

Technical Assessment of Dry Ice Limits on Aircraft

DETAILS

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HAZARDOUS MATERIALS COOPERATIVE RESEARCH PROGRAM

HMCRP REPORT 11

**Technical Assessment
of Dry Ice Limits on Aircraft**

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TRANSPORTATION RESEARCH BOARD

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HAZARDOUS MATERIALS COOPERATIVE RESEARCH PROGRAM

The safety, security, and environmental concerns associated with transportation of hazardous materials are growing in number and complexity. Hazardous materials are substances that are flammable, explosive, or toxic or that, if released, produce effects that would threaten human safety, health, the environment, or property. Hazardous materials are moved throughout the country by all modes of freight transportation, including ships, trucks, trains, airplanes, and pipelines.

The private sector and a diverse mix of government agencies at all levels are responsible for controlling the transport of hazardous materials and for ensuring that hazardous cargoes move without incident. This shared goal has spurred the creation of several venues for organizations with related interests to work together in preventing and responding to hazardous materials incidents. The freight transportation and chemical industries; government regulatory and enforcement agencies at the federal and state levels; and local emergency planners and responders routinely share information, resources, and expertise. Nevertheless, there has been a long-standing gap in the system for conducting hazardous materials safety and security research. Industry organizations and government agencies have their own research programs to support their mission needs. Collaborative research to address shared problems takes place occasionally, but mostly occurs on an ad hoc basis.

Acknowledging this gap in 2004, the U.S. DOT Office of Hazardous Materials Safety, the Federal Motor Carrier Safety Administration, the Federal Railroad Administration, and the U.S. Coast Guard pooled their resources for a study. Under the auspices of the Transportation Research Board (TRB), the National Research Council of the National Academies appointed a committee to examine the feasibility of creating a cooperative research program for hazardous materials transportation, similar in concept to the National Cooperative Highway Research Program (NCHRP) and the Transit Cooperative Research Program (TCRP). The committee concluded, in *TRB Special Report 283: Cooperative Research for Hazardous Materials Transportation: Defining the Need, Converging on Solutions*, that the need for cooperative research in this field is significant and growing, and the committee recommended establishing an ongoing program of cooperative research. In 2005, based in part on the findings of that report, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) authorized the Pipeline and Hazardous Materials Safety Administration (PHMSA) to contract with the National Academy of Sciences to conduct the Hazardous Materials Cooperative Research Program (HMCRP). The HMCRP is intended to complement other U.S. DOT research programs as a stakeholder-driven, problem-solving program, researching real-world, day-to-day operational issues with near- to mid-term time frames.

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The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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FOREWORD

By Joseph D. Navarrete

Staff Officer

Transportation Research Board

HMCRP Report 11: Technical Assessment of Dry Ice Limits on Aircraft describes a technical approach to determining the maximum quantity of dry ice (solid carbon dioxide) that can be safely carried aboard aircraft. A key finding of this research is that dry ice transport limits would best be based on packaging surface area rather than on the current mass-based limits. As a result of this finding, guidelines are provided that could be used to provide safe limits for carriage of dry ice on commercial airplanes. In addition, a software tool is provided to allow users to input variables for specific aircraft and trip profiles to determine appropriate dry ice loadings. This tool is located on the CD-ROM that accompanies this report.

Dry ice is widely used to keep perishable goods cold while in transit. Since dry ice sublimates (i.e., passes directly from a solid state to a gaseous state) to produce carbon dioxide gas, there are specified limits on the amount of dry ice that can be transported on passenger and cargo aircraft. The current dry ice limits are based on the mass of dry ice carried. However, there has been little experimental data on the sublimation rate of dry ice in packages, and much of the analysis was undertaken nearly 50 years ago. Thus, there is a need to review and update current recommendations.

The research, led by Battelle Memorial Institute, initially reviewed current regulations and guidance for dry ice shipments, and also reviewed aircraft manufacturer and air carrier guidelines and procedures. All the guidance focuses on establishing a mass-based limit on the quantity of dry ice that can be shipped. A heat transfer and dimensional analysis showed that the sublimation rate of dry ice is determined by specifying the surface area and insulation properties of the packages, not by the quantity of dry ice present in the package, and laboratory tests were performed to confirm these findings. Using the heat transfer analysis and the results of the laboratory tests, the research team developed a model to predict the performance of dry ice during flight conditions and tested the model with data obtained in flight. Based on the research findings, the team developed guidelines that could be used to provide safe limits for carriage of dry ice on commercial airplanes. The guidelines have two key parts: (1) a packaging standard that specifies a minimum amount of insulation and (2) a total surface area limit for dry ice packages. The team then developed a tool that enables operators of passenger or cargo aircraft to first determine the total surface area of dry ice packages that can be safely loaded onto a particular flight and, using this information, confirm that the dimensions of all the dry ice packages being shipped do not exceed these limits.

The report is organized into 12 chapters. Chapter 1 provides an introduction to the research. Chapter 2 provides an overview of the properties and use of dry ice in commerce. Chapters 3, 4, and 5 present a review of guidelines and regulations for dry ice shipments, aircraft manufacturer guidelines and procedures, and air carrier procedures. A dimensional

analysis of dry ice sublimation is described in Chapter 6, while Chapter 7 provides a rationale for basing dry ice limits on heat transfer analysis. Chapters 8, 9, and 10 describe the laboratory and field testing efforts undertaken as part of the research. The development of dry ice guidelines for aircraft is described in Chapter 11. Chapter 12 provides recommendations for future research.

The software tool, available on the CD-ROM that accompanies this report, illustrates how the surface area method can be used by airlines and shippers to estimate the total surface area of packages containing dry ice that can be loaded for specific aircraft and trip profiles. Prior to a flight, a carrier can verify that this surface area limit will not be exceeded using the dimensions of all the dry ice packages being shipped.

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

S U M M A R Y

Technical Assessment of Dry Ice Limits on Aircraft

The objectives of this project were to develop an understanding of the parameters affecting the buildup of carbon dioxide in both passenger and cargo aircraft and to develop a decision tool for air carriers to use in determining the maximum quantity of dry ice (solid carbon dioxide) that can be safely carried on board aircraft.

To accomplish this objective, a literature review was performed to identify pertinent information developed by others regarding the handling of dry ice on aircraft. By considering the physical characteristics of dry ice sublimation and the engineering characteristics of modern aircraft, the parameters that affect the buildup of carbon dioxide in the various compartments of the airplane were identified and assessed. A topology of dimensionless parameters was developed in an attempt to reduce the number of variables controlling the sublimation of dry ice and the subsequent transport of carbon dioxide in aircraft and to generalize their relationship.

The information gained from the literature review and dimensionless analyses was then used to identify knowledge gaps. The review found that there was little experimental data on the sublimation rate of dry ice in packages. Accordingly, several insulated packages used to transport items refrigerated with dry ice were obtained and filled with dry ice, and the sublimation rate of the dry ice was measured until most of the dry ice had sublimed. For actively cooled unit load devices (ULDs), vendors supplied data on the performance and dry ice usage of their cooled containers.

The major aircraft manufacturers were contacted to obtain the guidance that they provide to air carriers regarding the operation of ventilation systems and on establishing dry ice limits. Airbus and Boeing provided valuable information that filled in many of the knowledge gaps regarding the ventilation systems. Others, particularly the manufacturers of regional jets, did not provide information, and the details regarding the operation of their ventilation systems remain a knowledge gap.

From the literature review, the heat transfer experiments, and the data provided by Boeing and Airbus, a reasonable understanding of the parameters that govern the sublimation of the dry ice within the insulated packages and the subsequent increase of carbon dioxide concentrations in airplane compartments was developed. To demonstrate that it was possible to model and predict the performance of dry ice during flight conditions, a large quantity of dry ice (680 kg) was placed in a ULD and loaded onto a Boeing 777, and the carbon dioxide concentration in the passenger cabin was monitored during the flight. To identify any differences, the carbon dioxide concentration was also monitored on the return flight, which contained no dry ice in the cargo compartment.

These reviews, analyses, and tests resulted in the following key findings:

- Past efforts have been directed at establishing and regulating dry ice limits on commercial aircraft based on the mass of dry ice carried (e.g., 200 kg per compartment on a certain aircraft). The technical and dimensional analyses found no theoretical basis for such mass limits.

- This project showed that there is a sound theoretical basis for limiting the number of packages containing dry ice in a cargo compartment using an area-normalized sublimation rate (which can be thought of as a mass flux).
- Heat transfer experiments showed that for packages having an insulation thickness of 38 mm (1.5 in.), the average area-normalized sublimation rate was $170 \text{ g/m}^2 \cdot \text{hr}$. This sublimation rate can also be used for insulated ULDs with active ventilation systems.
- The use of a dry ice package limit based on surface area represents a change in industry practice. Thus, provision would need to be made to develop the procedures and standards necessary.
- Currently, there are no standards for the amount of insulation required in dry-ice-containing packages or ULDs. Because sublimation rates can vary by a factor of 10 or more depending on the type and thickness of insulation (or lack thereof), the industry needs to consider implementing insulation standards regardless of any other changes. For most shippers, these insulation standards would merely codify common practice, but standards are needed to prevent hazardous situations.

Additionally, the project resulted in findings that support the key findings listed previously:

- A one-dimensional heat transfer model can adequately predict the sublimation rate of dry ice in both actively and passively cooled packages.
- Using the area-normalized sublimation rate and available ventilation data, it is possible to estimate the amount of dry-ice-cooled cargo that could be stowed in a ventilated cargo compartment without exceeding a carbon dioxide concentration ceiling. A carbon dioxide concentration limit of 30,000 ppm could be used for this purpose. A 30,000-ppm limit would meet the American Council of Governmental Industrial Hygienists (ACGIH) short-term (15-min) limit for human exposure, thus protecting baggage handlers; also, this limit is currently used for transport of animals in aircraft cargo compartments.
- Since packages with dry ice are frequently shipped in stacks with other packages, the area-normalized sublimation rate was determined for a package with dry ice surrounded by other packages containing dry ice and also for a package with dry ice surrounded by packages not containing dry ice. For an array of packages all containing dry ice, the array could be treated as one large package using the outer surface area for determination of the sublimation rate. When a package containing dry ice was surrounded by other packages not containing dry ice, the sublimation rate was about 20% less than the sublimation rate observed for an individual package containing dry ice. Thus, it would be conservative to use the sublimation rate for single packages even when they are shipped in stacks containing other packages containing no dry ice.
- During this project, it was not possible to measure the in-flight concentration of carbon dioxide in the cargo compartment containing dry ice packages. However, in-flight measurements in the passenger cabin of a Boeing 777 verified the manufacturer's statement that there is very little transport of ventilation air from the cargo compartment to the passenger compartment. These measurements showed that the passengers were not exposed to high levels of carbon dioxide when a significant quantity of dry ice was stowed in the cargo compartment.
- If packages containing dry ice are stowed in an unventilated cargo compartment, then the allowable quantity analysis should take into consideration the concentration buildup during the flight compared to the 30,000-ppm limit, and the analysis should also take into consideration the void fraction of the cargo compartment and the flight duration. A cargo compartment void fraction greater than 50% should not be assumed unless it can be demonstrated that there is actually that much void space in the cargo compartment. This report suggests using the flight duration used to estimate fuel requirements when assessing the carbon dioxide buildup in unventilated cargo compartments.

- This analysis and associated findings have not considered the off-normal situation where there is a loss of ventilation. In such circumstances, the cargo hold containing the dry ice would become equivalent to an unventilated cargo hold. Air carriers would have to address this situation in their off-normal operating procedures and in the extreme might have to establish the carbon dioxide limits assuming the cargo hold is unventilated.
- Periodic reviews of the rationale should be conducted to account for possible changes in aircraft configuration and operation.
- This analysis did not consider the carriage of dry ice on the smaller regional jets because the aircraft manufacturers did not provide any information on their ventilation systems.
- Even if carriers continue to use mass-based limits for dry ice carriage, it is important that they also implement package standards that establish a minimum heat transfer resistance for dry ice packaging being carried on their airplanes.
- In the dimensional analysis, a dimensionless term that was called the sublimation number was identified. It is defined as follows:

$$\text{Sublimation Number} = \frac{\Delta T}{R\lambda r_a}$$

where

R is the R value of the insulation, $\text{m}^2 \text{K/W}$,

λ is the heat of sublimation, kJ/kg ,

ΔT is the temperature difference, K , and

r_a is the sublimation rate expressed as $\text{kg/m}^2 \cdot \text{hr}$.

For the insulated packages that were modeled experimentally, the observed sublimation number was 3.4. A value similar to that number might be used as a package design standard to ensure that the package had sufficient insulation. Including a safety factor of 1.5, a sublimation number of 2.3 might be used for calculating compartment limits.

Important findings from HMCRRP Project 09:

- The production of carbon dioxide by sublimation is controlled entirely by transfer of heat to the dry ice, and the rate of heat transfer in turn is controlled by the temperature difference, the area available for heat transfer, and the R value of the insulation (the reciprocal of thermal conductivity of the insulation divided by its thickness).
- Since mass does not appear in any of the equations for heat transfer, the current mass-based sublimation rates are based on rules of thumb and cannot be derived from any theoretically developed set of equations.
- A dry ice sublimation rate based on package dimensional area is technically sound and is a good predictor of carbon dioxide production from packages containing dry ice.
- Thermal performance (amount of insulation) of packages and ULDs is important, and a specification for the thermal performance of both packages and ULDs is needed.

CHAPTER 1

Introduction

Project Background

Solid carbon dioxide, or dry ice, is widely used to keep perishable goods cold while in transit. Dry ice does not melt, but sublimates (meaning that it passes directly from the solid to the gaseous state) at a temperature of -78°C (-108°F). This combination of a cold temperature and lack of a liquid product from phase change makes it particularly suitable for temporary refrigeration of goods in transit.

Because dry ice produces gaseous carbon dioxide and because exposure to excessive amounts of gaseous carbon dioxide can present a health hazard, it has long been recognized that there is a need to specify limits on the amount of dry ice that is present in the passenger and cargo compartments of commercial aircraft. Many aircraft operators have established such limits.

Several recommendations and advisory circulars have been formulated to establish safe limits for the amount of dry ice that may be used on board aircraft. However, the tests and analyses used to develop these recommendations are in need of updating; some date back to 1963.

Although airframe manufacturers may provide some information or guidance on dry ice carriage limits, the ultimate responsibility rests with the air carrier. However, there is no requirement that air carriers document the engineering basis for the dry ice limits they use, and in some cases, different air carriers use quite different limits for the same airframe.

Thus, there is a concern that these recommendations and limits are based on information that is incomplete or dated, and there is a recognition that the entire topic of dry ice limits for aircraft needs to be reviewed and updated.

In order to address this need, the Hazardous Materials Cooperative Research Program authorized HMCRP Project 09, “Technical Assessment of Dry Ice Limits on Aircraft.”

Project Objectives and Scope**Objectives**

The objectives of the project were to develop an understanding of the parameters affecting the buildup of carbon dioxide on both passenger and cargo aircraft and to develop a tool or tools for operators of passenger and cargo aircraft to use in determining the maximum quantity of dry ice (solid carbon dioxide) that can be safely carried on board passenger aircraft or cargo aircraft.

