). The mask has changed little since the late 1950s, but its deceptively simple appearance belies a well-thought-out design—the round shape allows for quick and easy donning regardless of mask orientation (i.e., there is no upside-down), it conforms to a wide range of face sizes and shapes, and one mask shape is easily used for infants, children, and adults.

Appendix C: Oxygen Systems and Oxygen Mask Assemblies

This section provides a brief overview of the most common oxygen systems used onboard commercial transport airplanes, as well as a general discussion of oxygen mask assemblies. Specific design details are not provided in this report because oxygen systems and oxygen mask assemblies contain proprietary information. Therefore, we provide only general information or publicly available information.

Oxygen Systems

The purpose of an airplane oxygen system is to provide a short-term, sustainable breathing environment in extreme conditions—to provide hypoxia protection in the event of exposure to high cabin pressure altitudes, or to protect against smoke/fumes/toxic gases from fire. Oxygen systems for the flight crew in the flight deck offer protection for both scenarios per applicable FAA regulations. Oxygen systems in the passenger cabin provide a highly concentrated oxygen supply only for hypoxia protection when exposed to high cabin pressure altitudes, also per applicable FAA regulations.

Current airplane oxygen systems may use either a gaseous, chemical, liquid, or onboard-generated oxygen supply. The various system types relate to oxygen storage and distribution methods because gaseous oxygen is always delivered to the user. Airplane oxygen systems are discussed in detail in SAE Aerospace Information Report AIR825/3, *Gaseous Oxygen and Oxygen Equipment, Introductory* (SAE International, 2015). We describe the two most common oxygen systems used onboard civil commercial airplanes: chemical oxygen generators and gaseous oxygen systems.

Chemical Oxygen Generators

Chemical oxygen generators produce gaseous oxygen using a chemical reaction. The decomposition of certain chemicals produces a continuous flow of nearly 100% oxygen for approximately 12 to 20 minutes, depending on the type and size of the generator installed (SAE International, 2016d; SAE International, 2014).

Gaseous Oxygen Systems

Gaseous oxygen systems store oxygen in its gaseous state in high pressure (1850 to 3000 Psig [12.75 to 20.7 Mpa]) or low pressure (400 to 500 Psig [2.76 to 3.45 Mpa]) cylinders. A regulator/shutoff device installed on the cylinder starts and stops the flow of oxygen. Additionally, the regulator lowers the oxygen pressure from the cylinder to 100 Psi (0.68 Mpa) or less to minimize the use of high-pressure oxygen lines. Some airplanes use centralized gaseous oxygen cylinders for the passenger oxygen system with one or more large, refillable cylinders

located within a cargo compartment. The large, centralized cylinders are connected with plumbing and other hardware to direct oxygen to the point of use. Other airplanes use a distributed gaseous oxygen system of small, single-use pressurized cylinders located near the point of use, such as above an individual seat row or within a lavatory (SAE International, 2015).

Oxygen Mask Assemblies

Oxygen is delivered from the supply source to the user through a mask assembly. The type of mask used depends on the applicable FAA regulations and the environment in which the mask assembly provides protection.

Crew Oxygen Mask Assemblies

Crew oxygen mask assemblies are typically “demand flow” (i.e., dispense oxygen only during breath intake) equipment. The mask assembly provides hypoxia protection at high cabin pressure altitudes and acts as PBE from fire smoke, fumes, and toxic gases. Demand flow equipment can be straight demand (i.e., delivers pure oxygen) or diluter-demand (i.e., mixes ambient air with oxygen), which conserves the gaseous oxygen supply. Additional information on crew demand oxygen systems may be found in SAE Aerospace Information Report AIR825/9, *Demand Oxygen Systems* (SAE International, 2017b).

Passenger Cabin Occupant Mask Assemblies

Passenger cabin occupant mask assemblies are discussed in detail on page 6 of this report (*Passenger Cabin Occupant Oxygen Mask Design and Function*).

Mask Assemblies with Portable Oxygen Cylinders

Portable oxygen cylinders are located throughout the passenger cabin for use by flight attendants as a supplemental oxygen supply for mobility or to be used by passengers for first aid. Oxygen mask assemblies installed for use with portable oxygen cylinders come in a variety of mask types and shapes. When portable oxygen equipment is used to administer first aid, FAA regulation 14 CFR § 25.1443(d) requires a minimum flow rate for transport airplanes of 4 liters per minute (lpm), standard temperature and pressure dry (STPD; air or gas at 60°F [15.6°C] and 14.67 psia [1 atm, 101.3 kPa]), with a means to decrease the flow rate to not less than 2 lpm-STPD. However, the FAA regulation does not specify the type of oxygen mask that may be used with a portable first aid oxygen cylinder. Typically, the type of oxygen mask installed with a portable oxygen cylinder for first aid varies based on the intended use and customer preference.

