Federal Aviation Administration

DOT/FAA/AM-06/19
Office of Aerospace Medicine
Washington, DC 20591

Sublimation Rate of Dry Ice Packaged in Commonly Used Quantities by the Air Cargo Industry

Douglas C. Caldwell
Russell J. Lewis
Robert M. Shaffstall
Robert D. Johnson
Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

August 2006

Final Report

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents thereof.

This publication and all Office of Aerospace Medicine technical reports are available in full-text from the Civil Aerospace Medical Institute's publications Web site:
www.faa.gov/library/reports/medical/oamtechreports/index.cfm

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-06/19		

4. Title and Subtitle

The Sublimation Rate of Dry Ice Packaged in Commonly Used Quantities by the Air Cargo Industry

5. Report Date

August 2006

6. Performing Organization Code

7. Author(s)

Caldwell DC, Lewis RJ, Shaffstall RM, Johnson RD

8. Performing Organization Report No.

9. Performing Organization Name and Address

FAA Civil Aerospace Medical Institute
P.O. Box 25082
Oklahoma City, OK 73125

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

Office of Aerospace Medicine
Federal Aviation Administration
800 Independence Ave., S.W.
Washington, DC 20591

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplemental Notes

This work was accomplished under the approved task AM-B-05-TOX-204.

16. Abstract

Dry ice is used as a refrigerant for the shipment of perishable goods in the aviation industry. The sublimation of dry ice can, however, lead to incapacitating levels of carbon dioxide in the aircraft cabin environment, as exemplified by the National Transportation Safety Board's (NTSB's) probable cause determination in a 1998 Brownsville, Texas, incapacitation incident. This incident prompted the NTSB to request that the Federal Aviation Administration (FAA) revisit the dry ice sublimation rate published in FAA Advisory Circular AC 103-4. The sublimation rate used in AC 103-4 to calculate permissible dry ice loads was based on a study conducted by Pan American Airlines where a single, large piece of dry ice (100 lb block) was used. Today, the majority of dry ice shipments contain smaller amounts of dry ice obtained in pellet form (•5 lb). This study focuses on the sublimation rate of dry ice packed in such commonly encountered amounts. In this study, approximately 5 lb of dry ice, in pellet form, was added to each of 20 pre-weighed TheromoSafe® shipping containers. The boxes were then weighed to obtain "preflight" weights and placed in an altitude chamber located at the FAA's Civil Aerospace Medical Institute. The chamber was depressurized to an altitude of 8000 ft at a rate of 1000 ft/min. The total "flight" time was 6 h. The containers were then removed and immediately weighed to obtain "post-flight" measurements. Using the differences in weight as well as the total flight time, an average sublimation rate of 2.0 +/- 0.3%/h was determined. Results indicate that the sublimation rate is greater when dry ice is packaged in pellet form in small quantities. These results contrast the Pan American Airlines study that employed one solid 100-lb block of dry ice. The current study improves air cargo safety by providing a sublimation rate for dry ice shipped in small, more representative quantities. The updated sublimation rate can be used to calculate safe dry ice loads for containers commonly used today.

17. Key Words	18. Distribution Statement
Carbon Dioxide, Sublimation, Dry Ice, Aircraft Accident Investigation	Document is available to the public through the Defense Technical Information Center, Ft. Belvior, VA 22060; and the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	8	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

The Sublimation Rate of Dry Ice Packaged in Commonly Used Quantities by the Air Cargo Industry

INTRODUCTION

The air cargo industry has seen a dramatic increase in the number of packages containing solid carbon dioxide or "dry ice" over the past 30 years. The FedEx® Dangerous Goods Administration Office reported that 50% of its workload, approximately 15,000 packages per day, contain dry ice.[1] The large volume appears to be predominantly due to the increased diversity of items shipped with dry ice. The Air Canada Web site lists fresh fish and meat as well as organs for transplant, human blood, drugs, and serums as some of the items they ship that contain dry ice for temperature control.[2] In recent years, the largest single area of increase is in the bio-medical industry, which requires overnight delivery of frozen specimens, reagents, and supplies all over the world.[1] The market for fresh foods has also expanded from predominantly seafood to include companies selling freshly prepared frozen foods over the Internet for at-home, overnight delivery.[3] The quantity of dry ice used aboard an aircraft varies depending on the amount of material that must be maintained in a frozen/chilled condition, the shipment time, the insulative nature of the packaging, and the desired temperature of the shipment. FedEx® reported that the vast majority of their dry ice shipments contain less than 5 lb of dry ice.[1] The small size (<5 lb) of these packages allows them to avoid the special handling requirements instituted by Title 49 of the Code of Federal Regulations (CFR) and subsequent surcharges imposed by air cargo shippers such as FedEx®.[1, 4, 5]