Scope

A series of tasks were planned and executed that taken together would enable the overall project objective to be met.

The objective of Task 1 was to collect information developed by others either through experience in handling dry ice packages or through documented analyses of carbon dioxide buildup in passenger and cargo-only aircraft.

The objective of Task 2 was to identify the parameters affecting buildup of carbon dioxide in passenger and cargo-only aircraft. The parameters were identified by considering the physical and engineering understanding of heat transfer and dry ice behavior, as well as building on the information collected from Task 1.

The objective of Task 3 was to develop a topology of dimensionless parameters* using the equations governing the transfer of heat to the dry ice and subsequent sublimation of carbon dioxide from the packaging and transport through the airplane ventilation system.

*Dimensionless parameters are combinations of several individual parameters and provide a minimum set of parameters that have to be specified to model the carbon dioxide concentration in the airplane compartments.

The objective of Task 4 was to develop a test protocol that would provide data to identify which of the topology of variables must be specified, monitored, and controlled if airplane operators are to predict the buildup of carbon dioxide in passenger and cargo-only aircraft.

The objective of Task 5 was to collect high-quality, in-flight data on the parameters identified in Task 3. In particular, data were collected by making measurements of CO₂ concentrations on flight segments with a known amount of dry ice on board.

The objective of Task 6 was to analyze the data collected in Task 5. In particular, the relative importance of various parameters was estimated.

The objective of Task 7 was to develop a decision tool that provides simple rules for controlling the important parameters

identified in Task 6. The decision tool developed in Task 7 will enable the operator of a passenger or cargo-only airplane to decide when adding additional cargo on a specific type of airplane would result in too much dry ice being on board.

The purpose of Task 8 was to meet with stakeholders to present the proposed decision rules and their bases. The presentations made to the stakeholders were intended to demonstrate that the proposed decision rules are based on sound science and can be implemented by the airlines.

The objective of Task 9 was to revise the decision rules based on the stakeholder input obtained in Task 8.

The objective of Task 10 was to summarize the findings from each of the tasks, thereby accomplishing the overall objective of the project.

CHAPTER 2

Dry Ice

Properties of Dry Ice

Dry ice is unusual in that it sublimates at normal atmospheric pressures—that is, it passes directly from the solid to the gaseous state. This behavior occurs because the triple-point pressure is above atmospheric pressure. The phenomenon of sublimation is discussed in more detail in standard thermodynamic treatments of the properties of pure substances.¹

The first pound of dry ice for commercial refrigerating purposes was sold by the Dry Ice Corporation of America in 1925,² and by 1929, production was 15,000 tons per year. Dry ice has remained popular for the refrigeration of perishable goods during shipment.

Some properties of carbon dioxide and of dry ice are shown in Table 1. Because dry ice is made by compressing carbon dioxide snow, the bulk properties, particularly the density, are somewhat dependent on the details of manufacture and in particular on the degree of compression. Table 2 shows how some properties of solid and gaseous carbon dioxide that are important in heat transfer calculations vary with temperature.

Use of Dry Ice in Commerce

Forms of Dry Ice Used in Commerce

In commerce, dry ice is available in various forms. Figure 1 shows some of these forms. The ½-in. diameter pellets are commonly used for shipping packages. Cut blocks of dry ice are used for keeping the food and beverages served on aircraft cold.

Types of Air Cargos that Use Dry Ice

Shipments by air of cargo that uses dry ice tend to fall into two categories: foodstuffs and medical products.

Dry ice is often used for shipments of foodstuffs that must be kept cold, particularly steaks, ice cream, and other frozen or high-value foodstuffs. Sometimes these foodstuffs are bulk

shipments of food from producers to distant markets for distribution. In other cases, these are mail order shipments of gourmet foods from vendors to individuals. Because some vendors of mail order foods use large, centralized warehouses, large numbers of packages containing dry ice can be shipped from one airport, particularly during busy holiday seasons. Thus, it is possible that individual cargo aircraft may be called upon to ship large numbers of packages containing dry ice.

Dry ice is also extensively used for medical shipments, such as tissue samples and frozen or temperature-sensitive pharmaceuticals.

Packaging for Dry Ice Shipments

A variety of packaging is in common use for shipments containing dry ice; these are discussed in the following sections. A common element is the inclusion of insulation to help maintain the cold temperatures. However, the shipments differ not only in size and construction but also in the way the temperature is controlled.

Passively cooled shipments simply contain the cargo packed in dry ice and maintain the cargo at or near the sublimation temperature of dry ice (-78°C). Passive cooling is relatively simple and inexpensive to implement. However, passive cooling cannot be used for materials that would be harmed by cooling to -78°C .

Actively cooled unit load devices (ULDs) are available that control the temperature inside a container by placing the dry ice, frequently in block form, in a separate section in the container and using a temperature-controlled fan to circulate a mixture of carbon dioxide and air from the dry ice chamber to the cargo section of the container, thereby maintaining the temperature of the cargo at a set temperature. This temperature may be well above the temperature at which the dry ice is sublimating (-78°C). Medical products are often shipped in actively cooled packages because, while they must be maintained close to 0°C to maintain their shelf life, exposure to

Table 1. General properties of carbon dioxide and dry ice.

Property	Value
Color	White or translucent white
Molecular weight	44.01 ³
Density of gas (kg/m ³ at 1 atm, 25°C)	1.799 ⁴
Specific gravity of gas (air = 1)	1.53 ⁵
Density of solid (kg/m ³)	1355 ⁶ 1400 to 1600 ⁷
Specific gravity of dry ice (water = 1)	1.35 ⁸
Sublimes at (°C)	-78.48 ⁹
Latent heat of sublimation at -78°C (kJ/kg)	573 ¹⁰

-78°C would damage them. For example, many vaccines are recommended to be kept between 2°C and 8°C.

Insulated Cardboard Cartons

Insulated cardboard cartons are commonly used for shipping goods cooled with dry ice. They consist of a cardboard carton with an inside layer of expanded polystyrene (EPS) foam. Figure 2 shows a typical insulated shipping carton. Figure 3 shows an inside view and the EPS insulation. The cardboard carton is not an essential element of the package, and some packages do not have a cardboard carton. The major purpose of the cardboard carton is to protect the more fragile EPS.

The insulation value of EPS foam is known to vary with density, temperature, and the exact formulation. A manufacturer of EPS packaging has provided the data shown in Table 3.* This table shows the effect of EPS density and temperature on the thermal conductivity of EPS foam. Note that although there is some variation in thermal conductivity of EPS with both density and temperature, the variation is about 15% to 25%. Considering the other uncertainties in thermal conditions during transport, all EPS was considered to have approximately the same insulating value, and a value of 0.035 W/m K was used in all the thermal analyses presented in this report.

Cartons insulated with polyurethane foam are also available. These are more expensive but offer a lower rate of heat transfer—about 30% less than for EPS. Figure 4 shows a shipping carton insulated with polyurethane foam insulation.

ULDs

Larger shipping containers for cold cargos are also available. These are generally based on the standard ULDs that are used on larger aircraft to load baggage and freight. ULDs come in different sizes to accommodate different amounts of cargo and to fit the interior spaces in different aircraft. These ULDs may be passively or actively cooled. The passively cooled ULDs typically consist of a ULD with insulation inserted between the structural members; dry ice is packed with the cargo to provide cooling.

If active cooling is used, the ULD is insulated and divided into an auxiliary chamber and a main chamber. The auxiliary chamber contains blocks of dry ice; the other, larger chamber

Table 2. Properties of carbon dioxide vapor at atmospheric pressure.¹¹

Temp., °C	Temp., K	Pressure, kPa	Density, kg/m ³	Enthalpy, kJ/kg	Specific Heat, kJ/kg K	Thermal Conductivity, mW/m K	Kinematic Viscosity, μPa·s	Thermal Diffusivity, cm ² /s	Prandtl Number
-55	218.15	101.33	2.494	440.8	0.780	10.78	10.97	0.0554	0.793
-50	223.15	101.33	2.436	444.7	0.783	11.11	11.22	0.0582	0.791
-40	233.15	101.33	2.327	452.5	0.791	11.77	11.72	0.0640	0.787
-30	243.15	101.33	2.228	460.5	0.799	12.46	12.22	0.0700	0.784
-18	255.15	101.33	2.120	470.1	0.810	13.32	12.82	0.0776	0.779
-10	263.15	101.33	2.054	476.7	0.817	13.92	13.22	0.0829	0.776
0	273.15	101.33	1.977	484.9	0.827	14.67	13.71	0.0898	0.773
10	283.15	101.33	1.906	493.2	0.836	15.45	14.20	0.0969	0.769
20	293.15	101.33	1.839	501.6	0.846	16.24	14.69	0.1044	0.765
30	303.15	101.33	1.778	510.1	0.856	17.05	15.17	0.1121	0.762
40	313.15	101.33	1.720	518.7	0.865	17.86	15.66	0.1200	0.758
50	323.15	101.33	1.666	527.4	0.875	18.69	16.13	0.1282	0.755

*The source data have been converted to SI units.



High-Density Dry Ice Pellets

- 1/8-in. diameter dry ice pellets for use in dry ice blast cleaning systems.



Dry Ice Rice Pellets

- 1/4-in. diameter dry ice pellets.
- Used primarily in frozen food applications.



Dry Ice Standard Pellets

- 1/2-in. diameter dry ice pellets.
- Used primarily in frozen food applications.
- Used in meat processing plants.
- Used for transportation of blood plasma and lab specimens.



Dry ice pellets are available wrapped in poly or brown Kraft paper.

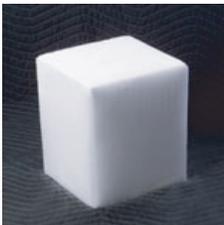


Cut Blocks of Dry Ice

- Dry ice available in custom sizes processed and packaged to customer specifications.
- Dry ice may be wrapped in Kraft paper or in poly.



Cut blocks of dry ice are available wrapped in poly or brown Kraft paper.

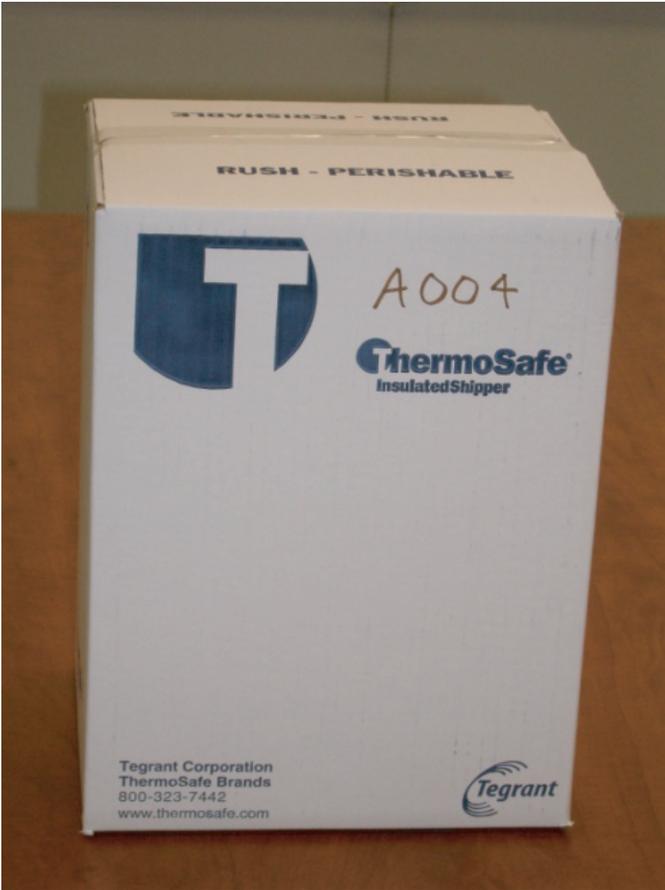


Block of Dry Ice

- Standard dry ice block measures 10 in. x 10 in. x 12 in.
- Approximately 60 lbs each.
- Used for frozen food applications, especially in shipping ice cream.
- Used in grocery warehouses.

Figure courtesy Continental Carbonic, Inc. Used with permission.

Figure 1. Forms of dry ice available for sale.¹²



Battelle photo

Figure 2. Typical insulated shipping carton.



Battelle photo

Figure 3. Inside view of insulated shipping carton.

Table 3. Thermal conductivity of expanded polystyrene foam.¹³

Density, kg/m ³	Temperature, °C	k, W/m K
16	-18	0.0317
16	4	0.0346
16	24	0.0375
16	38	0.0404
32	-18	0.0288
32	4	0.0303
32	24	0.0332
32	38	0.0361



Battelle photo

Figure 4. Insulated shipping carton with polyurethane foam insulation.



Figure 5. Photo of an insulated ULD.

contains the cargo. An electronic temperature controller and an associated battery-powered fan are used to monitor the temperature of the cargo in the ULD and to circulate cold gas from the dry ice chamber into the cargo section to maintain a desired temperature set point. Figure 5 shows one such insulated ULD.

The ability to consolidate many cold cartons within a single ULD, even if it is not insulated, can also be an important strategy for limiting overall heat transfer to the cartons: keeping the cold packages together reduces the overall surface area that is available for heat transfer.

CHAPTER 3

Review of Guidelines and Regulations for Dry Ice Shipments

Carbon Dioxide Exposure Limits

The product of sublimation of dry ice is gaseous carbon dioxide. Carbon dioxide is, of course, a natural component of human, animal, and plant metabolism and is a normal constituent of the atmosphere, which contains approximately 390 ppm* of carbon dioxide.

Exposure to high concentrations of carbon dioxide gas, above 5%, can cause asphyxiation. Since carbon dioxide is much more dense than air, it will settle in low spaces over time, and entry into the area when the carbon dioxide has collected can also result in asphyxiation. However, there are other health considerations as well.

The concentration of carbon dioxide gas in the lungs is an important factor in regulating human respiration, and therefore concentrations lower than those required for asphyxiation are harmful. If the concentration of carbon dioxide is 1% (10,000 ppm), a healthy individual will experience tiredness and fatigue. As the concentration builds, the heart rate and breathing rate increase. At 2%, these healthy individuals tend to feel heaviness in the chest and experience deeper respirations. At 3%, the breathing rate and heart rate double, and double again as the concentration reaches 5%. At concentrations above 5%, some individuals can become unconscious and die if not removed from the high carbon dioxide concentration. If a person is doing strenuous activities, such as loading or unloading baggage or cargo, the effects will occur at lower carbon dioxide concentrations.