When portable oxygen equipment is used as a supplemental oxygen supply, such as what flight attendants may use following a decompression event, additional FAA regulations and minimum

performance standards apply. Additional information for portable oxygen equipment used for flight attendant mobility on transport airplanes is provided in FAA Policy PS-ANM-25.1447-01; *Portable Oxygen Equipment Requirements for Cabin Attendants* (FAA, 2017b).

Appendix D: Flight Physiology

An in-depth discussion of flight physiology is beyond the scope of this document. Only the most relevant physiological information as it pertains to human performance at altitude and oxygen mask design is presented here.

Definitions

Respiration Rate = 12 to 20 breaths/minute, average 16 breaths/minute under resting conditions for a healthy adult; the rate can increase to 30 breaths/minute with moderate exercise and/or mild anxiety

Respiratory Minute Volume = Volume of air inspired per minute, normally 6 to 8 L/min at rest (0.5 L of oxygen X 12 breaths per minute = 6 L/min), increases to 10 L/min with light to moderate work/exercise or mild anxiety

Tidal Volume = Volume of air inspired and expired with each normal breath; approximately 500 ml (0.5 L) per breath for a healthy adult

The Atmosphere

The atmosphere is a mixture of gases of approximately 78% nitrogen and 21% oxygen, with the remaining 1% composed of carbon dioxide, water vapor, and trace gases. The combined weight, or force, of all atmospheric gases at any given point is the atmospheric (barometric) pressure (P_B). Atmospheric pressure (P_B) decreases with altitude. Gas molecules are in a state of constant motion, and as the pressure around the gas molecules decreases, the molecules spread out and travel farther apart. The air becomes less dense with altitude as P_B decreases, and gas volume expands (Boyle's Law: pressure is inversely proportional to volume). The total pressure of a gas mixture is equal to the sum of the partial pressure of each gas in the mixture (Dalton's Law). As total P_B decreases with altitude, the partial pressure of oxygen (PO_2) decreases as well; however, the percentage of oxygen remains constant (21%) (FAA, 2015; Pickard & Gradwell, 2008).

Partial Pressure of Oxygen

The partial pressure of oxygen (PO_2) is approximately 21% of the total atmospheric pressure. At sea level, total P_B is 760 millimeters of mercury (mmHg); thus, PO_2 is approximately 160 mmHg (i.e., $P_B \times 21\%$ oxygen). As air is drawn into the lungs, the oxygen is diluted by other gases that exert a constant pressure (water vapor at 47 mmHg and carbon dioxide at 40 mmHg). Water vapor and carbon dioxide displace part of the oxygen, reducing the PO_2 within the lung air sacs (alveoli) to approximately 100 mmHg. This alveolar partial pressure of oxygen (P_{AO_2}) is the "driving" pressure that oxygenates blood as it passes through the lungs (FAA, 2015; Green et al., 2019).

Pulmonary Gas Exchange

Oxygen and carbon dioxide are involved in pulmonary gas exchange within the alveoli; carbon dioxide is removed from the blood, and the oxygen supply is replenished.⁶ Pulmonary gas exchange occurs by diffusion and depends on a pressure gradient (i.e., movement of gas from an area of high pressure to an area of low pressure). At sea level, the high $P_{A}O_2$ within the lungs (100 mmHg) drives oxygen from the lungs into the bloodstream, where the PO_2 of venous blood is a constant 40 mmHg. Maintaining this pressure gradient within the lungs is critical to ensure adequate blood oxygen saturation (S_aO_2).⁷ As P_B decreases with altitude, so too does the $P_{A}O_2$ within the lungs, and the pressure gradient begins to diminish, decreasing S_aO_2 (McArdle et al., 2015; Pickard & Gradwell, 2008).

Atmospheric Areas and Normal Body Function

The human body functions normally in the atmospheric area from sea level to approximately 10,000 ft (3,048 m). In this range, S_aO_2 levels provide sufficient oxygen for normal body functions, especially for the brain and mental/cognitive performance. Optimal function occurs at a brain oxygen saturation level >96%. At 10,000 ft (3,048 m), brain oxygen saturation is approximately 88% to 90%, which begins to approach a level that affects cognitive performance (FAA, 2015). Between 10,000 ft (3,049 m) and 15,000 ft (4,572 m), the cardiopulmonary system compensates for the lack of oxygen by increasing heart rate and the rate and depth of breathing; above 15,000 ft (4,572 m), brain oxygen saturation levels steadily decline (Guyton & Hall, 2006; McArdle et al., 2015).

