U.S. Department
of Transportation
Federal Aviation Administration

Advisory Circular

Subject: Hazard Associated with Sublimation of Solid Carbon Dioxide (Dry Ice) Aboard Aircraft

Date: 5/22/2009
Initiated by: AAM-630

AC No: 91-76A
Change: 1

1. What is the purpose of this Advisory Circular (AC)?

This AC discusses the potential hazard associated with the sublimation of dry ice aboard aircraft. Precautionary measures and simple rules of thumb are indicated in order to preclude environmentally hazardous conditions affecting crews and passengers aboard aircraft.

2. Does this AC supersede any existing ACs?

AC 91-76, dated 9/30/2004, superseded AC 103-4, Hazard Associated with Sublimation of Solid Carbon Dioxide (dry ice) Aboard Aircraft, dated 5/01/74.

AC 91-76A, Change 1, updates dry ice sublimation rates (see the bolded numbers in Item 7 below) and provides a reference to an FAA Technical Report, DOT/FAA/AM-06/19, 2006 (see the bolded item under the REFERENCES section at the end of this document).

3. What do some of these words mean?

a. Dry Ice: Solidified carbon dioxide (CO_2) with a melting point of -78.5°C (-109.3°F).
b. Carbon Dioxide: A colorless odorless gas that is a natural product of animal respiration and other energy releasing processes.
c. Sublimation: The process of converting a solid substance (dry ice, solid CO_2) into a gas (CO_2 gas).

4. Why is an AC about the transportation of dry ice aboard aircraft important?

Dry ice sublimates to gaseous CO_2 at aircraft environment temperatures. Excessive CO_2 in the aircraft can cause aircrew incapacitation. Dry ice is generally carried aboard aircraft to keep food (galley or cargo), medicine, or biological materials in a frozen or chilled condition. The quantity of dry ice used on the aircraft may vary depending on the amount of material that must be maintained in a frozen/chilled condition, the shipment time, the insulative nature of the packaging, the desired temperature of the shipment, and other characteristics. Dry ice is a hazardous material under Title 49 of the Code of

Federal Regulations (CFR). Additionally, gaseous CO_2 that can result from sublimation of dry ice and other sources is regulated under 14 CFR. Dry ice sublimation producing excess CO_2 gas may be dangerous in confined spaces where there is an absence of ventilation or ventilation rates are low. The conversion rate of dry ice to gaseous CO_2 will vary depending on package insulation, dry ice particle size, surrounding temperature, and cabin pressure.

Tests conducted by Pan American Airlines in 1963 indicated that a sublimation rate of one pound per hundred pounds of dry ice per hour (1%/hour) can be expected for packages containing large amounts of dry ice, i.e., packages containing 100 lbs. of dry ice. More recent tests conducted by the Federal Aviation Administration demonstrated that the sublimation rate for small insulated shipping packages containing 4.6 to 5.3 lbs. of dry ice averaged 2%/hour.

There have been very few reported incidents of carbon dioxide hazards aboard aircraft resulting from sublimation of dry ice. In the incidents that have been reported, the aircrew recognized symptoms that they considered to be related to potential air contamination and took appropriate procedures to avoid any serious problems.

Modern aircraft reprocess or recirculate a portion of their cabin air. Even though the recirculated air passes through filters, these filters do not remove very small molecules such as CO_2. Even with recycled air, a properly functioning modern aircraft environmental control system provides fresh air for a substantial number of complete cabin air exchanges per hour, making buildup of carbon dioxide in the cabin an unlikely event. If aircraft ventilation is not effective, a buildup of CO_2 could occur.

5. What are the physiological effects of carbon dioxide?

CO_2 is categorized by the National Institute for Occupational Safety and Health (NIOSH) as a simple asphyxiant with symptoms resulting only when such high concentrations are reached that the gas affects the brain and other physiologic functions. The signs and symptoms of CO_2 poisoning are similar to those that precede lack of oxygen, namely headache, dizziness, muscular weakness, drowsiness, and ringing in the ears. CO_2 poisoning does have a greater effect on breathing than simple lack of oxygen, causing a significant increase in the rate and depth of breathing as an early symptom. Removal from exposure results in rapid recovery.

Exposures to CO_2 in aircraft should not exceed a sea level equivalent to 0.5% CO_2 (5,000 parts of CO_2 per million parts of air or 5,000 ppm)- 5000 ppm is also used by the Department of Labor, Occupational Safety and Health Administration (OSHA) as an 8-hour Time Weighted Average Permissible Exposure Limit (PEL) in general industries. Production of symptoms is related to the effect of increased CO_2 on certain bodily processes. No symptoms occur from inhalation of CO_2 if the atmosphere contains only slightly more than normal amounts of CO_2. When the concentration of CO_2 approaches 2%, the depth of respiration is increased so that the amount of air into the lungs with each breath increases up to 30%. If the concentration of CO_2 is as high as 4%, there is not only an increase in the depth of respiration but also an increase in the rate of respiration. At this point, breathing is deeper and somewhat faster and considerable discomfort is produced. A CO_2 concentration of 4.5-5% causes breathing to become extremely labored and almost unbearable in some individuals. The highest concentration of CO_2 that can be tolerated is 7% to 9%. More than 10% can cause loss of muscle control and unconsciousness.