General Industrial Exposure Limits

The American Council of Governmental Industrial Hygienists (ACGIH) has set workplace exposure limits for

*This value is for remote areas or high altitudes. The concentration of carbon dioxide in the lower atmosphere shows a spatial variation according to the proximity to human activity or vegetation; the latter results in diurnal and seasonal variations.

carbon dioxide. Their limits are an 8-hour time-weighted average (TWA) of 5,000 ppm, and a 15-min short-term exposure limit (STEL) of 30,000 ppm.¹⁴ The Occupational Safety and Health Administration (OSHA) personal exposure limit (PEL) is also 5,000 ppm.¹⁵

Carbon Dioxide Exposure Limits for Aircraft

The carbon dioxide concentration limit for aircraft was established by the FAA, and information on how this limit was determined has been summarized by the U.S. Department of Transportation (DOT) in a published notice entitled “Allowable Carbon Dioxide Concentration in Transport Category Airplane Cabins, Final Rule.”¹⁶ In this document the FAA sets a carbon dioxide exposure limit of 5,000 volume ppm.

The FAA document also summarizes the guidelines and limits on carbon dioxide concentrations as set by various other organizations. For convenience, these limits are summarized in Table 4. The FAA also provides a definition of the *sea-level equivalent* measurement conditions associated with the FAA carbon dioxide limit.¹⁷ These conditions are 25°C and 760 mm of mercury pressure.*

This project uses the carbon dioxide limit already established by the FAA. It is beyond the scope of this project to provide a critical evaluation of the FAA limit, an analysis of its basis, or a comparative analysis or critique of the FAA carbon dioxide limits with limits set by other organizations.

As a side note, in their discussion of indoor air quality, OSHA recommends an indoor carbon dioxide limit and states that “1000 ppm [of carbon dioxide] indicates inadequate ventilation; complaints such as headaches, fatigue, and eye and throat irritation will be more widespread; 1,000 ppm should be used as an upper limit for indoor levels.”¹⁸ However, this limit is based on the use of elevated levels of carbon dioxide as a surrogate for other air contaminants and as an indicator

*In SI units, 760 mm of mercury pressure equals 101.325 kPa.

Table 4. Carbon dioxide exposure limits.

Organization	Limit in Volume, %	Limit in Volume, ppm
OSHA interim rule	0.5	5,000
OSHA final rule	1.0	10,000
ACGIH short-term exposure limit (15 min)	3.0	30,000
ACGIH 8-hour threshold limit value	0.5	5,000
FAA	0.5	5,000

of a general lack of ventilation of occupied spaces and does not address the health effects of the carbon dioxide itself or the situation where the carbon dioxide in the occupied space results from dry ice sublimation.

Dry Ice Packaging Requirements

ICAO and IATA Packaging Requirements

The International Civil Aviation Organization (ICAO) provides instructions for shipments containing dry ice. The International Air Transport Association (IATA) follows the ICAO instructions.

General Requirements

Under ICAO instructions, packages containing dry ice are designated as “Class 9 miscellaneous.”

The UN packing group is III. This is a low-hazard classification. The maximum net quantity of dry ice per package is 200 kg for both passenger and cargo aircraft. In addition, the packaging must be designed to allow the carbon dioxide generated to vent from the package and thereby not pressurize the package.

Shipments of Dry Ice in Packages

ICAO provides the following special packing instruction (No. 904) for shipments of dry ice in packages:¹⁹

Solid carbon dioxide (dry ice) in packages when offered for transport by air must be packed in accordance with the general packing requirements of Part 4, Chapter 1 and be in packaging designed and constructed to permit the release of carbon dioxide gas to prevent a build-up of pressure that could rupture the packaging. Arrangements between shipper and operator(s) must be made for each shipment, to ensure that ventilation safety procedures are followed. The dangerous goods transport documentation requirements of Part 5, Chapter 1 are not applicable provided alternative written documentation is supplied describing the contents. The information required is as follows and should be shown in the following order: UN 1845, (Dry ice or Carbon

dioxide, solid), class 9 (the word “class” may be included prior to the number “9”), the number of packages and the net quantity of dry ice in each package. The information must be included with the description of the goods. The net mass of the Carbon dioxide, solid (Dry ice) must be marked on the outside of the package.

The general packing requirements of “Part 4, Chapter 1” that are referred to are somewhat lengthy, but generally call for sturdy packaging that can withstand the rigors of shipment.

Bulk Shipments and Larger Shipping Containers

In the case of bulk shipments, the ICAO instruction No. 904 provides that:

Dry ice used as a refrigerant for other than dangerous goods may be shipped in a unit load device or other type of pallet prepared by a single shipper provided that the shipper has made prior arrangements with the operator. In such case, the unit load device, or other type of pallet must allow the venting of the carbon dioxide gas to prevent a dangerous build-up of pressure. The shipper must provide the operator with written documentation stating the total quantity of the dry ice contained in the unit load device or other type of pallet.

The ICAO instructions also contain “notified variations from the instructions.” This section contains official notifications* of state variations. There is one such variation for Continental Airlines, number CO-9.²⁰ This variation states:

- The carriage of UN 1845 — Carbon dioxide, solid (dry ice) will be limited to the following established limits:
- all narrow-body aircraft (B737, B757, ERJ) – 114 kg per aircraft;
 - all wide-body aircraft (B767, B777) – 200 kg per aircraft.

*Note that these are notifications only. ICAO is not evaluating or approving the variation.

Exception: Due to the limited sublimation rate of dry ice when carried in “refrigerated/insulated” containers, the following quantities of dry ice may be carried in any containers with the carrier code “PC” or any containers with the prefix code “R”:

B777-200 – 1,088 kg
 B767-400 – 816 kg
 B767-200 – 635 kg
 B757-200 – 590 kg
 B757-300 – 725 kg
 B737-(all series) – 430 kg

The above container limitations are per aircraft.

Note: The carrier code “PC” is used for Air Fiji, Ltd. Containers with the prefix code “R” are “Thermal Certified Aircraft Containers” and include the RKN- and RAP-size ULD containers. Our understanding of this exception is that it applies only to ULDs shipped on Continental Airlines/Air Fiji.

DOT Regulations for Dry Ice Packaging

The Pipeline and Hazardous Materials Safety Administration (PHMSA) places the following requirement on dry ice packaging:

173.217 Carbon dioxide, solid (dry ice). (a) Carbon dioxide, solid (dry ice), when offered for transportation or transported by aircraft or water, must be packed in packagings designed and constructed to permit the release of carbon dioxide gas to prevent a buildup of pressure that could rupture the packagings. Packagings must conform to the general packaging requirements of subpart B of this part but need not conform to the requirements of part 178 of this subchapter.

Note that the requirement is on venting and not the concentration of carbon dioxide in the compartment following the release. Requirement 173.217(b), “Transport by Aircraft,” specifies the requirements that must be met when dry ice is used as a refrigerant in packages offered for shipment on aircraft. The requirements in this section exempt the shipping paper requirements of Part 172 Subpart (c) provided written documentation containing the following information is supplied: the proper shipping name of “Dry Ice or Carbon Dioxide, solid, class 9, UN 1845,” the number of packages and the net quantity of dry ice in each package, and the description of the refrigerated material being shipped. Such packages are also exempt from 49 CFR Part 178, “Specification of Packagings.” Provided the requirements in 173.217(a) quoted previ-

ously are met, packages containing less than 2.5 kg of dry ice are exempted from all DOT packaging requirements.

FAA and NTSB Guidelines

An early FAA advisory circular, issued in 1974, discussed the hazard from carbon dioxide from dry ice and presented a method of determining the maximum allowable amount of dry ice. This document recommends using a 5,000-ppm maximum carbon dioxide concentration and a weight-based sublimation rate of 1% per hour.²¹ Although there have been subsequent notifications and publications, the mass-based sublimation-rate methodology and associated assumptions have not changed.

The FAA later issued another advisory circular that echoed the 1974 document.²² This circular was updated in May of 2009 to change the amount of CO₂ made by the sublimation of 1 pound of dry ice from 8.5 to 8.8 cubic feet.²³ Given the other uncertainties in the estimation of carbon dioxide concentrations on aircraft, this difference is not significant.*

In 2000 the FAA issued an advisory circular that addressed ventilation requirements for crew and passengers but did not directly discuss the use of dry ice.²⁴ One significant point from this document is that, as part of the discussion of ozone levels, the FAA established an official standard temperature and pressure to be used for gas concentration calculations, namely a temperature of 25°C and a pressure of 760 mm of mercury.[†]

In 2001, the National Transportation Safety Board (NTSB) issued a safety recommendation in response to a 1998 incident in Texas.²⁵ In this incident, the crew of a cargo aircraft became short of breath after being exposed to an excessive amount of carbon dioxide from a shipment consisting of 198 packages of frozen shrimp, each containing 2.2 kg of dry ice, for a total of 436 kg of dry ice on the DC-8-51 cargo airplane. The incident occurred after a ground delay without provision for adequate ventilation.

More recently, in 2006, the FAA issued a report with data on measured dry ice sublimation rates.²⁶ Although this report will be discussed in more detail later, the document may be summarized by noting that this report retained the original 1974 recommendation to use a mass-based percentage sublimation rate to determine the amount of dry ice.

*This number is discussed in Chapter 9; in particular, see Table 8.

†Equivalent to 101.325 kPa.

CHAPTER 4

Review of Aircraft Manufacturer Guidelines and Procedures

There are two principal manufacturers of full-sized jet aircraft: Airbus and Boeing. Battelle contacted both manufacturers to obtain information relevant to the carriage of cargo containing dry ice and the determination of limits for the use of dry ice on board aircraft.

Information from Airbus

Airbus has a publication that addresses in detail the carriage of dry ice.²⁷ The publication reviews the Airbus understanding of applicable technical information and regulations related to carbon dioxide and dry ice. Although this publication does not provide an Airbus-approved limit for the amount of dry ice that can be carried, it does examine the technical and regulatory basis for setting such limits and the method for calculating them. This publication also provides data on the cargo compartment volumes and ventilation rates for various Airbus aircraft.

The Airbus guidance proposes that the maximum concentration in the cargo hold not exceed 5,000 ppm. Two methods of setting limits on the mass of dry ice are proposed, one for ventilated cargo holds and one for unventilated cargo compartments.

For ventilated cargo compartments, two situations are considered: one where the aggregate quantity of dry ice in the compartment is less than 45 kg, and one where a single package contains more than 45 kg.

If the aggregate quantity of dry ice is less than 45 kg, the assumed sublimation rate, based on the initial inventory, is 2% per hour. If the quantity of dry ice in the single package is greater than 45 kg, a sublimation rate of 1% per hour is assumed. The assumed sublimation rate is then used in conjunction with the number of air exchanges per hour and the volume of the compartment to ensure that the final concentration in the cargo compartment does not exceed 5,000 ppm.

For an unventilated cargo compartment, the total volume of carbon dioxide generated over the duration of the flight

must be limited to the volume of the cargo compartment times 0.005, representing a final concentration of 5,000 ppm.

Overall, the Airbus guidance recommends using 200 kg of dry ice per cargo compartment as a general limit. However, since any limit is the sole responsibility of the operator, Airbus notes that the operator can have a written agreement with a shipper for a different limit.

Information from Boeing

Boeing has prepared general information that describes the operation of the environmental control system (ECS) on Boeing aircraft.^{28, 29} With regard to carriage of dry ice, Boeing has prepared a presentation on the calculation of allowable dry ice loads³⁰ and a more recent service letter with recommended allowable dry ice carriage limits.³¹

The Boeing presentation contains an equation for the calculation of acceptable dry ice loads based on the mass of dry ice and a mass-based sublimation rate; the calculation takes into account the carbon dioxide generated by the occupants in the passenger cabin. It also conservatively assumes that all of the carbon dioxide generated from sublimation of shipments of dry ice is distributed to the passenger cabin.

The Boeing service letter presents additional information in the form of graphs showing the maximum suggested dry ice load for various aircraft models and for various assumed sublimation rates in percent of weight per hour. The service letter also suggests different sublimation rates based on the type of packaging. For example, for a 23-kg (50-lb) block of dry ice wrapped in paper and exposed to an ambient temperature of -18°C , a sublimation rate of 2% per hour is suggested; if the ambient temperature condition is increased to 24°C , the recommended rate is 3% per hour.

A sublimation rate of 3% per hour is also used if the same size dry ice block, but without any insulation, is exposed to an ambient temperature of -18°C . The rate increases to 4% per hour if the ambient temperature is 0°C , and to 6% at 24°C .

In addition to presenting graphs of the mass limits for different assumed sublimation rates, Boeing presents additional curves according to the number of air conditioning packs operating.

To give one example, according to the Boeing graphs, for a 1% sublimation rate, the maximum dry ice load on a 757 passenger aircraft is 725 kg; on a 757 freighter the maximum dry ice load is 2,835 kg. If the sublimation rate were 2%, then the maximum dry ice load limits would be cut in half.

As with Airbus, Boeing provides guidance but states that it is the responsibility of the carrier to establish dry ice limits for their airplanes.

Information on Regional Jets

Regional jets are smaller than full-sized aircraft and have correspondingly smaller cabins and cargo compartments. Bombardier and Embraer are the two principal manufacturers of regional jets.

Both Bombardier and Embraer were contacted as part of this study, but neither elected to provide information.

Because of their small size and the limited amount of cargo-carrying capacity, regional jets do not carry much freight, and the question of dry ice limits for such aircraft was judged to be of secondary importance.

CHAPTER 5

Review of Air Carrier Procedures for Shipments Containing Dry Ice

Major air carriers were interviewed to ascertain their policies and procedures for shipments containing dry ice.

Packaging Requirements for Air Shipments Containing Dry Ice

General IATA packaging requirements were discussed in Chapter 3. It is possible for individual air carriers to impose additional packaging requirements.

Procedures for the Tender of Dry-Ice-Containing Packages

Packages Tendered by Companies and Shipping Agents

Large shippers may tender cargos directly to airlines; smaller concerns often use shipping agents. In either case, the shipper prepares documents that describe the amount of dry ice.

Anecdotal evidence suggests that the stated weight of dry ice may not be derived from an actual weight on a scale, but is often merely an estimate or is based on memory from previous shipments and could vary from the actual tendered weight.

Packages Tendered by Individuals

On Passenger Aircraft

Personal shipments containing dry ice may be carried on board aircraft as carry-on luggage or tendered as checked baggage. The shipments typically contain less than 2.5 kg (5.5 lbs) of dry ice, thereby avoiding the requirement to place a placard on the package. Carry-on luggage or checked baggage containing dry ice may or may not be required to be declared to the airline and the passenger may or may not

actually make the required declaration; for both carry-on luggage and checked baggage, the air carrier depends on the customer to declare the presence and the quantity of dry ice contained in the package.

In both cases, the quantity of dry ice accepted by an agent is not added to the hazardous material manifest given to the pilot so there is no way to account for the dry ice shipments received at check-in or transferred onto the plane as checked baggage unloaded from another plane.*

However, the practicalities of air travel (the need to carry baggage and personal effects combined with limited onboard storage space) and the fees charged by some airlines for carrying dry ice on board† will discourage many from carrying packages containing dry ice on board; overall, however, the amount of dry ice brought on board by passengers is not likely to be very significant.

Assuming that at most 10% of passengers would have packages that might contain dry ice, for a plane carrying 150 passengers, there would be at most 15 packages, each containing 2.5 kg of dry ice, resulting in a total of 38 kg of dry ice that might be present on a large airplane.