Dry ice is designated as a miscellaneous hazardous material because it sublimates to gaseous carbon dioxide (CO_2) at aircraft environment temperatures, and high concentrations of CO_2 in the aircraft can cause aircrew incapacitation.[5, 6, 8] Dry ice is listed as a miscellaneous hazardous material under 49 CFR, and gaseous CO_2 resulting from the sublimation of dry ice and other possible sources is regulated under 14 CFR. Dry ice sublimation may be dangerous in confined spaces where there is an absence of ventilation or low ventilation rates. The conversion of dry ice to gaseous CO_2 varies depending on package insulation, dry ice particle size, ambient temperature, and cabin pressure.

Carbon dioxide is categorized by the National Institute for Occupational Safety and Health as a simple asphyxiate with symptoms resulting only when such high concentrations are reached that the gas affects the brain and other physiologic functions.[9] The signs and symptoms of CO_2 poisoning are similar to those of oxygen deprivation, namely headache, dizziness, muscular weakness, drowsiness, and ringing in the ears. CO_2 poisoning has a greater effect on breathing than a simple lack of oxygen. An early symptom of CO_2 poisoning is a significant increase in the rate and depth of breathing. Removal from exposure results in rapid recovery. Exposures to CO_2 in aircraft should not exceed a sea level equivalent of 0.5% CO_2 (5000 parts of CO_2 per million parts of air - 5000 ppm). Five-thousand ppm is also used by the United States Department of Labor, Occupational Safety and Health Administration as an 8-h time-weighted average Permissible Exposure Limit in general industry.[10] Increased CO_2 concentrations negatively affect the human respiratory system. Few, if any, noticeable effects are produced when CO_2 levels are only slightly above normal. However, significant effects begin to occur with increasing concentrations of CO_2, as can be seen in Table 1.

High concentrations of CO_2 have the potential to cause in-flight incapacitation, which is defined as "any state that affects a pilots' health during the performance of their duties, preventing them from performing normal operations and coping with emergency situations."[11] Two recent incidents show the gravity of such incapacitation and why data on the sublimation of dry ice in small packages has become increasingly important. One of these incidents occurred on April 29, 1998. "At approximately 2100 CDT, a Douglas DC-8-51 cargo airplane was taxiing for takeoff at Brownsville/South Padre Island International Airport when all four crewmembers became short of breath. They acted appropriately by donning oxygen masks and the pilot taxied back to the ramp. The crewmembers were later treated and released from a local hospital. The NTSB determined that this near accident was caused by a buildup of gaseous CO_2 in the cockpit, with the CO_2 originating from the cargo hold, where numerous containers with dry ice were present."[12] Although no one was injured, the presence of CO_2 in the cabin at higher than normal concentrations caused a significant

Table 1. Physiological effects of CO_2 at Various Concentrations.[7]

CO_2 concentration (%)	Physiological effect
0.3	Normal Respiration
0.5	Slight increase in respiration
2	Respiration increased 50%
3	Respiration increased 100%
5	Respiration increased 300%
12-15	Unconsciousness

distraction for the flight crew, forcing them to respond to their increased rate of respiration. Stimulation of the respiratory center and subsequent rapid breathing caused by an increased concentration of CO_2 posed the threat of incapacitation to this crew. This threat was averted by the proper use of supplemental oxygen. It must be pointed out, however, that the normal aircraft ventilation systems were not functioning, and prior to departure, auxiliary cabin ventilation was not used.