Hypoxia

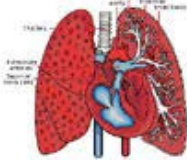


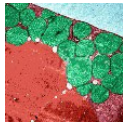
Hypoxia is an insufficient supply of oxygen to the tissues leading to impairment of body functions (FAA, 2015; Pickard & Gradwell, 2008). Any condition that impedes the delivery or use of oxygen at the cellular level places the body in a hypoxic state. All cells require oxygen, and brain cells demand a great deal of oxygen for optimal function. If the blood supply to the body is reduced, the brain is one of the first organs affected.

⁶ Nitrogen is physiologically inert in that it is neither used nor produced in metabolic reactions; nitrogen levels remain essentially unchanged during pulmonary gas exchange.

⁷ Simultaneous with oxygen diffusion, carbon dioxide diffuses from the bloodstream (partial pressure of 47 mmHg) into the lungs (constant partial pressure of 40 mmHg) and is exhaled.

Brain cells are unable to store oxygen and rapidly deplete their oxygen reserve. Fully 100% oxygen must be administered in 3 to 4 minutes before irreversible brain cell damage and death begins (Guyton & Hall, 2006; Pickard & Gradwell, 2008). Many conditions can interrupt the normal flow of oxygen to body tissues and cells, leading to hypoxia. The remainder of this discussion focuses on hypoxic (altitude) hypoxia. Table 1 lists the types of hypoxia, the location or organ impaired, and a description of the impairment (FAA, 2015).

Table 1. *Hypoxia Types*

Hypoxia Type	Location/Organ Impaired	Impairment
Hypoxic (Altitude) Hypoxia	Lungs 	Any condition that interrupts the flow of oxygen into the lungs. Encountered at altitude due to the decrease in the partial pressure of oxygen
Hypemic Hypoxia	Blood 	Any condition that interferes with the ability of the blood to carry oxygen, such as: <ul style="list-style-type: none"> • Anemia • Bleeding • Carbon monoxide poisoning • Smoking • Certain prescription drugs
Stagnant Hypoxia	Blood Transport 	Any condition that interferes with normal blood circulation. Heart failure, shock, and positive G- forces (acceleration) can result in blood pooling in the lower extremities
Histotoxic Hypoxia	Cell 	Any condition that interferes with the normal use of oxygen in the cell. Alcohol, narcotics, and cyanide can all interfere with the cell's ability to use oxygen in support of metabolism

Hypoxic (altitude) Hypoxia

Hypoxic (altitude) hypoxia is caused by an insufficient partial pressure of oxygen (PO_2) due to a decrease in atmospheric pressure (P_B) at altitude. Hypoxic hypoxia poses the greatest potential physiological hazard to the flight crew and cabin occupants when at altitude, as decreasing blood (and brain) oxygen saturation levels (S_aO_2) lead to reduced mental/cognitive and physical ability (FAA, 2015). As P_B decreases with altitude, there is a corresponding decrease of PO_2 in the inspired air and ultimately in the lungs. The decreased “driving pressure” in the lungs (P_AO_2) leads to reduced blood (and brain) S_aO_2 levels (Table 2).

Table 2. *Altitude, Atmospheric and Lung Gas Pressures, and Blood Oxygen Saturation Levels*

Altitude (ft) <i>(meters)</i>	P_B (mm Hg)	P_AO_2 (mm Hg)	S_aO_2 (%)
Sea Level	760	100	96-98
10,000 <i>(3,048)</i>	523	61	88-90
15,000 <i>(4,572)</i>	429	46	75
25,000 <i>(7,620)</i>	282	30	50

Ten thousand feet (3,048 m) is considered a physiological “breakpoint” where most healthy individuals begin to exhibit mild hypoxic symptoms (e.g., headache, fatigue). At 15,000 ft (4,572 m), the maximum cabin pressure altitude at which passenger oxygen masks automatically deploy, hypoxic symptoms are more pronounced with noticeable cognitive and physical impairment. At 25,000 ft (7,620 m), the pressure gradient within the lungs is nearly non-existent, S_aO_2 drops to 50%, and most individuals become profoundly hypoxic and lose consciousness within 3 to 5 minutes if not given highly concentrated oxygen (Green et al., 2019; Pickard & Gradwell, 2008; FAA, 2015).