On Cargo Aircraft

Shipments from individuals that contain dry ice might also be carried on all-cargo aircraft. However, due to U.S. Transportation Security Administration (TSA) requirements, the ability of individuals to ship packages directly via air freight is greatly restricted.‡ In fact, nearly all such

*It is also possible, but unlikely, that the last-minute placement of gate-checked luggage in the cargo compartment could result in additional dry ice in the cargo compartment.

†Such fees range from \$40 to \$100 per package.

‡This discussion would also apply to individuals making a freight shipment with the air freight division of a passenger air carrier.

parcels are tendered to a package shipping firm such as UPS or FedEx. In this case, shipments containing less than 2.5 kg of dry ice are merely labeled as containing dry ice; shipments with more than this amount must be shipped as hazardous goods, with the amount of dry ice stated on the shipping documents.

With regard to acceptance of a package containing dry ice for shipment on cargo aircraft at a storefront package shipping service location, we note that:

- The store employees are generally not trained in handling hazardous materials, so they cannot accept any packages containing more than 2.5 kg of dry ice—the regulatory threshold for requiring a placard on the package;
- They depend on the customer to declare the presence and quantity of dry ice in a package; and
- The main materials shipped by individuals that are cooled with dry ice are specialty and gourmet foods such as ice cream, pizza, and steaks.

Again, anecdotal evidence suggests that the stated amount of dry ice is often merely an estimate and could vary from the actual amount.

Aircraft and Compartment Limits

Each air carrier must establish limits on the amount of dry ice that can be carried on the aircraft and also for individual compartments. The current determination of limits varies somewhat among air carriers, but commonly, there is a simple limit on the mass of dry ice that may be carried, either by compartment, for the aircraft as a whole, or both.

These limits are generally based on assumptions about the sublimation rate of the dry ice and the ventilation capabilities of the aircraft. Air carriers may use either their own calculations or follow a calculation procedure suggested by the aircraft manufacturer. In either case, the air carrier has the final responsibility to ensure that the FAA guideline of 5,000-ppm carbon dioxide concentration for occupied spaces is met. In most cases these calculations are based on assumed mass-based sublimation rates.

Some air carrier limits reported to Battelle during the course of this study are summarized in Table 5. In addition to aircraft limits, some carriers have established limits for individual compartments.

While the examples listed do not show all the many airframes operated by different carriers, it can be seen that the limits for the 737 vary from 82 kg to 400 kg. Clearly, different carriers are making different assumptions when establishing the carbon dioxide limits.

Table 5. Some air carrier limits for dry ice.

Airline	Aircraft	Aircraft Limit, kg ^a
Alaska Airways	737	82
	737+ F	318
	737F	500
	CRJ,Q400	200
American ^b	737	400
	757	544
	767	590
	777	680
	A300	907
	MD80	600
	CRJ, ERJ	23
FedEx	727	1,080
	757	900
	777	2,100
	A300	3,031
	A310	2,532
	MD10/11	2,744
Southwest ^c	737	400
United/Continental	narrow body	114
	wide body	200
Military Aircraft (according to TM 38-250 ³²)	C130	272
	C135	91
	KC10	1,041
	C5	2,131

^a For consistency, all limits have been converted to kg, even if they were originally stated in pounds.
^b The amount of dry ice carried on by passengers is tracked, but there is no specific limit.
^c The amount of dry ice carried on by passengers is not tracked.

Special Loading, Unloading, and Location Procedures

In addition to overall limits on the mass of dry ice carried, some air carriers have special procedures.

Considerations Related to Transport of Animals

Many airlines have established specific procedures to ensure that if animals are being shipped, they are not exposed to high levels of carbon dioxide. The airlines may establish lower compartment limits for dry ice shipments, a prohibition of animals and dry ice in the same compartment, or, if there is more than one compartment on the aircraft, a requirement that either the animals or the dry ice be carried in a specific compartment. Some airlines, notably Southwest Airlines, do not

carry any animals in the cargo compartment. UPS carries some live animals but does not transport mammals.

Unloading

Air carriers recognize that situations may occur where unusually large amounts of dry ice are present in a cargo compartment and/or that the compartment has been without active ventilation for a period of time. If this is the case,

some carriers have procedures that call for waiting a period after opening the compartment before cargo handlers enter the compartment to unload the cargo.

Location and Climate

Likewise, some carriers have more stringent procedures for handling cargo with dry ice if the local climate is very hot.

CHAPTER 6

Dimensional Analysis of Dry Ice Sublimation

Dimensional Analysis for Heat Transfer

Even without doing experiments or heat transfer calculations, dimensional analysis can provide insight into the variables that govern carbon dioxide production. First, it is important to realize that for a given amount of dry ice, the sublimation rate* is entirely determined by the rate of heat gain. Once heat reaches the dry ice, the dry ice sublimates and the gaseous carbon dioxide leaves quickly through a bulk flow of gas. (A more detailed discussion of the importance of heat transfer is presented in Chapter 7.)

The equations governing steady-state heat transfer are frequently expressed in terms of dimensionless numbers. For the analysis of heat transfer from the air to the outer surfaces of the packaging, there are three major dimensionless numbers: the Prandtl, Nusselt, and Grashof numbers. The Nusselt number governs convective heat transfer, and the product of the Grashof and Prandtl numbers, also called the Rayleigh number, governs buoyant convective heat transfer. The definitions are:

$$\text{Prandtl Number} = \frac{C_p \mu}{k}$$

where

C_p is the specific heat, kJ/kg · °C,
 μ is the kinematic viscosity, N·s/m² or kg/m · s, and
 k is the thermal conductivity, kJ/m · s · °C.

$$\text{Nusselt Number} = \frac{hL}{k}$$

*By sublimation rate is meant the mass of dry ice per unit time that changes from a solid to a gas. In SI units, this would be grams or kilograms of dry ice per hour.

where

h is the heat transfer coefficient, J/cm² · s · °C,
 L is the characteristic length of the surface, cm, and
 k is the thermal conductivity, kJ/m · s · °C.

$$\text{Grashof Number} = \frac{L^3 \rho^2 \beta_g \Delta T}{\mu^2}$$

where

β is the thermal expansion coefficient, 1/°C,
 ΔT is the temperature difference between the surface and the bulk fluid, °C, and
 g is the acceleration due to gravity = 9.8 m/s².

Because the Grashof and Prandtl numbers are often used together, the Rayleigh number is defined by:

$$Ra = Gr Pr$$

This latter parameter is used to estimate the value of h for the outer surface of the package. When estimated in this way, h is proportional to the product of the Grashof and Prandtl numbers taken to the ¼ power.

Probably more important for sublimation is the dimensionless number that is formed by expressing the sublimation rate of the dry ice as a function of the rate of heat transfer through the insulation and rearranging the equation to make the resulting equation dimensionless:

$$\text{Sublimation Number} = \frac{kL^2 \Delta T}{t \lambda_s r} = \frac{\Delta T}{R \lambda_s r_a}$$

where

λ is heat of sublimation, kJ/kg,
 t is the thickness of the insulation, m,
 r is the sublimation rate, kg/s,
 L^2 is the total surface area of the package, m², and
 ΔT is the temperature difference between the sublimation temperature and the ambient temperature, °C.

In the equation, if r is expressed in terms of kg/hr, then the conversion factor of 3,600 s/hr must be included to keep the value of the sublimation number dimensionless. The sublimation number can be modified slightly by combining the rate and area term into an area-normalized loss rate term. That modification is also shown in the second expression, where r_a is an area-normalized loss rate (kg/m² · hr). In addition, since t/k defines the R number for the insulation, the sublimation number can be simplified even more. Since the temperature difference and the amount of energy required to sublime a kilogram of dry ice are constants, the only terms that can be controlled are the dimensional terms and the reciprocal of the thermal conductivity divided by the thickness of the insulating barrier—the R value of the insulation.

Dimensional Analysis for Ventilation Flow

There is another part of the dimensional analyses that is related to the flow of air through a compartment. That equation is first expressed with dimensional terms, and then terms are combined to make the equation dimensionless.

First, the dimensional case:

$$C_{in}F_{in}\rho_{CO_2} + E_pN_p + fr_aL^2 + E_cN_c = C_{out}F_{out} = C_{out}F_{in}\rho_{CO_2}$$

In the equation, F is the volumetric flow rates in and out, and since the airplane pressure is maintained at a constant, the volume flow in must equal the flow out, the volume associated with the generation of carbon dioxide being neglected. The second term is the emission rate from a passenger, E_p , times the number of passengers, N_p . Then we have the emission rate from the dry ice packages expressed as r_a times their total area L^2 times the fraction of in leakage from the cargo compartment f . The final term is the emission rate from any carts using dry ice, E_c , times the number of such carts, N_c . For the purposes of dimensional analysis, these three terms can be combined into one term, the emission rate in the passenger cabin, R_c . Thus, in dimensionless terms, the two terms are:

C_{out}/C_{in} and $R_c/C_{in}F_{in}\rho_{CO_2}$, as shown in the following equation:

$$\frac{R_c}{C_{in}F_{in}\rho_{CO_2}} = \frac{C_{out}}{C_{in}} - 1$$

Since C_{in} is currently equal to a volume or mole fraction of 0.00039 or 390 ppm, if C_{out} is the FAA regulatory limit of 5,000 ppm (mole fraction 0.005), then the production rate of carbon dioxide in the main cabin divided by the rate of carbon dioxide entering into the ventilation system with the outside air, $R_c/C_{in}F_{in}\rho_{CO_2}$, cannot be greater than 11.8. This

equation can be rearranged to express the limit in terms of air exchanges per hour. The resultant equation is:

$$\frac{R_c}{C_{in}F_{in}\rho_{CO_2}} = \frac{R_c}{C_{in}ACH V_{comp}\rho_{CO_2}} = 11.8.$$

The second expression expresses the inlet volumetric flow in terms of the air exchanges per hour (ACH) and the volume of the compartment, V_{comp} . Once again, note that the mass of dry ice in the aircraft does not appear in either form of this equation.

The FAA CO₂ concentration limit of 5,000 ppm is for areas occupied by passengers and crew. When packages containing dry ice are shipped, most are placed in the cargo compartment areas of the airplane. Some air carriers use a 30,000-ppm CO₂ limit for cargo compartments containing live animals. If this limit were used for ventilated cargo compartments containing dry ice packages, then the equation becomes:

$$\frac{R_c}{C_{in}F_{in}\rho_{CO_2}} = \frac{R_c}{C_{in}ACH V_{comp}\rho_{CO_2}} = 75.9.$$

Using this higher limit for areas not used by passengers or crew results in an allowed production rate of CO₂ that is more than six times the total CO₂ production rate allowed in the passenger cabin.

Discussion of Dimensional Analysis Results

It is believed that the sublimation number can be used to describe any carbon dioxide release rate from packages. If this is the case, then parameters such as thermal conductivity of the package, the area available for heat transfer, and the difference between the temperature inside the package and the outside ambient temperature are all important variables; the mass of dry ice does not appear in any of the equations. On the other hand, the equations do contain an area term that is a measure of the size of the package. Using a sublimation rate based on the mass of dry ice in a package is not supported by the dimensional analysis and does not make technical sense.

It is recognized that the mass of dry ice has been used for setting aircraft limits for decades. While it is in none of the equations, why might it still be an effective limit? One observation is that most packages are loaded so that they can maintain the desired internal temperature for several days, and such a thermal performance rate is easily attained with standard EPS insulation. The generous use of EPS is the underlying assumption behind much of the dry ice loading—using this much insulation can provide a large factor of safety, making the use of mass loss rates acceptable.

CHAPTER 7

Heat Transfer and Carbon Dioxide Production

This chapter considers carbon dioxide production and focuses on the effect of heat transfer on carbon dioxide production; Chapter 9 considers ventilation and the removal of carbon dioxide through ventilation.

Rationale for Basing Dry Ice Limits on Heat Transfer Analysis

Cargo and packages that contain dry ice are sources of carbon dioxide gas. The carbon dioxide gas is given off when the dry ice sublimates.

The sublimation rate* is determined by the rate of heat gain. Once heat reaches the dry ice, it sublimates and the gaseous carbon dioxide leaves quickly through a bulk flow of gas. Thus, the dry ice sublimation rate is determined solely by the transfer of heat to the dry ice and is not limited by the transfer of carbon dioxide away from the surface. Therefore, understanding the dry ice sublimation rate requires an understanding of the rate of heat transfer.

The rate of heat transfer is in turn determined by the packaging or container specifications and design, as well as by the ambient conditions. In this section we examine calculated heat transfer rates. The objective of the heat transfer calculations is to provide an estimate of the amount of heat energy transferred per unit of time.†

The rate of heat transfer and the resulting dry ice sublimation rate are related through the heat of sublimation, which for dry ice is 573 kJ/kg. If we know the rate of heat transfer, we can do a simple calculation to convert to an equivalent dry ice sublimation rate, also called the dry ice loss rate. For example, a heat transfer rate of 100 watts is equivalent to a dry ice loss rate of 630 g/hr, and a dry ice loss rate of 1 kg/hr is equivalent to a heat transfer rate of 160 watts (J/s).

*By sublimation rate is meant the mass of dry ice per unit of time that changes from a solid to a gas. In terms of SI units, this would be grams or kilograms of dry ice per hour.

†In common SI units, this would be joules per second, or watts.

Review of Existing Information on Heat Transfer to Cold Cargo

Insulated Cardboard Cartons Containing Dry Ice

The manufacturers of insulated packages do not provide any detailed heat transfer performance characteristics of their packages. When this was discussed with the package manufacturers' sales representatives, they said it was the shipper's responsibility to ensure that the proper quantity of dry ice was added to the package. Several package manufacturers stated that they had a testing laboratory and that if the shipper requested, they could do a performance testing experiment, for a fee, which consisted of loading a given quantity of dry ice in a package and measuring the internal temperature as a function of time. Some would vary the ambient temperature for a few hours to simulate a higher ambient temperature, perhaps for the time between when the package leaves the air-conditioned cargo handling facility and when the package is loaded on the aircraft and the ventilation system is turned on. These simple experiments were done in lieu of any heat transfer modeling. There is an ASTM standard for such tests,³³ though it is not clear how widely it is used.

Some organizations, such as universities whose staff may frequently need to ship packages containing dry ice, have developed their own internally produced guidelines.^{34, 35, 36} The origin and basis for the guidelines in the publications are generally obscure and probably based on rules of thumb gained through experience.

Insulated ULDs Containing Dry Ice

Discussions with two manufacturers of insulated ULDs indicated that they had done heat transfer analyses but considered the results of those analyses to be proprietary.

Other Cold Cargo

There is a limited amount of technical literature on heat transfer modeling of cold packages in transit.³⁷ For example, Kumar and Panigrahi modeled frozen fish placed in polyform-insulated cardboard cartons.³⁸

Heat Transfer Calculations

Heat Transfer to Packages

As long as the thickness of the insulating material is much less than the dimensions of the sides of the package, the steady-state heat transfer rate can be modeled using the following equation:

$$Q = UA\Delta T$$

where

Q = rate of heat transfer, W,

U = overall heat transfer coefficient, W/m² K,

A = package area, m², and

ΔT = temperature difference between dry ice sublimation temperature and cargo bay temperature, K.