6. What are the hazards associated with dry ice?

The hazard associated with the carriage of dry ice aboard all aircraft is considered minimal under normal cabin ventilation conditions. However, in the absence of proper ventilation, the sublimation of dry ice could result in unacceptable levels of CO_2 in the cabin environment that could produce the symptoms described in paragraph 5.

7. What are the precautions and recommendations for the transportation of dry ice aboard aircraft?

Maintaining adequate input and circulation of fresh air is the single most important precaution that must be taken when dry ice is transported. Additionally, the aircrew should be aware of the hazards involved in the transport of dry ice and be prepared to take appropriate emergency procedures. Emergency procedures should include instructions that if symptoms occur or if a buildup of CO_2 is suspected, the use of emergency oxygen should be considered. When dry ice is stored aboard aircraft, if the normal ventilation system is not functioning, auxiliary cabin ventilation is needed before takeoff. This will avoid the buildup of CO_2 concentration prior to boarding. In the absence of ventilation, it would take a small amount of dry ice to produce an unacceptable level of CO_2 in an aircraft.

Estimations of the amount of dry ice that can be transported relative to the volume of fresh air circulation in the aircraft can be calculated as follows:

The dry ice sublimation rate will depend on the amount of dry ice stored in a package, the packaging of dry ice, and numerous other variables. The experimentally determined sublimation rate for large (100 lbs.) amounts of dry ice per single package is 1%/hour. The experimentally determined rate for small (5 lbs.) amounts of dry ice per single package is 2%/hr. One lb. of dry ice sublimates to **8.8** cubic feet of CO_2 gas. Thus, a sublimation rate can be defined as X ft^3 CO_2 gas per hour. A dry ice sublimation rate of 1% per hour provides **8.8** ft^3 CO_2 gas per 100 lbs. dry ice per hour. A 2% per hour sublimation rate provides **17.6** ft^3 CO2 gas per 100 lbs (20 x 5 lb packages) of dry ice per hour.

NOTE: If the packages in a given load contain less than 100 lbs. of dry ice, it is recommended that shippers use the 2%/hour sublimation rate or conduct evaluations to determine the sublimation rates for variable-weight dry ice packages.

The following formula provides a rule-of-thumb for dry ice loading relative to the volume of air circulation. Examples include calculations using a 1%/hour sublimation rate and a 2%/hour rate.

X = Dry ice loading in lb

$$X = \frac{(CO_2 \text{ concentration})\ (\text{Aircraft Volume, ft}^3)\ (\text{Complete air exchanges per hour*})}{(\text{sublimation rate})}$$

Example 1a:
Aircraft volume: 5000 ft^3
Complete air exchanges per hour: 10
Allowable CO_2 concentration (TLV, 0.5%): 0.005
Sublimation rate of 1%/hour (**8.8** ft^3 CO_2/100 lb dry ice/hour): **0.088**

$$X = \frac{(0.005)\ (5000)\ (10)}{(0.\mathbf{088})} = \mathbf{2841} \text{ lbs. of dry ice}$$

Example 1b:
Conditions same as example 1 except that the complete air exchange has doubled.
Complete air exchanges per hour: 20

$$X = \frac{(0.005)\ (5000)\ (20)}{(0.\mathbf{088})} = \mathbf{5682} \text{ lbs. of dry ice}$$

Example 2: Applies when the shipment consists of small (5 lb) packages of dry ice.
Aircraft volume: 5000 ft^3
Complete air exchanges per hour: 20
Allowable CO_2 concentration (TLV, 0.5%): 0.005
Sublimation rate of 2%/hour ((2 x **8.8** ft^3 CO_2)/100 lbs. dry ice/hour): 0.**176**

$$X = \frac{(0.005)\ (5000)\ (20)}{(0.\mathbf{176})} = \mathbf{2841} \text{ lbs. of dry ice}$$

* Since newer models of airplanes recycle as much as 50% of the cabin ventilated air, instead of providing 100% fresh air as older models did, the number of complete cabin air exchanges of fresh air is required to determine the amounts of dry ice that can be transported.

REFERENCES

Caldwell DC, Lewis RJ, Shaffstall RM and Johnson RD "The Sublimation Rate of Dry Ice Packaged in Commonly Used Quantities by the Air Cargo Industry," DOT/FAA/AM-06/19, 2006

Airgas. Carbon Dioxide – CO_2 MSDS (doc # 001013)

Pan American Maintenance Engineering Report #ME 124, Feb. 6, 1963, Air Conditions, Dry Ice Quantity Limitations, DC-7CF Flight Test.

Dangerous Properties of Industrial Materials, 1957, N. Irving Sax.

Textbook of Toxicology, 1959, DuBois and Ceiling.

Industrial Hygiene and Toxicology, Vol. II, 1963, Frank A Patty.

Goodman and Gilman's Pharmacological Basis of Therapeutics, 10th Ed, 2002, Joel Hardman and Lee Limbird

Gibbons HL. Carbon Dioxide Hazards in General Aviation. *Aviat. Space Environ. Med.*, 48, 261 (1977)

Martin-Saint-Laurent A, Lavernhe J, Casano G, Simkoff A. Clinical Aspects of Inflight Incapacitations in Commercial Aviation. *Aviat. Space Environ. Med.*, 61, 256 (1990)

Carbon Dioxide Fact Book. Htpp://www.airspill.com/co2report.html (accessed Oct 2002)

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