Physiological Requirements and Mask Performance Standards

14 CFR § 25.1443(c) prescribes minimum tracheal partial pressures of oxygen. To meet compliance, oxygen masks are tested using AS8025A standards to determine the minimum oxygen flow required to the mask as a function of cabin pressure altitude (see “Mask Performance Testing Standards,” p. 13). Typical oxygen flow rates to the mask range from 0.00 to 4.50 lpm-normal temperature and pressure dry (NTPD; air or gas at 68°F [20°C] and 14.7 psia [1 atm, 101.3 kPa])). During certification/validation testing, human participants engage in light to moderate exercise (approximately 3.5-mph walking on a level treadmill) to increase their

respiratory minute volume (and thus the flow rate to the mask) to approximately 10 lpm.

Peak inspiratory flow rate is an important consideration in oxygen mask design. The mask needs to provide a sufficient quantity of oxygen to meet the instantaneous demand of a large, deep breath, as well as the rapid breathing rate during hyperventilation (Sheffield & Heimbach, 1996; McFadden et al., 1962). Peak inspiratory flow is determined by multiplying respiratory minute volume by three; thus, a respiratory minute volume of 10 lpm in a working individual produces a peak inspiratory flow of 30 lpm.

Per 14 CFR § 25.1443(c), at cabin pressure altitudes above 10,000 ft (3,048 m) up to and including 18,500 ft (5,639 m), the oxygen flow rate to the mask must maintain a mean tracheal partial pressure of oxygen of 100 mmHg when breathing 15 lpm-body temperature and pressure saturated (BTPS), and a tidal volume of 700 cc with a constant time interval between respirations. At cabin pressure altitudes above 18,500 ft (5,639 m), up to and including 40,000 ft (12,192 m), oxygen flow rate to the mask must maintain a mean tracheal partial pressure of oxygen of 83.8 mmHg when breathing 30 lpm-BTPS, and a tidal volume of 1,100 cc with a constant time interval between respirations.

Time of Useful Consciousness or Effective Performance Time

A loss of cabin pressurization results in an increase in cabin pressure altitude and the onset of hypoxia if highly concentrated oxygen is not used. Most depressurizations result from malfunctions in the cabin pressurization system, leading to a slow, gradual increase in cabin pressure altitude; however, in the event of a rapid decompression, cabin occupants must react quickly.

The TUC is the time from interruption of the oxygen supply, or exposure to an oxygen-poor environment, to the time when an individual is no longer capable of taking proper corrective actions (i.e., donning oxygen mask); the TUC **does not** span the time to the onset of unconsciousness (FAA, 2015). Time of useful consciousness decreases with altitude. Additionally, the faster the rate of ascent (e.g., rapid decompression), the worse the impairment and the more rapid the onset (FAA, 2015; Green et al., 2019). The TUC is reduced by 50% following a rapid decompression to cabin pressure altitudes between 25,000 ft (7,620 m) to 40,000 ft (12,192 m) (FAA, 2015). At 40,000 ft (12,192 m), the TUC is < 10 seconds—essentially the time it takes the blood to circulate from the lungs to the brain (FAA, 2015; Guyton & Hall, 2006). Figure 14 (p. 40) depicts TUC at altitude in the event of a slow/gradual decompression and a rapid decompression (Fan, 2018; FAA, 2015).