The overall heat transfer coefficient U can be broken into components by considering the reciprocal of the coefficient to be a resistance that is made up of several resistances to heat transfer: one at the outside wall, another through the insulation, a third at the inside wall, and if necessary, the resistance at the surface of the dry ice. These individual resistances are normally expressed as shown by the following equation:

$$\frac{1}{U} = \frac{1}{h_o} + \frac{x_c}{k_c} + \frac{1}{h_g} + \frac{x_f}{k_f} + \frac{1}{h_i} + \frac{1}{h_s}$$

In the equation, the subscripts o , g , i , and s indicate the heat transfer coefficients for the outside surface, the gap between the foam and the cardboard box, the inside surface of the foam, and the dry ice surface, respectively. There are two thermal resistance layers—the cardboard box and the foam—indicated by the subscripts c for the cardboard and f for the foam. The resistance of the cardboard and foam is expressed at a thickness x divided by its thermal conductivity k .

The equation assumes that the heat transfer through the air gap between the cardboard and the foam is entirely by conduction. If convection within the air gap were occurring, the gap heat transfer coefficient, h_g , would be specified by h'_c in the following equation for vertical enclosed spaces, as found in McAdams:³⁹

$$\frac{h'_c x}{k_f} = \frac{C}{\left[\frac{L}{x}\right]^{1/9}} * \left[\frac{x^3 \rho_f g \beta \Delta t}{\mu_f^2} \left(\frac{c_p \mu}{k} \right) \right]^n = \frac{C}{\left[\frac{L}{x}\right]^{1/9}} * [x^3 \Delta t Y]^n$$

However, according to McAdams, for Grashof numbers (based on clearance gap thickness) below 2,000, natural convection is suppressed and the amount of heat transfer is controlled by conduction. For this situation, the Grashof number is defined as:

$$\text{GrNum} = \frac{L_{\text{gap}}^3 \cdot \rho_{\text{air}}^2 \cdot g \cdot \beta \cdot \Delta T}{\mu_{\text{air}}^2}$$

Estimating that the ΔT across the air gap is 10 K*, the Grashof number is calculated to be less than 20, which is far less than 2,000. Thus, we are justified in considering there to be simple conduction in the air gap; if only conduction is occurring, the equation would be:

$$\frac{1}{h'_c} = \frac{x_g}{k_g}$$

where x_g is the thickness of the gap and k_g is the thermal conductivity of air.

The heat transfer coefficient on the outer wall, h_o , would either be heat transfer to an adjacent package or heat transfer to air in the cargo hold.

If the package containing the dry ice was in a ULD, the entire ULD could be filled with dry ice packages. In this case, there would be no heat transfer from the package to the adjacent packages, which would be equally cold.

If a package containing the dry ice was loaded into a ULD with other mixed packages, since the adjacent packages are likely to be contained in cardboard cartons and packed with a lot of poorly conducting padding, even here there would be little heat transfer to three or more of the sides of the cold package.

The limiting condition occurs when the cold package is located such that there is convective heat transfer from the cold package on several of the surfaces, say all four sides and from the top. Because the desire in this modeling is to try to identify a heat transfer coefficient that would be bounding, convective heat transfer to air was chosen for further study. While the external heat transfer could be controlled by natural or forced convection, only the natural convection case will be shown in what follows.

Heat Transfer with Free Convection

As a first assumption, the heat transfer to the top will be neglected. From McAdams,⁴⁰ the following equation can be used to estimate the heat transfer coefficient from a vertical surface.

*Subsequent experimental measurements with packages showed the ΔT to be more like 5 K.

$$\frac{h_o L}{k} = 0.52 \left[\left(\frac{L^3 \rho_a g \beta \Delta T}{\mu_a^2} \right) \left(\frac{c_p \mu}{k} \right) \right]^{0.25} = 0.52 [L^3 \Delta T Y]^{0.25}$$

Where L is the length of the surface and ΔT is the difference between the ambient air temperature and the temperature of the surface of the package. The first term within the brackets is the Grashof number and the second the Prandtl number. Because the temperature difference is unknown, what must be done is to estimate the heat transfer rate across the insulation, then using that heat transfer rate, guess at a ΔT and iterate until the heat transfer rate across the gap is the same as it is for the insulation.

The heat transfer on the inside surface of the package is somewhat problematic in that initially the package might be full of dry ice, and later in the journey the dry ice might only half fill the package. Inside there are two parallel heat paths, one from the surface to the void space filled with carbon dioxide and then to the dry ice itself and the other from the surface to the dry ice.

In the experiments performed to look at the sublimation rate of dry ice from some typical packages, it was observed that toward the end of the effective cooling period the dry ice pellets were covered with a frost composed of ice crystals. In fact, if the package was filled with dry ice pellets on a humid day, the supply of dry ice pellets may have been frosted even prior to use. Such ice crystals could provide a significant thermal resistance. Because of this thermal resistance, the temperature of the gas inside the package can be somewhat warmer than the sublimation temperature, and we did observe this during our package tests.

However, again, in keeping with the need to provide a bounding estimate of the dry ice sublimation rate, calculations were performed using an assumed carbon dioxide gas temperature of -78°C . This implies a temperature difference of about 100°C , assuming the ambient air is at 22°C .

Given these simplifications, it is now possible to estimate the value of the overall heat transfer coefficient and to obtain from that estimate the rate of sublimation of the dry ice. The box that was modeled was 290 mm (0.94 ft) by 240 mm (0.79 ft) by 200 mm (0.66 ft) high. Thus, the total surface area of the box was 0.212 m^2 (2.28 ft^2). The thickness of the EPS foam* was 42.5 mm (0.139 ft). The thermal conductivity of the EPS was taken as 0.035 W/m K . The heat of sublimation of dry ice at atmospheric pressure is 573 J/g .

The equation for the top of the package is of the same form as the equation for the vertical surfaces. The only difference is that the coefficient in front of the equation changes from 0.53 to 0.27, reflecting the less efficient transfer when cooling a horizontal surface facing upward.

*Also known and sold under the trademark Styrofoam.

Because there is no convection from the bottom of the package and because of the probability that the package sits on another package, most likely with padding, the heat loss from the bottom is estimated to be zero.

It may be seen that each of these assumptions could be investigated and clarified and the model made correspondingly more sophisticated. However, the goal here is to provide a reasonable estimate.

The calculated heat gain for such a package is estimated to be 9.4 W , leading to a calculated area-normalized dry ice loss rate of $169 \text{ g/m}^2 \cdot \text{hr}$.

Heat Transfer to Insulated Unit Load Devices

In addition to considering dry ice loss rates from cardboard cartons, we believe that it is important to look at insulated ULDs. The reasons are twofold: (1) Large-scale shipments often use insulated ULDs, and these ULDs use lots of dry ice, up to 200 kg each, so insulated ULDs are potentially big sources of carbon dioxide. (2) Regulations have been written and policies established that give ULDs special treatment, such as higher limits for the total number of kg of dry ice per aircraft* and a waiver from the per-package limit.† Thus, we believe it is crucial to understand how ULDs behave, how they may be different from EPS-insulated cartons, and whether this special treatment is justified.

The heat transfer analysis for insulated ULDs is similar to that for packages. In the case of insulated ULDs, the walls are composites of structural and insulating materials. We do not have a blueprint for their design, and we do not know the wall thickness, the type of insulation used, and the configuration of the structural components. Thus, an *a priori* calculation of the expected heat transfer through the wall of an insulated ULD is not possible. However, we can calculate apparent overall U values based on available dry ice loss rate data and then use these U values in other calculations.

Discussion of Heat Transfer Analysis Results

Uncertainties in the Heat Transfer Analysis

There are several uncertainties in this model. First of all, a one-dimensional steady-state heat transfer model was used. Clearly, with these small packages there are edge effects both within the EPS and also on the outside of the package. If a

*For example, consider ICAO variation No. CO-9 for Continental Airlines whereby the dry ice limit for a Boeing 777 goes from 200 kg to 1,088 kg if ULDs are used.

†See statement in 49 CFR 173, Section 217 that “The quantity limits per package . . . are not applicable to dry ice being used as a refrigerant . . . in a unit load device.”

two-dimensional model had been used, the temperature drop between the surface of the package and the ambient air would have been lower on the corners, lowering the rate of heat gain and therefore the calculated rate of sublimation.

Another uncertainty is in the thermal conductivity of the EPS. Looking in the literature, it is possible to obtain a range of thermal conductivity values. This is not the result of experimental error but is due to differences in the density of the EPS and in the temperature at which the thermal conductivity is measured. Less dense EPS tends to have a lower thermal conductivity. It would be possible to improve the agreement with the experimental results by adjusting the thermal conductivity, and the adjusted thermal conductivity would still be in the range of published thermal conductivities listed in the literature. The modeling could be made more conservative by picking a higher EPS conductivity when setting these dry ice carriage limits.

On the other hand, it is also possible that the heat transfer to the dry ice pellets is reduced because the pellets are coated with a layer of water ice crystals. Such frost may be observed visually if dry ice pellets are left to sublime in the open air. This behavior, which was observed when dry ice pellets were placed in a simple, uninsulated cardboard box and allowed to sublime, is complex and dependent on the amount of moisture available when the package is packed with dry ice. Under humid conditions, this heat transfer phenomena could be a significant resistance to heat transfer that was not modeled.

Cargo compartments are generally supplied with ventilation air. Interior air flows are complex and we do not know the exact pattern of air flows and associated air velocities, which in any case would change with the configuration of each different load. The possibility of air currents over or against the package is one reason why onboard measurements are desirable.

Steady-State Versus Transient Analysis

In modeling the heat transfer, there is a steady-state phase and perhaps several transient phases. The first transient phase occurs when the dry ice is first loaded and the internals of the package cool down. The extent of this phase depends heavily on whether the load has been pre-cooled. A second transient phase occurs if the ambient air temperature changes, and a third occurs if the ambient pressure changes. Of those three transient phases, the cool-down phase has the potential for the greatest rate of carbon dioxide emission.

For example, if the material being shipped has to be cooled down from 22°C to -78°C, a temperature difference of 100 K, and its mass of material is comparable to the mass of dry ice loaded in the package, 10% to 20% of the dry ice can be sub-

limed just cooling down the material prior to being shipped. Since this loss occurs within the first 1 to 2 hours, and the quantity of dry ice reported on the shipping papers is usually based on the weighing performed before this cool-down period, the quantity of dry ice present during shipment is often overstated. (This is another way that mass-based limits may benefit from an unintentional safety factor.)

The other two transient phases, the change in ambient temperature and pressure, are smaller. The magnitude of the environmental temperature change may be estimated as follows: on a warm day, the exterior temperature might increase 10°C to 15°C when going from the cargo building to the cargo bay of an airplane, going from perhaps 25°C to 40°C. Based on a dry ice sublimation temperature of -78°C or 195 K, the difference between the dry ice temperature and the ambient temperature would increase from 103 K to 115 K. Because the rate of heat transfer is proportional to the difference in temperature, if the temperature change persisted for long enough, the 15°C exterior temperature change would result in a 15% increase in the emission rate of carbon dioxide.

A change in ambient pressure will occur as the aircraft gains altitude. Although aircraft cabins and cargo compartments are pressurized, the pressure maintained in the cabin or compartment is not sea-level pressure* but a lower pressure. This lower pressure is limited to the equivalent of ambient pressure at an altitude of 2,440 meters (8,000 ft), corresponding to a pressure of 75.26 kPa.⁴¹ The reduction in pressure from the pressure at sea level to the pressure at 2,440 meters results in the lowering of the sublimation temperature of dry ice by about 3.4 K, from about 195 K to 191 K.

With this pressure change, there are really two transient phases in the dry ice sublimation rate: the first is the rapid carbon dioxide gas release from the cooling down of the contents of the package to the new equilibrium dry ice sublimation temperature, which is about 3.4 K lower, and the second is the 4% increase in temperature difference between the new dry ice temperature and cargo compartment temperature.

While a 4% increase in the emission rate from one individual package is relatively small, if the carbon dioxide concentration is near the limit, the aggregate effect could be significant because all packages on the airplane would be experiencing the transition at the same time.

It is recognized that the sublimation rate will be affected by changes in the ambient pressure and temperature. The largest changes in temperature are expected to occur on the ground when the packages are sitting out in the hot sun before loading. The changes in pressure occur as the plane ascends to its cruising altitude and then again when the plane starts its descent. These transient phases are expected

*Sea-level pressure is 101.325 kPa.

to be relatively brief and result in changes in the sublimation rate of a few percent, and it is believed that there will be long periods of time where steady-state heat-transfer models will be applicable.

Summary of Dimensional Analysis and Heat Transfer Model Results

The dimensional analysis results showed that the sublimation rate depends on the surface area of the package or ULD, the temperature difference between the inside and the outside, and the thermal conductivity of the package walls, and that the mass of dry ice does not matter.

Many details of heat transfer can be included in a model: heat transfer to the inside wall of the box, the thermal conductivity of the EPS foam insulation, the thermal conductivity of the cardboard, free or forced convection on the outside of the box, contact resistances, radiation losses, and so forth. But looking at the heat transfer model carefully, nearly all of the resistance to heat transfer is determined by the thickness of the EPS foam; everything else is either negligible or small.

The heat transfer process that leads to dry ice sublimation and consequent carbon dioxide gas production is well enough understood that the observed sublimation rate for packages and insulated ULDs can be modeled adequately with a fairly simple one-dimensional heat transfer model.

CHAPTER 8

Experimental Measurements of Dry Ice Sublimation Rates

In addition to calculating sublimation rates from heat transfer rates, both laboratory and field tests were performed to measure sublimation rates experimentally. These results are reported in the following. The objective of these experimental package tests was to determine the observed sublimation rate under a variety of experimental circumstances.

Laboratory Tests of Single Packages

Objective

The objective of the laboratory tests was to establish the dry ice loss rate of packages under controlled conditions.

Test Packages

The test packages were EPS-insulated cardboard cartons of three different sizes. Basic information about these packages is provided in Table 6.

Mass and Temperature Measurement

The scale used for these tests had a full-scale range of 15 kg, a readability of ± 2 g, and repeatability and linearity of ± 5 g. The scale was zero-checked, then calibrated at mid-scale and near full-scale with calibrated weights; the calibration of these weights is traceable to the National Institute of Standards and Technology (NIST). The scale pan was approximately 210 mm square. The cross-sectional dimensions of all the packages were greater than 210 mm. Thus, part of the bottom surface of the package was in contact with the scale pan, and the balance of the area was surrounded by air. The internal temperature measurements were made using type E thermocouples connected to a Fluke 52II thermocouple temperature meter.

Procedure

The procedure used for the package weight loss tests was simple: the tare weight of the package was determined, the

package was filled with dry ice pellets, the top was closed and taped, and the package was placed on the scale. The weight was recorded manually at intervals along with the time and, in some tests, one or more inside temperatures.