A second incident involving CO_2 occurred in an Air France transport aircraft. In this incident, the crew was preparing for takeoff. "The flight was loaded with perishable goods preserved using dry ice. The plane was loaded and sealed for 40 min before engine start-up. The ventilation system in this type of aircraft does not operate without the engines running, and auxiliary ventilation was not being used at the time. Headaches and rapid breathing occurred among all crewmembers due to the increased concentration of CO_2. The prompt use of oxygen masks by the crew relieved all respiratory symptoms, and starting the engines resulted in proper ventilation, which dissipated the high CO_2 concentrations."[11]

In 1963, Pan American Airlines designed an experiment utilizing 100 lb blocks of dry ice to determine the sublimation rate of CO_2 and subsequently evaluate the performance of the air conditioning units they used in their cargo aircraft.[13] Based on this study, a recommended CO_2 sublimation rate of 1%/h was established in FAA Advisory Circular AC103-4. In 1977, H. L. Gibbons *et al.*[14] measured the sublimation rate of 1 lb and 5 lb blocks of dry ice that were wrapped in paper and placed in the cockpit of a Cessna 150 that remained on the ground for the duration of the experiment at an ambient temperature of 72°F. This study found that under these specific conditions the sublimation rate for dry ice was 14%/h. In actual practice, the shipment of dry ice must comply with the provisions of 49 CFR 173.217, which specifies that the shipment must be appropriately packaged. Paper wrappings would not generally be used to ship a perishable item frozen in dry ice. Therefore, experimentation was needed to determine CO_2 sublimation rates utilizing commonly used shipping containers, conditions, and practices.

Experimental Evaluation

This experiment was designed to determine the sublimation rate of dry ice during operational conditions most commonly encountered by flight crews in present-day transport aircraft. Twenty TheromoSafe® model 318 shipping boxes (8x6x4.25 in inside dimensions, 11x9x7.25 in outside dimensions, with 1.5 in-thick Styrofoam walls) were obtained from Polyfoam Packers Inc. (Waukegan, IL). The boxes were numbered and then weighed using an Ohause (Pine Brook, NJ) Precision Plus electronic balance. Dry ice was acquired at a local Air Liquide (Oklahoma City, OK) outlet in the form of pellets. The pellets were uniform in size with dimensions of approximately 1 x 2 cm. Approximately 5 lb of dry ice was added to each container. Any remaining headspace was filled with common carpet padding, as recommended by a dry ice shipping Web site.[15] The size and shape of the dry ice mirrored a style commonly utilized by the air cargo industry. Following the addition of dry ice to each individual shipping container and the filling of extraneous headspace, the boxes were immediately taped shut. Each container was then weighed to determine an initial "pre-flight" weight. The boxes were stacked in 4 columns, each column containing 5 boxes, on a cart approximately 3 ft above the floor and placed in an Environmental Techtronics (Southampton, PA) altitude chamber at the FAA's Civil Aerospace Medical Institute. The initial temperature inside the chamber was 72°F. The chamber was depressurized to an altitude of approximately 8000 ft at a rate of 1000 ft/min. This depressurization process took 7.2 min, at which time the final altitude had been reached. An altitude of 8000 ft was maintained for 5.75 h, at which time the decent began and the chamber was pressurized back to ground level at a rate of 1000 ft/min, resulting in a total "flight" time of 6 h. The final temperature of the chamber was 84°F. The containers were then removed and immediately weighed to obtain a "post-flight" weight. The total time between the two weight measurements was 6.25 h.

RESULTS AND DISCUSSION

The average sublimation rate of dry ice packaged in 5 lb quantities was determined to be 2.0±0.3 %/h with a range of 1.59 to 2.88%/h. Individual data for each shipping container are shown in Table 2. The sublimation rate of solid CO_2 determined in this experiment is substantially lower than the 14%/h produced by Gibbons *et al.*[14] in 1977, but is double the 1%/h rate determined in 1963[13] and used until recently to establish dry ice shipping regulations. It is clear that the sublimation rate of dry ice depends on the particle size, the shipping container, and how the shipping containers are packaged; thus, recommendations regarding dry ice load and aircraft ventilation requirements should be based on commonly used shipping containers and dry ice characteristics. While the two early sublimation studies do not reflect "real world" shipping practices, the current study incorporates commonly used shipping industry boxes, dry ice amounts, and dry ice pellets. Thus, our results should closely reflect what is experienced during air cargo transportation of dry-ice refrigerated goods.