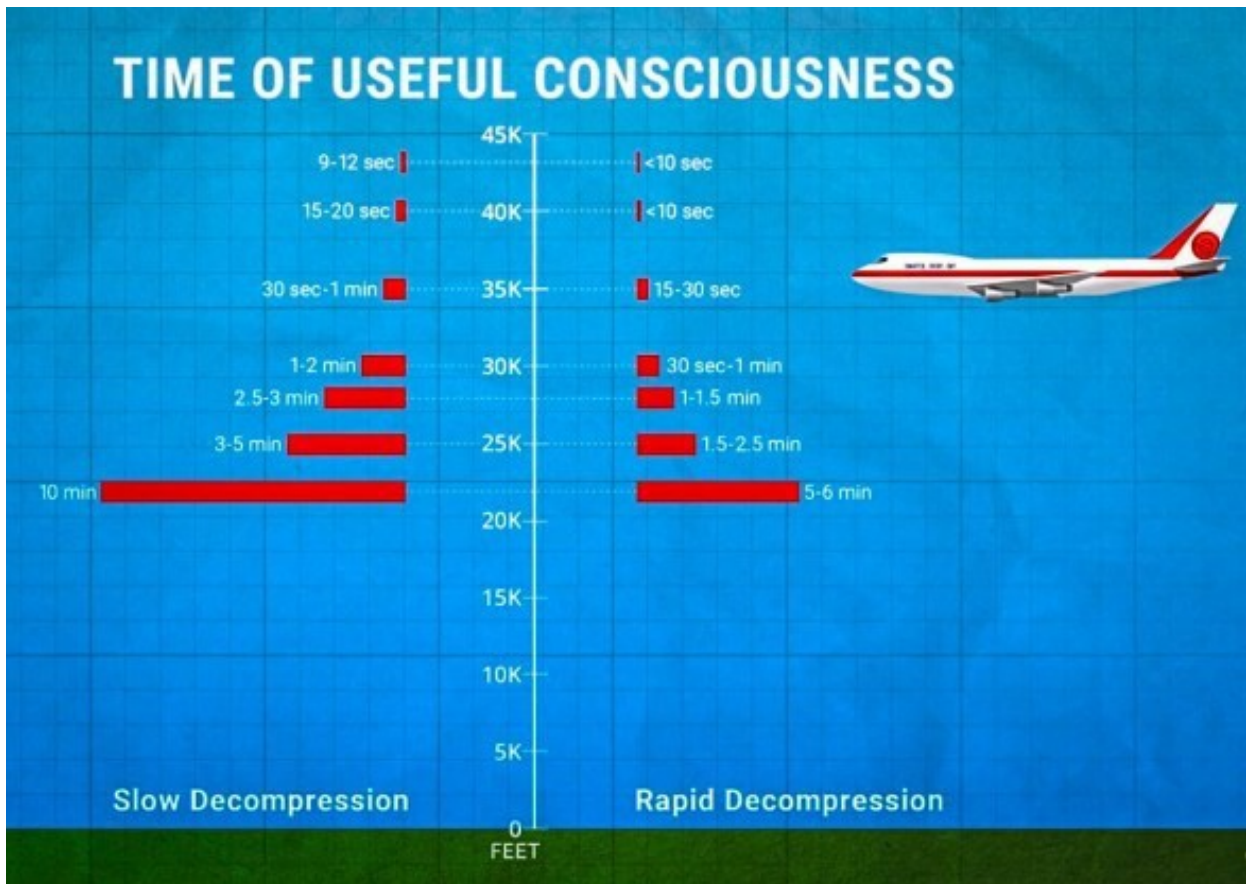


Figure 14: Average Times of Useful Consciousness at Altitude in the Event of a Slow or Rapid Decompression

Hyperventilation

Hyperventilation is rapid, shallow breathing typically induced by anxiety or stress, but it can also be triggered by hypoxic conditions. Hyperventilation “blows off” excessive amounts of carbon dioxide, which slows the rate and depth of breathing and exacerbates hypoxia (Pickard & Gradwell, 2008). Once the passenger oxygen mask is donned, it is important for passengers to breathe as normally as possible (even if the reservoir bag appears not to inflate) so they do not hyperventilate. A build-up of carbon dioxide can also induce hyperventilation. The original 1950s cylindrical facepiece was modified to the current smaller, more conical shape to prevent a build-up of carbon dioxide in the mask during exhalation.

Emergency Procedures

The treatment for hypoxia, regardless of type, is highly concentrated oxygen. In the event of a loss of cabin pressurization with oxygen mask deployment, passenger cabin occupants must don

the mask quickly and breathe 100% oxygen to prevent the onset of hypoxia. Once 100% oxygen is administered, recovery usually begins in a matter of seconds (FAA, 2015).

Donning the oxygen mask is only part of an overall emergency procedure in the event of a loss of cabin pressurization. The first and most important protection against hypoxia is the airplane emergency descent initiated by the flight crew. For commercial airplanes with pressurized cabins, FAA regulation 14 CFR § 25.841(a)(2) prescribes airplane design requirements intended to limit the potential exposure of high cabin pressure altitudes following a sudden loss of cabin pressure. To meet these regulations, emergency procedures performed by the flight crew include the initiation of an emergency descent. The emergency descent will be steep and rapid, and flight attendants may be unable to render immediate assistance until the airplane reaches a safe level off altitude, which could take several minutes. Airline and FAA policies require flight attendants to don the closest available oxygen mask and brace against/sit in the nearest available seat until the airplane levels off, and they can safely move about the cabin. During the emergency descent, it is imperative that passengers don the oxygen mask quickly and correctly, first for themselves (to avoid hypoxia-induced impairment) and then assist others.

Once the oxygen mask is donned, passengers must breathe as normally as possible; highly concentrated oxygen is flowing into the reservoir bag even if the bag does not appear to inflate. Typically, there is more bag inflation at higher cabin pressure altitudes (high oxygen flow and low ambient air pressure) and less inflation at lower cabin pressure altitudes (low oxygen flow and higher ambient air pressure).