The test packages were held in an air-conditioned room with a nominal temperature of 22°C to 24°C during the tests.

Some additional tests were made to determine the density of the EPS foam and the thermal resistance of the cardboard.

Results

Some representative results for the laboratory package tests are shown in Figure 6. The area-normalized sublimation rates were in the range of 130 to 180 g/m² · hr. Note that the mass of dry ice declines smoothly with time and the area-normalized mass loss is approximately constant.

Several of the test conditions were repeated using about half the normal loading of dry ice in the package; the carbon dioxide emission rate measured in kg/m² · hr did not change appreciably.

Laboratory Tests of Multiple Package Configuration

Objective

The objective of the multiple-package tests was to gain insight into the effect of neighboring packages on the dry ice sublimation rate.

Test Configurations

Two basic test configurations were studied. In both configurations, the test package was resting on a plywood base (to simulate the top of a wooden pallet) and was surrounded by packages of the same dimensions on all four sides and on the top. The adjacent packages were touching the test package but were not held in place by bands, shrink wrap, or

Table 6. Test package information.

Package Designation	Width x Depth x Height, mm	Surface Area, m ²	Insulation Thickness, mm	Tare Weight, kg
A	300 x 240 x 390	0.56	38	0.70–0.75
B	290 x 240 x 200	0.35	38	0.40–0.45
C	370 x370 x 390	0.85	38	1.1

other constraints. It should be noted that although all the packages were new and unused, the corrugated cardboard used to construct the packages was not perfectly flat, and not all the packages were perfectly square. We believe this situation would be typical of packages actually shipped in the field.

For this test configuration, the surrounding packages contained EPS foam lining but were otherwise empty. These

packages were intended to simulate general merchandise, which is often surrounded by foam- or paper-based cushioning to prevent breakage.

Results

As expected, the dry ice sublimation rate was lower for a package surrounded by other packages and therefore not

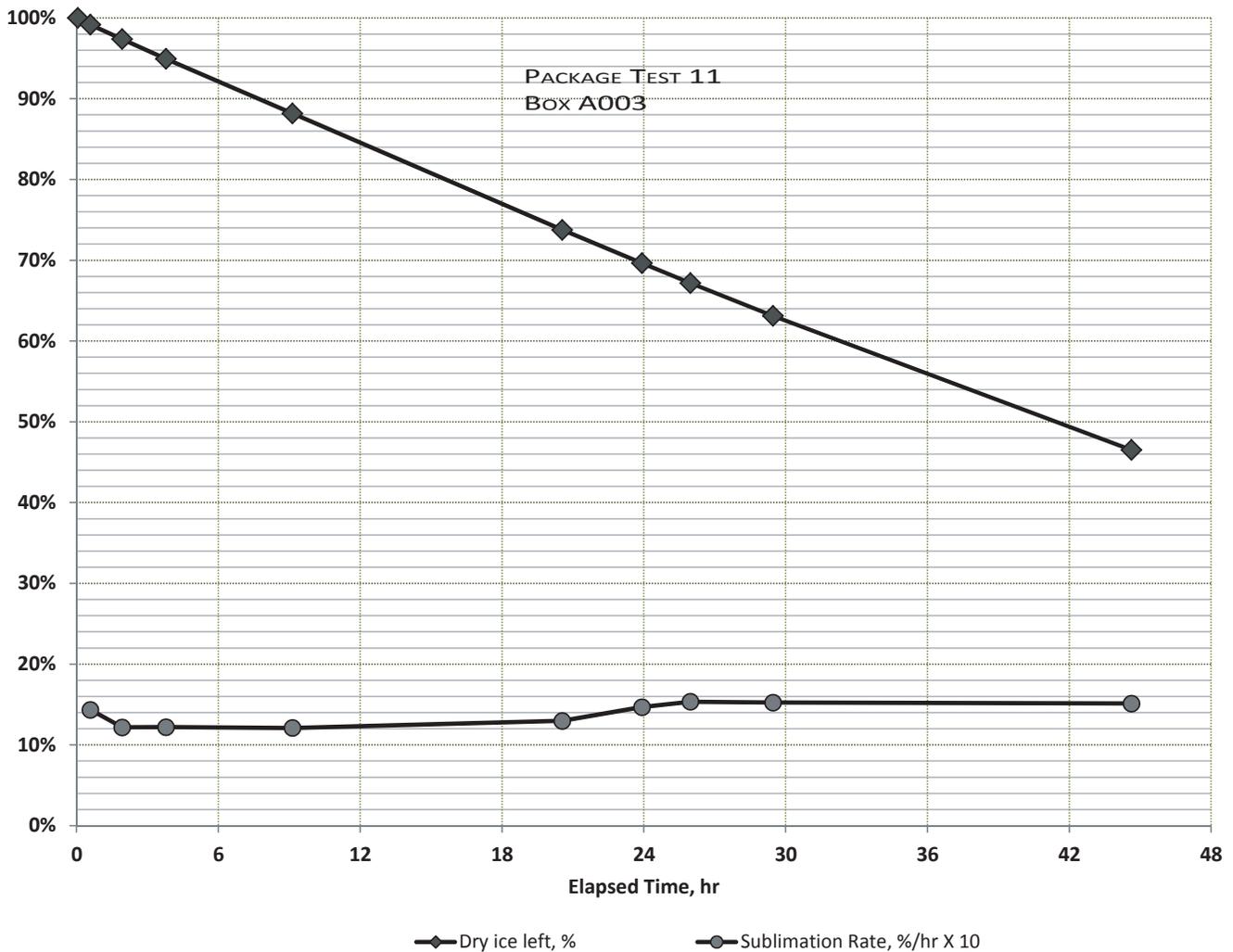


Figure 6. Representative package test results.

exposed to the free air convection and radiant heat exchange that would obtain for a single package for which these processes are effective means of heat transfer. For this configuration, the measured area-normalized sublimation rates were in the range of 130 to 160 g/m² · hr.

Package Shipment Tests

Procedure

In these experiments, the same type of EPS-insulated shipping cartons used in the laboratory tests were filled with dry ice pellets and shipped between two Battelle offices: the Battelle headquarters in Columbus, Ohio, and a field office near Phoenix, Arizona. The packages were shipped via normal FedEx next-day service.

Otherwise the procedure was similar to that for the laboratory tests.

Two scales of the same make and model were used to weigh the packages. The scale used in Phoenix was compared to the one used in Columbus using the same calibration weights, and the two scales were found to read the same within the specified ±2 g repeatability.

Results

Some representative results for the dry ice package shipment tests are shown in Figure 7. Note that the first weight loss measurement data point could not occur until the package was received in Phoenix, about 24 hours after the package was packed with dry ice for shipment. The break in the curves at about 100 hours reflects the depletion of the dry ice pellets. In practice, shipment times would likely be less than 100 hours, and for a lesser amount of time the area-normalized sublimation rates are comparable to those obtained during the laboratory tests.

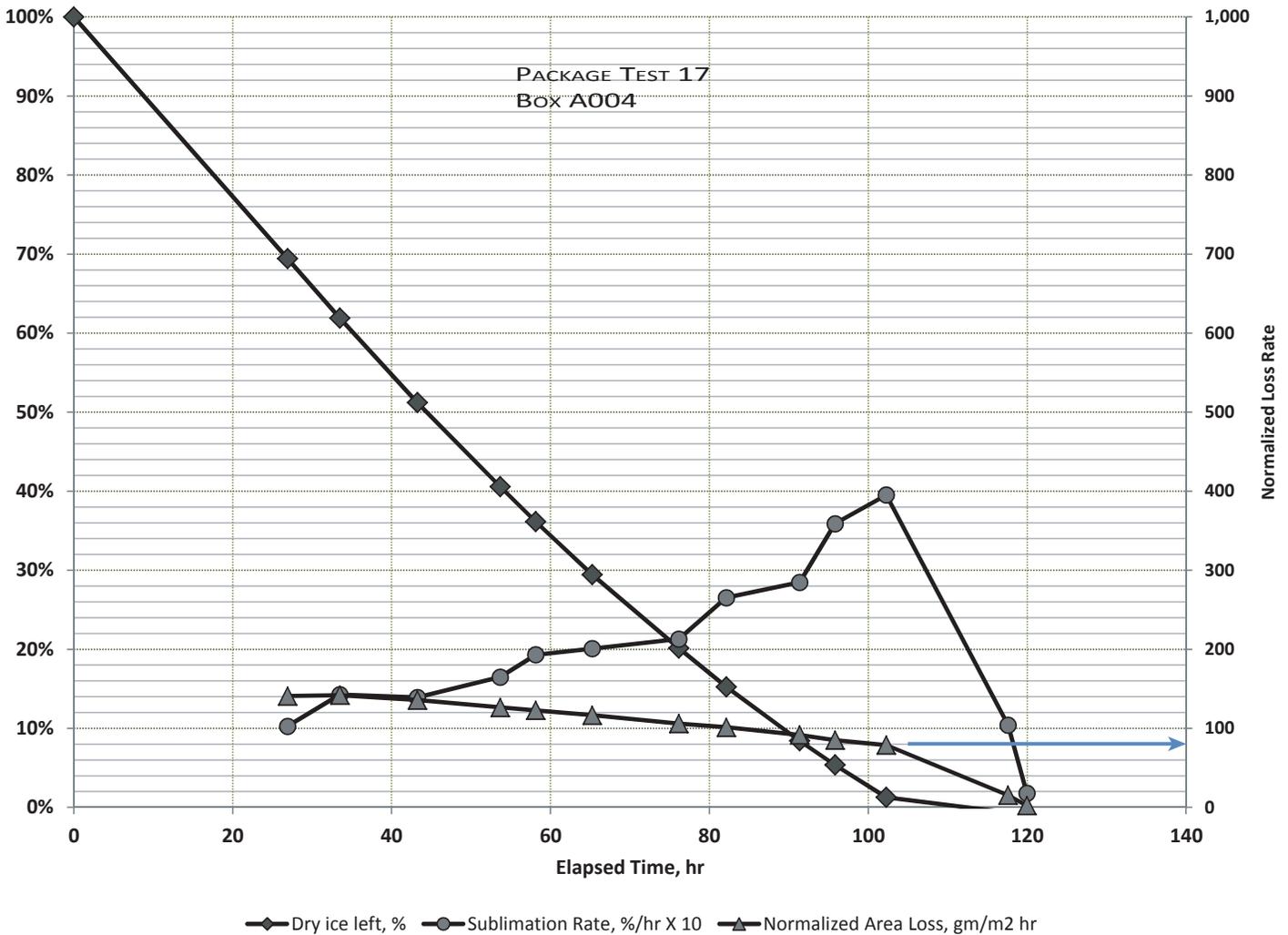


Figure 7. Representative results from package ship tests.

Discussion of Experimental Test Results

General Observations

In Figure 6 and Figure 7, the weight loss with time is a smooth downward curve. Both these figures show the normalized area loss as a relatively constant number between 140 and 170 g/m² · hr. In Figure 7 we also show the apparent mass-based sublimation rate, expressed as %/hr. Note that the mass-based sublimation rate is not very constant.

Uncertainties in Experimental Measurements

Regarding the uncertainties in the experimental data, the observed steady-state loss rate from the experiment is believed to be quite accurate. The scale was calibrated using a weight traceable back to NIST. The display was accurate to ±2 g, and because the mass loss was measured over a period of several hours, the mass loss was great enough that this inaccuracy did not significantly affect the measured loss rate.

The sublimation of dry ice is believed to be the only cause of a weight change on the scale. No condensation was observed on the outside of the boxes, and because the dry ice is constantly subliming, there is a constant carbon dioxide gas flow outward through any gaps between the package lid and the top that would limit any diffusion of moist air into the package and minimize any weight gain from the buildup of water ice crystals on the dry ice pellets.

Comparison of Single- and Multiple-Package Test Results

Although the area-normalized dry ice loss rates for the multiple-package ensembles were lower than for single packages, the reduction was not extreme—on the order of 20%.

Comparison with Heat Transfer Analysis

When the dry ice sublimation rates observed in the package tests were compared with the results of the heat transfer analysis presented in Chapter 7, it was found that there was good agreement. The heat transfer rates, in watts per square meter, which were calculated for the packages (based on 38 mm of EPS foam insulation and free convection on the outside of the package), were within 20% of the actual heat transfer rates derived from the laboratory measurements of the dry ice loss rate.

Proposed Use of an Area-Normalized Dry Ice Loss Rate

The dimensional analysis, the heat transfer model, and the dry ice use rate tests all support the use of an area-normalized dry ice loss rate.

We therefore propose that the principal metric for the assessment of the carbon dioxide generating potential of both packages and ULDs carried on aircraft be a normalized area loss rate (mass of dry ice lost per unit of surface area per unit of time).^{*} If this were part of the protocol to establish dry ice limits, the carrier would have to be provided with the dimensions of the dry ice packages being loaded on the plane. We think that this is reasonable because in order to assess shipping charges, carriers such as FedEx, UPS, and USPS already check package dimensions in order to compute their dimension weight, and because ULDs come in standard sizes whose dimensions are well-known and whose area could even be stenciled on the unit.

The graph in Figure 8 presents the results of the package tests along with vendor information on insulated ULDs. Please note the following comments related to the graph:

The data for the cartons come from tests conducted by Battelle. Because the results for the shipped packages were about the same as those for the package tests in the lab, they have been grouped together.

The data for the ULDs come from vendors and have not been independently verified.

The package and ULD sizes cover a surface area range from 0.3 m² to 32 m², a factor of over 100 from the smallest to the largest, and cover the entire range of sizes likely to be seen on aircraft.

The temperature inside of the cartons^{*} was near dry ice temperature, leading to a ΔT of about 100 K. The set point for the insulated ULDs (which have active temperature control) was taken at −20°C for a ΔT of 40 K.[†] So, the cartons and the ULDs do not have the same ΔT. However, it appears that, because of the need for an aluminum support frame in the ULDs, even though

^{*}In SI units, this would be grams or kilograms of dry ice per square meter per hour.

^{*}Based on measurements performed in this task.

[†]Many insulated ULDs are set to maintain interior temperatures of 3°C to 8°C, not −20°C. However, these ULDs are advertised to work at −20°C, and the manuals give the dry ice loadings required to maintain −20°C. The air carrier does not inspect the ULD control panel to check the temperature setting prior to loading, and the crews are not advised of the temperature setting. So, if the basis for higher dry ice limits for ULDs is a higher 3°C to 8°C set point, then (a) the shipper should certify the temperature setting, (b) the airline should have a way to verify the setting, and (c) regulations and policies may need to be rewritten to include a temperature setting requirement. And then there would need to be another procedure for those ULDs whose contents do need to be deep frozen at the lower −20°C temperature. Some pharmaceuticals do need to be deep frozen.