The complete sublimation of 1 lb of dry ice results in 8.8 ft^3 of CO_2 gas.[6] Therefore, a sublimation rate can be defined as X ft^3 CO_2 gas per h. A dry ice sublimation rate of 1%/h produces 8.8 ft^3 CO_2 gas per 100 lb (20 x 5 lb packages) of dry ice per h. A 2%/h sublimation rate produces 17.6 ft^3 CO_2 gas per 100 lb (20 x 5 lb packages) of dry ice per h. The following formula provides a rule-of-thumb for dry ice loading relative to the volume of aircraft air circulation. Examples, including calculations using a 1%/h sublimation rate and a 2%/h sublimation rate, are shown below.

X = Dry ice weight in lb

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

Example 1a: A shipment that consists of one large block (100 lb) of dry ice.

Aircraft volume: 5000 ft^3

Complete air exchanges per h: 10

Allowable CO_2 concentration (TLV, 0.5%): 0.005

Sublimation rate of 1%/h (8.8 ft^3 CO_2/100 lb dry ice/h): 0.088

$$X = \frac{(0.005)\ (5000)\ (10)}{(0.088)} = 2841 \text{ lb of dry ice}$$

Example 1b: Conditions are the same as example 1a except that the number of complete air exchanges has doubled.

Complete air exchanges per h: 20

$$X = \frac{(0.005)\ (5000)\ (20)}{(0.088)} = 5682 \text{ lb of dry ice}$$

Example 2: A shipment that consists of 20 small (5 lb) packages of dry ice.

Aircraft volume: 5000 ft^3

Complete air exchanges per h: 20

Allowable CO_2 concentration (TLV, 0.5%): 0.005

Sublimation rate of 2%/h ((2 x 8.8 ft^3 CO_2)/100 lb dry ice/h): 0.17

$$X = \frac{(0.005)\ (5000)\ (20)}{(0.176)} = 2841 \text{ lb of dry ice}$$

These examples demonstrate the need for a more representative CO_2 sublimation rate for today's air cargo industry. Following the guidelines that were established in 1963, the aircraft used in example 1b could have carried 5882 lb of dry ice in the cargo hold without fear of cabin air contamination from elevated CO_2 levels. However, when dry ice is utilized as pellets in small quantities instead of large blocks the sublimation rate increases by a factor of two. This means that under the same conditions as example 1b, this aircraft should only safely carry 2941 lb of dry ice, half the amount. It becomes obvious that two variables must be known before the amount of dry ice that may safely be carried on an aircraft can be calculated. These variables are the aircraft volume, and the number of complete air exchanges per h. If one of these variables is unknown, a reliable calculation cannot be made. However, if these variables are known, dry ice loads can safely be calculated using the "realistic" sublimation rate of 2%/h.

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

Table 2. CO_2 sublimation rate for 20 insulated shipping containers filled with approximately 5 lb of dry ice pellets.

Sublimation Rate of Small Dry Ice Pellets in 5-lb Quantities							
Box #	Box weight empty	Initial wt. box and ice	Final wt. box and ice	Wt. initial ice	Wt. final ice	Total ice loss	Sublimation rate (%/h)
1	1.448	6.360	5.823	4.912	4.375	0.537	**1.75**
2	1.383	6.322	5.738	4.939	4.355	0.584	**1.89**
3	1.367	6.313	5.782	4.946	4.415	0.531	**1.72**
4	1.391	6.154	5.561	4.763	4.170	0.593	**1.99**
5	1.431	6.682	6.148	5.251	4.717	0.534	**1.63**
6	1.383	6.263	5.669	4.880	4.286	0.594	**1.95**
7	1.397	6.614	5.840	5.217	4.443	0.774	**2.37**
8	1.418	6.085	5.488	4.667	4.070	0.597	**2.05**
9	1.396	6.122	5.575	4.726	4.179	0.547	**1.85**
10	1.404	6.293	5.755	4.889	4.351	0.538	**1.76**
11	1.500	6.029	5.412	4.529	3.912	0.617	**2.18**
12	1.380	6.042	5.399	4.662	4.019	0.643	**2.21**
13	1.399	6.632	5.689	5.233	4.290	0.943	**2.88**
14	1.407	6.651	6.130	5.244	4.723	0.521	**1.59**
15	1.405	6.402	5.813	4.997	4.408	0.589	**1.89**
16	1.406	6.298	5.641	4.892	4.235	0.657	**2.15**
17	1.387	6.204	5.654	4.817	4.267	0.550	**1.83**
18	1.431	6.503	5.792	5.072	4.361	0.711	**2.24**
19	1.401	6.503	5.963	5.102	4.562	0.540	**1.69**
20	1.393	6.693	5.905	5.300	4.512	0.788	**2.38**
						Average	**2.00**
						s.d.	**0.32**
						C.V.	**15.82**