Passengers may need to keep the oxygen mask in place at lower altitudes after the emergency descent. Flight crews typically perform an emergency descent to 10,000 ft (3,048 m). However, some air routes prevent descent to lower altitudes due to terrain and/or fuel burn limitations. Passenger cabin occupants should continue to wear the oxygen mask until instructed by flight attendants to remove them.

References

- Barach, A. L. (1937). "Pilot Error" and oxygen want; with a description of a new oxygen face tent. *Journal of the American Medical Association*, 108(22), 1868-1872. <https://doi.org/10.1001/jama.1937.02780220026007>
- Boothby, W. M., & Lovelace, W. R. (1938). Oxygen in aviation. The necessity for the use of oxygen and a practical apparatus for its administration to both pilots and passengers. *Journal of Aviation Medicine*, 9(4), 172-198.
- Cooper, M. G., & Street, N. E. (2017). High altitude hypoxia, a mask, and a Street. Donation of an aviation BLB oxygen mask apparatus from World War 2. *Anaesthesia and Intensive Care*, 45(1)S, 45-48. <https://doi.org/10.1177/0310057X170450S107>
- DeSteiguer, D., Pinski, M. S., Bannister, J. R., & McFadden, E. B. (1978). *Aircrew and passenger protective breathing equipment* (DOT/FAA-am-78/4). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1970s/media/AM78-04.pdf
- DeSteiguer, D., & Saldivar, J. T. (1983). *An analysis of potential protective breathing devices intended for use by aircraft passengers* (DOT/FAA/AM-83/10). <https://apps.dtic.mil/dtic/tr/fulltext/u2/a132648.pdf>
- Emanuel, I., Alexander, M., & Churchill E. (1959). *Anthropometric sizing and fit-test of the MC-1 oral-nasal oxygen mask* (WADC Technical Report 58-505).
- European Transport Safety Council (1996). *Increasing the Survival Rate in Aircraft Accidents: Impact Protection, Fire Survivability, and Evacuation*. <https://etsc.eu/increasing-the-survival-rate-in-aircraft-accidents-impact-protection-fire-survivability-and-evacuation/>
- Fan, K. (2018). 7 tips for staying alive in a plane emergency. *The Points Guy*. <https://thepointsguy.com/news/7-tips-for-staying-alive-in-a-plane-emergency/>
- Federal Aviation Administration. (2008). *Passenger oxygen mask assembly, continuous flow* (Technical Standard Order (TSO)-C64b). [https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgTSO.nsf/0/ae1e8c96aff207e86257451004f88f4/\\$FILE/TSO-C64b.pdf](https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgTSO.nsf/0/ae1e8c96aff207e86257451004f88f4/$FILE/TSO-C64b.pdf)

- Federal Aviation Administration. (2014). *Requirements for Chemical Oxygen Generators Installed on Transport Category Airplanes* (FAA NPRM Docket No. FAA-2012- 0812).
<https://www.federalregister.gov/documents/2014/03/11/2014-05291/requirements-for-chemical-oxygen-generators-installed-on-transport-category-airplanes>
- Federal Aviation Administration. (2015). *Aircraft operations at altitudes above 25,000 feet mean sea level or Mach numbers greater than .75* (Advisory Circular 61-107B with change 1). https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1020859
- Federal Aviation Administration (2017a). Timeline of FAA and Aerospace History. <https://www.faa.gov/about/history/timeline/>
- Federal Aviation Administration (2017b). *Portable oxygen equipment requirements for cabin attendants* (Policy Statement PS-ANM-25.1447-01).
http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgPolicy.nsf/0/AA4805B9D44986558625817900789DB5?OpenDocument
- Federal Aviation Administration. (2019a) *Passenger safety information briefing and briefing cards* (Advisory Circular 121-24D). https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_121-24D.pdf
- Federal Aviation Administration. (2019b). *Portable electronic devices*. <https://www.faa.gov/about/initiatives/ped/>
- 'Forgotten switch' leads to on-flight scare in Jaipur-bound Jet Airways plane. (2018, September 21). *The Hindu*.
<https://www.thehindu.com/news/national/forgotten-switch-leads-to-on-flight-scare-in-jaipur-bound-jet-airways-plane/article25003015.ece>
- Garner, R. P. (1996). *Performance of a continuous flow passenger oxygen mask at an altitude of 40,000 feet* (DOT/FAA/AM-96/4). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1990s/media/AM96-04.pdf