Normalized Dry Ice Loss Rate vs. Surface Area

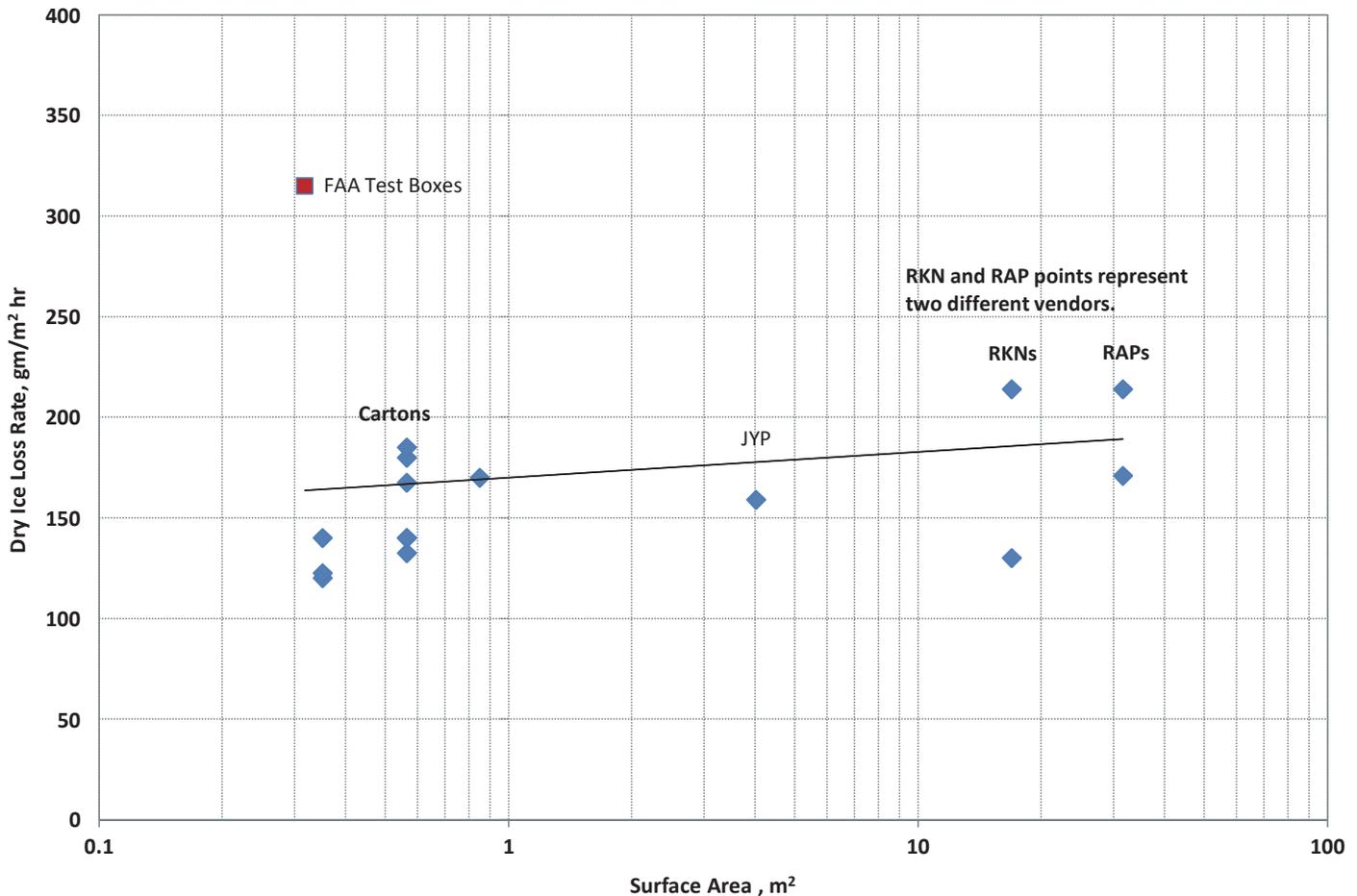


Figure 8. Normalized dry ice loss rates for various cargos.

the ΔT for a typical ULD package is about half the ΔT for a typical dry ice carton, the overall thermal conductivity of the ULD is about twice the thermal conductivity of the EPS in a typical dry ice package, and the two factors cancel out. If a ULD were maintained at the -78°C sublimation temperature of dry ice, then an adjustment would need to be included in the correlation. This is very unlikely because even deep-frozen cargo only requires a temperature set point of -18°C or -20°C .*

The correlation shows that the normalized loss rates, except for the FAA data point, are in the range of about 120 to 210 $\text{g}/\text{m}^2 \cdot \text{hr}$, with an average of about 170 $\text{g}/\text{m}^2 \cdot \text{hr}$. For a package with a ΔT of 100 K, an insulation thickness of 38 mm, and a typical dry ice loss rate of 170 $\text{g}/\text{m}^2 \cdot \text{hr}$, the sublimation number may be calculated as follows:

$$\text{Sublimation Number} = \frac{kL^2\Delta T}{i\lambda_r} = \frac{\Delta T}{R\lambda_{s,r_a}} = 3.4$$

While some additional analyses might be required to demonstrate the validity of these findings, it could be reasonable to require the design of dry ice packages to have a sublimation number of 3.4 .

The result of the 2006 FAA sublimation rate test[†] is also shown. It is believed that this data point is higher than the others because:

- (1) According to the report, the boxes were initially weighed immediately after filling with dry ice, so the loss rate data would include the time when they were in a cool-down mode. In actual practice, packages would need to be transported from the shipper to an airport (which takes time), and in any case, airlines will not accept freight less than a minimum of 1 hour (domestic) or 2 hours (international) prior to flight time, so in actual practice, cool down would not be an issue.
- (2) Other factors could also contribute, including (a) the FAA test used relatively small dry ice pellets (10 mm in diameter by 20 mm in length), (b) the lower pressure in the altitude chamber leads to a dry ice equilibrium sublimation temperature about 4°C lower than at atmospheric pressure, leading to a ΔT and associated expected heat transfer rate about 4% larger, and (c) the chamber temperature of 29°C is higher than the ambient temperature used for the other tests (and is higher than typically seen inside an aircraft cargo compartment during flight).

*A company that ships pharmaceuticals reported that they aim to keep their deep-frozen products at -14°C during shipping.

[†]As reported in DOT/FAA/AM-06/19.

CHAPTER 9

Factors Affecting Carbon Dioxide Concentrations on Aircraft

Carbon dioxide concentrations on aircraft are determined by the amount of carbon dioxide introduced into the aircraft and the amount of ventilation.

Carbon Dioxide Sources

Before considering dry ice limits for aircraft, we must identify all the sources of carbon dioxide. There are four sources of carbon dioxide that can contribute to the concentration of carbon dioxide in the air inside an aircraft:

1. The carbon dioxide already present in fresh air from outside.
2. Carbon dioxide produced from human metabolism by the crew and the passengers, if present.*
3. Carbon dioxide produced from metabolism by any animals present on the aircraft.
4. Carbon dioxide produced by the sublimation of dry ice. The dry ice could be from (a) packages carried on board by passengers, (b) dry ice used to keep food cold that is served on board, and (c) dry ice used to keep cargo cold.

Information on levels of carbon dioxide in the ventilation air and on the amounts of carbon dioxide produced through human metabolism is reviewed briefly here. The balance of this section focuses on carbon dioxide produced through the sublimation of dry ice.

Carbon Dioxide in Ventilation Air

The air outside the aircraft contains a certain amount of carbon dioxide—about 390 ppm. Measurements made outside commercial aircraft show that the range of variation in the carbon dioxide content of the outside air at altitude is on the order of 5 ppm.⁴² Measurements of carbon dioxide

concentration from NASA test aircraft flights show a similar amount of variation.⁴³ Although geographic variations in carbon dioxide concentration have been modeled and displayed graphically,⁴⁴ for the purposes of assessing potential carbon dioxide levels inside aircraft, the variation in carbon dioxide concentration in the outside air with time or location is not significant. Compared with a typical outside concentration of about 390 ppm, this variation is only about 1%, and for our purposes, the concentration of carbon dioxide in outdoor air may be taken as a constant.

Carbon Dioxide Produced by Human Metabolism

People produce carbon dioxide as a product of metabolism. The rate of generation of carbon dioxide from people varies with the size of the person* and his or her level of activity. The estimation of human production of carbon dioxide is discussed in detail in the ASTM standard for using carbon dioxide concentrations to evaluate indoor air quality.⁴⁵

Based on estimates developed by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) for evaluating indoor air quality in buildings⁴⁶, an average-sized adult who is seated and engaged in reading/writing activities produces 0.0043 L/s of carbon dioxide. Based on a density of carbon dioxide of 1.799 g/L (see Table 1), this is 0.00773 g/s, or 28 g/hr of carbon dioxide per passenger.

As an aside, if we were to use the 2% per hour dry ice sublimation rate quoted in the FAA report as a basis for calculation,⁴⁷ we could estimate that from a carbon dioxide production point of view, each passenger would be equivalent to a block of dry ice weighing 1.4 kg. Continuing this analogy, and using it to place dry ice carriage limits in perspective, the approximate dry ice equivalent of a full passenger load of

*Cargo aircraft generally have no passengers.

*The rate of carbon dioxide production is best correlated with the body surface area of the person. In this respect people are similar to packages.

Table 7. Dry ice equivalents of aircraft passenger loads for selected aircraft types.

Aircraft	Typical No. Passengers	Equivalent Dry Ice, kg ^a	Equivalent Number of Boxes ^b
737-300	124	174	36
737-800	157	220	46
767-400	256	358	75
777-200	285	399	84

^a Based on 1.4-kg dry ice equivalent per passenger.
^b Based on 12-in. x 10-in. x 16-in. boxes with 1.5-in. EPS insulation.

various aircraft at common seating arrangements would be as shown in Table 7.

Or, assuming an area-normalized sublimation rate of 170 g/m² · hr, the carbon dioxide produced from boxes for which data are shown in Figure 6 would be equivalent to the carbon dioxide produced by two passengers.

Carbon Dioxide Produced by Animal Metabolism

Consideration of this source of carbon dioxide is not within the scope of the present study. We note that Boeing has provided guidance for the carriage of animals,⁴⁸ and that carbon dioxide emissions are an important part of this guidance, as is the need to manage heat and humidity.

Volume of Carbon Dioxide Produced by Sublimation of Dry Ice

The production of carbon dioxide from dry ice carriage has been discussed previously, and the area-normalized dry ice loss rate has been suggested as the best way to estimate the amount of carbon dioxide produced from the sublimation of dry ice.

Experimentally, the sublimation of dry ice is conveniently studied on a mass basis: the mass of dry ice sublimed is related to the amount of heat transferred, and therefore the loss of dry ice as carbon dioxide can be determined by using a scale.

Ventilation, on the other hand, is conveniently studied on a volume basis. The size of cargo compartments on airplanes is measured in terms of volume, air flows are often measured in volumetric flow units (e.g., L/s, ft³/min), and carbon dioxide concentrations are generally stated in volume ppm or volume percent, both of which are volume ratios.

Thus, there needs to be a bridge between the measurement of the mass of dry ice and the volume of carbon dioxide gas produced. That bridge is the gas density, defined as the mass per unit volume. Gas density has SI units of kg/m³, and is usually represented by the symbol ρ .

For an ideal gas,

$$\rho := \frac{\text{Press} \cdot \text{MW}}{R_{\text{gas}} \cdot \text{Temp}}$$

where

Press = gas pressure—standard atmospheric pressure is 101.325 kPa,

MW = gas molecular weight—44.01 kg/kmole for carbon dioxide,

R_{gas} = universal gas constant—8.314 kPa · m³/kmole K, and

Temp = the absolute temperature of the gas—K.

This means that we must know the pressure and temperature to calculate the gas density. Table 8 shows various gas densities used in the literature related to carbon dioxide concentrations in aircraft cabins, as well as the assumed temperature and pressure associated with those gas densities.

Clearly, as Table 8 shows, within the range of reports or regulations related to carbon dioxide and dry ice on aircraft, there have been differing opinions as to the proper conditions to use for calculating the specific volume of carbon dioxide gas. Also, clearly these differences are quite small in comparison to the other uncertainties in the estimation of dry ice sublimation rates and associated ventilation requirements. In the interest of consistency, we choose to use the value of $\rho = 1.799 \text{ kg/m}^3$ since this is the value legally adopted by the FAA in their Final Rule on Allowable Carbon Dioxide Concentration in Transport Category Airplane Cabins, wherein the FAA lists their standard conditions as a pressure of 101.325 kPa and a temperature of 25°C.⁴⁹ This density of 1.799 kg/m³ was used in the calculations shown in this report.

Carbon Dioxide Removal: Ventilation Air Flows

Ventilation is the process of introducing fresh air into an enclosed space. On aircraft the ventilation process is necessarily accompanied by air conditioning, the process of changing the temperature and humidity of the air to meet human comfort requirements. Ventilation may also be accompanied by the process of air purification, which has the goal of removing gaseous and particulate contaminants.

Aircraft Ventilation Requirements

Aircraft require ventilation, air conditioning, and air purification. Ventilation is required to provide air with sufficient oxygen for people (and any animals that may be on board) to breathe and for removal of air contaminants. Air condition-

Table 8. Various statements of the density and specific volume of carbon dioxide gas.

ρ , kg/m ³	Specific volume, ft ³ /lb	Temp., °C	Pressure, kPa	Comments
1.799 ^a	8.904	25	101.325	Calculated for conditions in FAA standard in 61 FR 63951
1.808 ^b	8.862	25	101.325	NIST data for carbon dioxide
1.820 ^c	8.8	Not stated	Not stated	Density used in FAA sublimation rate study ⁵⁰
1.842 ^a	8.695	18	101.325	Perhaps a more realistic cargo compartment temperature
1.884 ^c	8.5	Not stated	Not stated	Used in: Boeing dry ice carriage document ⁵¹ Airbus SIL 00-081 ⁵² FAA Advisory Circular (AC) No. 91-76 ⁵³
^a Calculated from ideal gas law. ^b Based on NIST database. For real gas. ^c Calculated from specific volume listed at right.				

ing is required because, in general, the air outside the aircraft is too hot or too cold for comfort. Air purification is required for gaseous contaminant* and particulate matter† removal. In addition, at all but the lowest altitudes, the aircraft is required to be pressurized because the ambient air pressure at altitude is too low.

Although the electronic equipment on an aircraft does not require air to operate, such equipment does need to be kept within operating temperature limits, and air cooling is required. Thus, conditioned ventilation air must be supplied to the aircraft electronic equipment as well.

Understanding of Aircraft Ventilation Air Flows

Based on discussions with major airframe manufactures Boeing and Airbus, we may visualize the ventilation air flows to the various compartments as follows:

The fresh air supply is extracted off the compression section of the jet engine and conditioned, with a small amount being sent directly to the flight deck and the balance sent to a mixing box. In the mixing box, the incoming air combines with recycled air from the cabin that has been filtered. This air is then sent to the passenger cabin.

*Such as ozone.

†Particulate contaminants include both nonviable particulate matter, such as dust, and viable particles, such as bacteria and viruses. Outside air at altitude is generally free of both types of particulate matter, but inasmuch as recirculated air is mixed with the fresh air supply, air filtration is necessary.