All weights in lb.

Time between weighings was 6.25 h.

Chamber temp at T=0 was 72°F, at T=6h was 84°F

CONCLUSIONS

There have been very few reported incidents involving carbon dioxide incapacitation aboard aircraft resulting from the sublimation of dry ice. In the incidents that have been reported, the aircrew recognized symptoms of air contamination and took appropriate precautions to avoid any serious consequences. The incidents that have occurred demonstrate that maintaining adequate input and proper circulation of fresh air into the cabin environment is the single most important precaution that can be taken when dry ice is transported.[16] In the absence of adequate ventilation, a small amount of dry ice can produce unacceptable levels of CO_2 in an aircraft. The current research found that the amount of dry ice used in a shipment of perishables is generally less than 5 lb per container and that this amount of dry ice, packaged in an appropriate manner, sublimes at a rate of 2%/h. Based on these findings, revisions in ventilation requirements were incorporated into the FAA Advisory Circular 91-76.

In addition to ventilation considerations, aircrew should be aware of the hazards involved with the transportation of dry ice and should be prepared to take appropriate emergency precautions if CO_2 levels increase in the cabin. The first emergency precaution would be the use of supplemental oxygen supplies. This should be followed by attempts to ventilate the cabin to outside air. If dry ice is stored aboard aircraft, and the normal ventilation system is not functioning, auxiliary cabin ventilation is necessary before takeoff.

REFERENCES

1. FedEx®. Dangerous Goods Administration Office. 1-800-463-3339. personal conversation. (08/2003).
2. Air Canada. www.aircanada.com/cargo/products/perishables.html (04/2006).
3. Omaha Steaks. www.omahasteaks.com (04/2006).
4. Fed Ex®. www.fedex.com/us/services/options/express/dangerousgoods/fees.html#1 (04/2006).
5. U.S. Government Printing Office. www.gpoaccess.gov. 49CFR173.140 (04/2006).
6. Airgas. Carbon Dioxide – CO_2 MSDS (doc # 001013).
7. Smith Garry K. Carbon Dioxide, Caves and YOU. (1997) http://thelances.org/hr3/CO2paper.html (04/2006).
8. W.E. Kuriger Associates. Carbon Dioxide Fact Book. www.airspill.com (04/2006).
9. Centers of Disease Control, National Institute for Occupational Safety and Health. www.cdc.gov/niosh/homepage.htm (04/2006).
10. Occupational Safety and Health Administration. www.osha.gov/dts/hib/hib_data/hib19881130.html (04/2006).
11. Martin-Saint-Laurent A, Lavernhe J, Casano G, Simkoff A. Clinical Aspects of In-flight Incapacitations in Commercial Aviation. *Aviat Space Environ Med*, 61, 256 (1990).
12. National Transportation Safety Board. www.ntsb.gov/aviation/FTW/1narr_98A196.htm (04/2006)
13. Pan American Airlines. Pan American Maintenance Engineering Report #ME 124, Feb. 6, 1963, Air Conditions, Dry Ice Quantity Limitations, DC-7CF Flight Test.
14. Gibbons HL. Carbon Dioxide Hazards in General Aviation. *Aviat Space Environ Med*, 48, 261 (1977)
15. Advantage Dry Ice. www.advantagedryice.com (04/2006).
16. The Boeing Company. Boeing Service letter, ATA: 2100-010, 19 November 1998.