- General Civil Aviation Authority. (2016). *Runway impact during attempted go-around. Preliminary accident report* (AAIS Case No: AIFN/0008/2016). <https://aviation-safety.net/database/record.php?id=20160803-0>
- Grant, R. G. (2002). *Flight: 100 years of aviation*. DK Publishing.
- Green, N., Gaydos, S., Hutchison, E., & Nicol, E. (2019). Acute hypoxia and hyperventilation. In N. Green, S. Gaydos, E. Hutchison, & E. Nicol (Eds.), *Handbook of aviation and space medicine* (pp. 51-60). New York, NY: CRC Press.
- Guyton, A. C. & Hall, J. E. (2006). Aviation, high-altitude, and space physiology. In J.E. Hall & A.C. Guyton (Eds.), *Textbook of medical physiology* (11th ed., pp. 537- 544). Elsevier.
- Higgins, E. A., Saldivar, J. T., Lyne, P. J., & Funkhouser, G. E. (1985). *Evaluation of a passenger mask modified with a rebreather bag for protection from smoke and fumes* (DOT/FAA-AM-85/10). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1980s/media/AM85-10.pdf
- Higgins, E. A. (1987). Summary report of the history and events pertinent to the Civil Aeromedical Institute's evaluation of providing smoke/fume protective breathing equipment for airline passenger use (DOT/FAA/AM-87/5). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1980s/media/AM87-05.pdf
- Kalei, K. (2008). A history of US military aviation oxygen breathing systems to 1945 (part 1 of 2). AuthorsDen. <http://www.authorsden.com/visit/viewarticle.asp?id=36665>
- Lovelace, W. R., Bulbulian, A.H., & Boothby, W.M. (1941). *Apparatus for delivering and permitting normal breathing of mixtures of gases* (U.S. Patent No 2,241,535). U.S. Patent and Trademark Office. <https://www.uspto.gov/patent>
- Luft, U. C. (1951). *Evaluation of the K-S disposable oxygen mask* (Special Project, January 1951). USAF School of Aviation Medicine.
- McArdle, W. D., Katch, F. I., & Katch, V. L. (2015). Gas exchange and transport. In W. D. McArdle, K. I. Katch, & V. L. Katch (Eds.), *Exercise physiology, nutrition, energy, and human performance* (8th ed., pp. 269-283). Wolters Kluwer.

- McFadden, E. B. (1955). *Time factors in passenger utilization of emergency oxygen* [Unpublished preliminary report]. Civil Aeronautics Medical Research Laboratory.
- McFadden, E. B., Raeke, J. W., & Young, J. W. (1962). *An improved method for determining the efficiency of crew and passenger oxygen masks; A preliminary report* (DOT/FAA/AM-62/21). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1960s/media/AM62-01.pdf
- McFadden, E. B., Reynolds, H. J., & Funkhouser, G. E. (1967). *A protective passenger smoke hood* (DOT/FAA/AM-67/4). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1960s/media/AM67-04.pdf
- McLean, G. A., Higgins, E. A., Lyne, P. J., & Vant, J. H. B. (1989). The effects of wearing passenger protective breathing equipment on evacuation times through Type III and Type IV emergency aircraft exits in clear air and smoke (DOT/FAA/AM- 89/12). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1980s/media/AM89-12.pdf
- Miller, J. M. (1995). BLB oxygen mask and aviation. *Mayo Clinic Proceedings*, 70(10), 1020. <https://doi.org/10.4065/70.10.1020>
- Mohler, S. R., & Collins, W. E. (2005). *Historical Vignette: Origin of the jet passenger drop-out oxygen system and the double pane protective decompression windows* (DOT/FAA/AM-05/3). A Milestone of Aeromedical Research Contributions to Civil Aviation Safety: The 1000th Report in the CARI/OEM Series. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2000s/2005
- National Transportation Safety Board. (1976a). *Special Study, Chemically Generated Supplemental Oxygen Systems in DC-10 and L-1011 Aircraft* (Report No. NTSB- AAS-76-1). <https://huntlibrary.erau.edu/collections/aerospace-and-aviation-reports/ntsb/aviation-special-studies>
- National Transportation Safety Board. (1976b). *Safety Recommendation A 76-20 through 28 (issued April 29, 1976)*. http://www.nts.gov/safety/safety-recs/recletters/A76_20_28.pdf

- National Transportation Safety Board. (1985). *Airline Passenger Safety Education: A Review of Methods Used to Present Safety Information* (Report No. NTSB-A-85-094). https://www.nts.gov/safety/safety-recs/_layouts/nts/recsearch/Recommendation.aspx?Rec=A-85-094
- National Transportation Safety Board. (2001). *Survivability of Accidents Involving Part 121 U. S. Air Carrier Operations, 1983 Through 2000* (Safety Report NTSB/SR-01/01). <https://www.nts.gov/safety/safety-studies/Documents/SR0101.pdf>
- National Transportation Safety Board. (2016). *Powerplant Group Chairman's Factual Report* (NTSB Accident ID ENG14IA028). <https://dms.nts.gov/pubdms/search/hitlist.cfm?docketID=58159&CFID=2702498&CFTOKEN=22795886d6b380cc-B447B47D-C946-A69C-F3F56ECF9F7E5962>
- National Transportation Safety Board. (2017a). *Survival Factors Specialist's Factual Report* (NTSB Accident ID DCA15FA185). <https://dms.nts.gov/pubdms/search/hitlist.cfm?docketID=59741&CurrentPage=2&EndRow=30&StartRow=16&order=1&sort=0&TXTSEARCHT=>
- National Transportation Safety Board. (2017b). *Survival Factors Group Chairman's Factual Report* (NTSB Accident ID DCA17FA021). <https://dms.nts.gov/pubdms/search/hitlist.cfm?docketID=60058&StartRow=16&EndRow=30&CurrentPage=2&order=1&sort=0&TXTSEARCHT=>
- Nelson, C. W. (1995). Dr. W. Randolph Lovelace II, aviation medicine, and Mayo. *Mayo Clinic Proceedings*, 70(4), 316. <https://doi.org/10.4065/70.4.316>
- Pickard, J. S., & Gradwell, D. P. (2008). Respiratory physiology and protection against hypoxia. In J. R. Davis, R. Johnson, J. Stepanek, & J. A. Fogarty (Eds.), *Fundamentals of aerospace medicine* (4th ed., pp. 20-45). Lippincott Williams & Wilkins.
- SAE International. (2006). *Passenger Safety Information Cards* (Aerospace Recommended Practice ARP1384). SAE International.
- SAE International. (2014). *Chemical oxygen supplies* (Aerospace Information Report AIR113B). SAE International.

- SAE International. (2015). *Gaseous oxygen and oxygen equipment, introductory* (Aerospace Information Report AIR825/3). SAE International.
- SAE International. (2016a) *Passenger oxygen equipment* (Aerospace Standard AS8025A). SAE International.
- SAE International. (2016b). *History of the SAE A-10 Aircraft Oxygen Equipment Committee* (Aerospace Information Report AIR5354A). SAE International.
- SAE International. (2016c). Location of crew and passenger oxygen masks, portable oxygen system, and protective breathing equipment (Aerospace Recommended Practice ARP6390) SAE International.
- SAE International. (2016d). *Chemical oxygen systems* (Aerospace Information Report AIR825/4). SAE International.
- SAE International. (2017a). *Supplemental oxygen devices with automatic or manual presentation* (Aerospace Recommended Practice ARP4287). SAE International.
- SAE International. (2017b). *Demand oxygen systems* (Aerospace Information Report AIR825/9). SAE International.
- SAE International. (2019). *Oxygen flow indication* (Aerospace Standard AS916C). SAE International.
- Seeler, H. W. (1961). *Development of oral-nasal masks, oxygen, MC-1 and MBU-5/P* (ASD Technical Report 61-395). <https://apps.dtic.mil/dtic/tr/fulltext/u2/267151.pdf>
- Shapiro, E. (2018, April 18). Woman ‘partially sucked out a window’ dies after engine failure on Southwest flight. *ABC News*. <https://abcnews.go.com/US/plane-makes-emergency-landing-philadelphia/story?id=54530003>
- Sheffield, P. J., & Heimbach, R. D. (1996). Respiratory physiology. In R. L. DeHart (Ed.), *Fundamentals of Aerospace Medicine* (2nd ed., pp. 69-108). Lippincott Williams & Wilkins.
- Swearingen, J. J. (1957). An adhesive type of oxygen mask. *Journal of Aviation Medicine*, 28(1), 19-22.
- Tuttle, A. D., Marbarger, J. P., & Luft, U. C. (1951). K-S Disposable Oxygen Mask. *Journal of Aviation Medicine*, 22(4), 265-277.

Whitemule. (2019). A-7 nasal oxygen mask: try not to laugh. The Dreamy Dodo.

<https://elpoderdelagalaxias.wordpress.com/2019/02/05/a-7-nasal-oxygen-mask-try-not-to-laugh/>

Young, J. W. (1966). *Selected facial measurements of children for oxygen-mask design*

(DOT/FAA/AM-66/9). https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/1960s/media/AM66-09.pdf