In most new aircraft, the supply of fresh air amounts to about half the air flow supplied to the cabin. The air displaced by the addition of fresh air is exhausted. Some air from the cabin is exhausted directly from galley and toilet areas to the outside. Some air that was previously in the passenger cabin is used to provide cooling air to electronics; this air is also exhausted. And some air leaves the passenger cabin to flow to the cargo compartment(s). These flows are shown schematically in Figure 9.

It is possible for an air carrier to order aircraft equipped with separate air conditioning systems for one or more of the cargo compartments; this would be done if the carrier expects to carry particularly temperature-sensitive cargo. In discussions with some passenger air carriers, their loading schedule was to place any live animals in one of the air-conditioned compartments and the dry ice packages in the other, presumably non-air-conditioned compartment.

There is also the possibility that a cargo compartment may not receive any ventilation air.*

Information on Ventilation Rates

Airbus and Boeing supplied information on the ventilation rate for various models and configurations of their aircraft. Although presented somewhat differently, the information from both manufacturers describes the amount of fresh air introduced into the aircraft and into various compartments.

*For example, the aft cargo compartments in the Airbus A300, A310, A300-600, and A318 aircraft are unventilated.

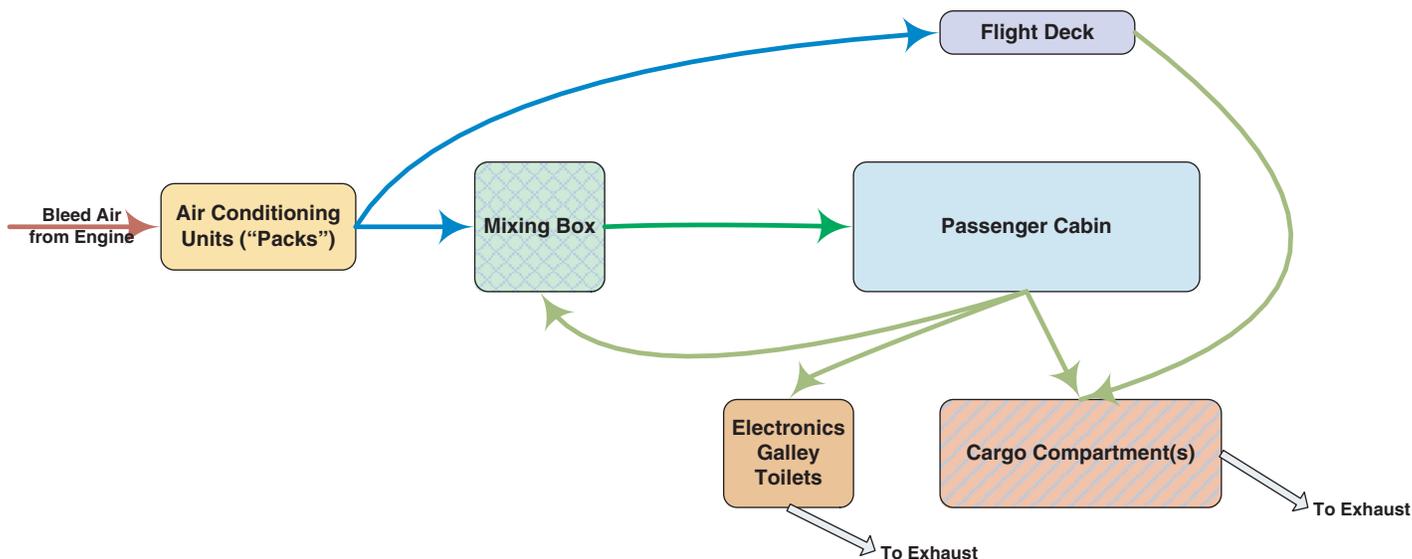


Figure 9. General ventilation air flows in an aircraft.

Calculation of Expected Carbon Dioxide Concentrations

With information on ventilation (fresh) air flows and with information about the volumetric rate of production of carbon dioxide gas from dry ice and the target carbon dioxide concentration limit, the calculation of the maximum amount of dry-ice-containing cargo that can be carried is straightforward.

The concentration of carbon dioxide in a steady flow situation is given by the relationship:

$$\text{CO}_2 \text{ Concentration} = \frac{\text{Volume CO}_2 \text{ in Ventilation Air} + \text{Volume CO}_2 \text{ Generated}}{\text{Volume of Ventilation Air}}$$

Examples of Carbon Dioxide Concentration Calculations

Two examples of carbon dioxide concentration calculations follow. They are intended to illustrate the general magnitude of cargo compartment carbon dioxide concentrations that might be expected.

For these calculations it is assumed that the air supplied to the cargo compartment was previously in the passenger cabin. Passenger cabin air has been found to have from 1,000 to 2,000 ppm of carbon dioxide.* Here a value of 2,000 ppm is used as the concentration of carbon dioxide in the ventilation air entering the cargo compartment. It is also assumed that the air in the cargo compartment is well-mixed.

Based on the experimental tests with packages and the analysis of industry information on insulated ULDs, a con-

servative value of 250 g/m² · hr for the rate of carbon dioxide production from dry ice is used.†

Example 1

Consider a passenger aircraft with a forward cargo compartment volume of 3,742 ft³ and a ventilation rate of 992 ft³/min. If there were packages or ULDs containing dry ice with a dimensional area of 75 m², the concentration of carbon dioxide would be expected to be about 8,200 ppm. (Note that the compartment volume is not needed for the calculation.)

Example 2

Assume an aircraft carrying four type RKN-insulated ULDs (with a total area of 67.7 m²) and 200 EPS-insulated cartons that are 290 mm × 240 mm × 200 mm (with a collective area of 70.2 m²). The total dimensional area would then be 138 m². Assume that this cargo is carried in a compartment with a volume of 3,613 ft³ and a ventilation rate of 21.8 air changes per hour, leading to a ventilation flow rate of 1,313 ft³/min.

For these conditions, the total allowable dimensional area would be 450 m², so the amount of dry-ice-containing cargo is well within limits.

These two calculations show how the dimensional-area method may be used to obtain information relative to carbon dioxide buildup from packages containing dry ice once the surface area of the dry ice packages is specified.

A spreadsheet for doing such calculations is available on the CD-ROM that accompanies this report.

*See discussion in Chapter 10 for a review of these measurements.

†Actual measured values were typically 140 to 170 g/m² · hr. The value of 250 g/m² · hr includes a safety factor of 1.5.

CHAPTER 10

Measurements of Carbon Dioxide Concentrations on Aircraft

Review of Previous Measurements

Studies of Carbon Dioxide Concentrations in Aircraft Passenger Cabins

There have been several studies on the concentration of carbon dioxide in the air in the cabins of passenger aircraft.

In 1991, Nagda et al. reported carbon dioxide levels in the passenger cabin on 92 commercial airliner flights and found that the average for narrow-body aircraft was 1,700 ppm and the average for wide-body aircraft was 1,200 ppm.⁵⁴ The same year O'Donnell reported carbon dioxide concentrations, temperature, and humidity on 45 commercial airliner flights; the mean carbon dioxide concentration was 719 ppm.⁵⁵

In 1999, Pierce et al. reported carbon dioxide concentrations on eight Boeing 777 flights.⁵⁶ The average for domestic flights was 1,600 ppm, while the average for international flights was 1,400 ppm. Hocking has compared these and other data with calculated carbon dioxide concentrations based on information about cabin air supply.⁵⁷ Also in 1999, Lee et al. measured carbon dioxide levels in aircraft cabins on 16 flights and found an average of 935 ppm.⁵⁸

More recently, Murphy reported calculated ventilation rates based on measured carbon dioxide concentrations on board passenger aircraft and found apparent ventilation rates of 9 to 16 air changes per hour.⁵⁹

Studies of Carbon Dioxide Concentrations in Aircraft Cargo Compartments

No published information was found that describes the results of measurements of carbon dioxide concentrations in aircraft cargo compartments. There is anecdotal information that some air carriers may have performed such tests, but the results have not been published or made available publicly.

Results of Previous Studies

Reviewing the studies mentioned previously:

- The observed carbon dioxide concentration in the passenger cabin varied over a 700- to 2,000-ppm range but was typically about 1,200 to 1,500 ppm.
- There was not always sufficient information on passenger loading to estimate carbon dioxide production from human metabolism. Moreover, human production of carbon dioxide depends not only on the number of people but also on their size and activity level.
- Even though there is a high circulation rate of air in the cabin, sampling location may also play a part.
- It is not clear whether the range of observed concentrations is due to variations in passenger loading and metabolism, sampling errors, or variations in the operation of the aircraft ventilation system.
- Because of these uncertainties, a safety factor may need to be applied to the ventilation rate when setting dry ice limits. Additional work would be needed to resolve this issue.

Measurements Made for This Study

As part of the HMCRP Project 09 study, measurements of carbon dioxide concentrations were made in the passenger cabin of a Boeing 777 aircraft flying a transatlantic route from a U.S. hub to London. On the outbound trip, the aircraft had approximately 680 kg of dry ice in the cargo compartment; on the return trip, it had none. In terms of passenger load, both flights were essentially full, with fewer than five empty seats.

Experimental

Instrumentation

The study used two Li-Cor LI-820 CO₂ monitors. This instrument is a non-dispersive infrared (NDIR) gas analyzer. As configured for this study, one monitor had a 14-cm cell length and a



Battelle photo

Figure 10. Carbon dioxide meter.

range of 0 to 2,000 ppm of carbon dioxide, and the second had a 5-cm path length and a range of 0 to 5,000 ppm carbon dioxide. An SKC “Grab Air” sample pump was used to draw a sample of cabin air through the Li-Cor at a nominal rate of 1 liter per minute. A particulate filter was used upstream of the sample inlet to remove any dust particles. Because of the duration of the flights (9 to 10 hours), the seat-based power ports were used to power the gas analyzer* and the notebook computer. The sample pump was powered by a standard 9-volt alkaline battery. Figure 10 shows the gas analyzer and sample pump.

There were two sets of instruments, and measurements were planned to be made at two locations in the cabin on both the outbound and the return flights. However, one of the instrument packages, the one with the greater range, was disabled at the outset of the outbound flight by a voltage surge or sag in the power provided to the seat-based power ports. The trouble was subsequently traced to a blown fuse on an internal circuit board, and the instrument was repaired in time for use on the return flight.

Procedures

Two flights were tested. The outbound flight was from a U.S. hub to London; the return flight was from London back to the same U.S. hub.

Carbon dioxide concentration measurements were made at one sample location on the outbound trip and two sample locations on the return trip. Both sample locations were at normal passenger seats. The equipment was placed under-

*The power needed was about 4 watts. An auxiliary battery pack with 8 D-cell batteries could power the instrument for about 4 hours; the battery pack was used for measurements during boarding when seat power was not available.



Figure 11. Dry ice load placed on outbound flight.

neath the seat in front, and the inlet to the sample pump was positioned about 40 cm above cabin floor level. For the outbound flight, the sampling location was in the business class section. For the return flight, one sampling location was in the business class section and one was in the coach class section.

Data were recorded at 2-second intervals and stored on a notebook computer. The data recorded included time, carbon dioxide concentration, cabin pressure, and the cell temperature inside the NDIR instrument.*

Dry Ice Load

In cargo compartments. The dry ice test load in the cargo compartment* on the outbound flight consisted of 680 kg[†] of dry ice in 60-lb blocks[‡] loaded on a wooden pallet that was in turn placed inside a ULD. The blocks were wrapped in shrink wrap. Figure 11 shows the configuration of the dry ice load. Exact weights were obtained for the dry ice just prior to departure and again just after landing in London.

The return flight did not contain any dry ice in the cargo compartment.

In passenger cabin. Dry ice is used in the passenger cabin to keep food/beverage carts cold. As shown in the left photo in Figure 12, for a large aircraft like a Boeing 777, a

*The sample cell in the NDIR instrument is heated and kept at a nominal temperature of 50°C in order to eliminate the effect of variations in gas density caused by variations in temperature. The instrument contains a built-in pressure sensor and uses a correction algorithm to account for variations in ambient pressure.

*Cargo loading was managed such that the test load was the only dry ice cargo on this particular flight.

[†]This is the airline’s legal limit for this type of aircraft.

[‡]Dry ice blocks typically measure 10 in. × 10 in. × 12 in. and weigh 60 lbs.



Figure 12. Food carts showing use of dry ice.

considerable amount of food must be stowed, and dry ice is used to provide additional cooling.[§] As the right photo in Figure 12 shows, the food in some of these carts is covered with slabs of dry ice.

Results of Measurements

The data collected on the outbound flight are shown in Figure 13; Figure 14 and Figure 15* show the data collected on the return flight. For both the outbound and return flights, measurements were made while the aircraft was on the ground and passengers were boarding, but were suspended during takeoff and did not resume until the aircraft reached an altitude of 10,000 ft, resulting in a gap in the data near the beginning of the flight. Data collection was ended as the plane descended through the 10,000-ft level on landing. Other small gaps resulted from minor power interruptions. During the time labeled as Note 1 on Figure 15, the sample tube became disconnected and air was not entering the analyzer cell.[†]

General Observations

Looking at the results for the outbound flight in Figure 13 and the return flight in Figure 14 and Figure 15, it can be seen that:

[§]Many aircraft are also equipped with chiller systems, thus reducing the amount of dry ice required for refrigeration of food and beverages.

*The effect of using the instrument with the shorter path length can be shown by comparing the traces in Figure 15 with those in Figure 14. The data in Figure 15 show more noise.

[†]This was one of several experimental challenges related to working in the close quarters of a coach seat space.

Over 100,000 individual measurements of time, carbon dioxide concentration, and cabin pressure were taken.

The FAA carbon dioxide limit of 5,000 ppm was never exceeded or even approached. Note that in Figure 13, the 2,000-ppm range was briefly exceeded once the instrument was turned on after the airplane reached 10,000 feet and electronic instruments could be used.

In the absence of temporary excursions, the carbon dioxide concentration on the outbound flight averaged about 1,300 ppm. On the return flight, the carbon dioxide concentration averaged about 1,250 ppm at the business class location and 1,300 ppm at the coach class location. This difference is not considered to be significant.

The general range of carbon dioxide concentration values observed is consistent with previous studies.

The spikes above the general background were associated with food/beverage service and tended to occur when a food/beverage cart was near the sample inlet. There was a spike at the beginning of the outbound flight that exceeded the 0 to 2,000 ppm range of the instrument. The period was brief and clearly did not approach 5,000 ppm at the location where the instrument was positioned. At this time the flight attendants were busily opening the many food carts, each of which had kilogram quantities of dry ice that had been stowed during passenger loading and takeoff. It is believed the carbon dioxide that had accumulated in the carts during passenger loading and takeoff was now being emitted as the carts were being opened. There can be no other explanation for the transient in Figure 13. The transient on the return flight, shown in Figure 14, is smaller because less dry ice was being carried in the carts and because the carts were opened at a slower pace, reflecting the difference between doing a full dinner service in first and business class for the outbound evening flight and a more leisurely brunch being served on the return flight that left mid-morning.

Looking at the steady-state portions of Figure 14 and Figure 15, the data show that the carbon dioxide concentration did not vary significantly with the seat location.

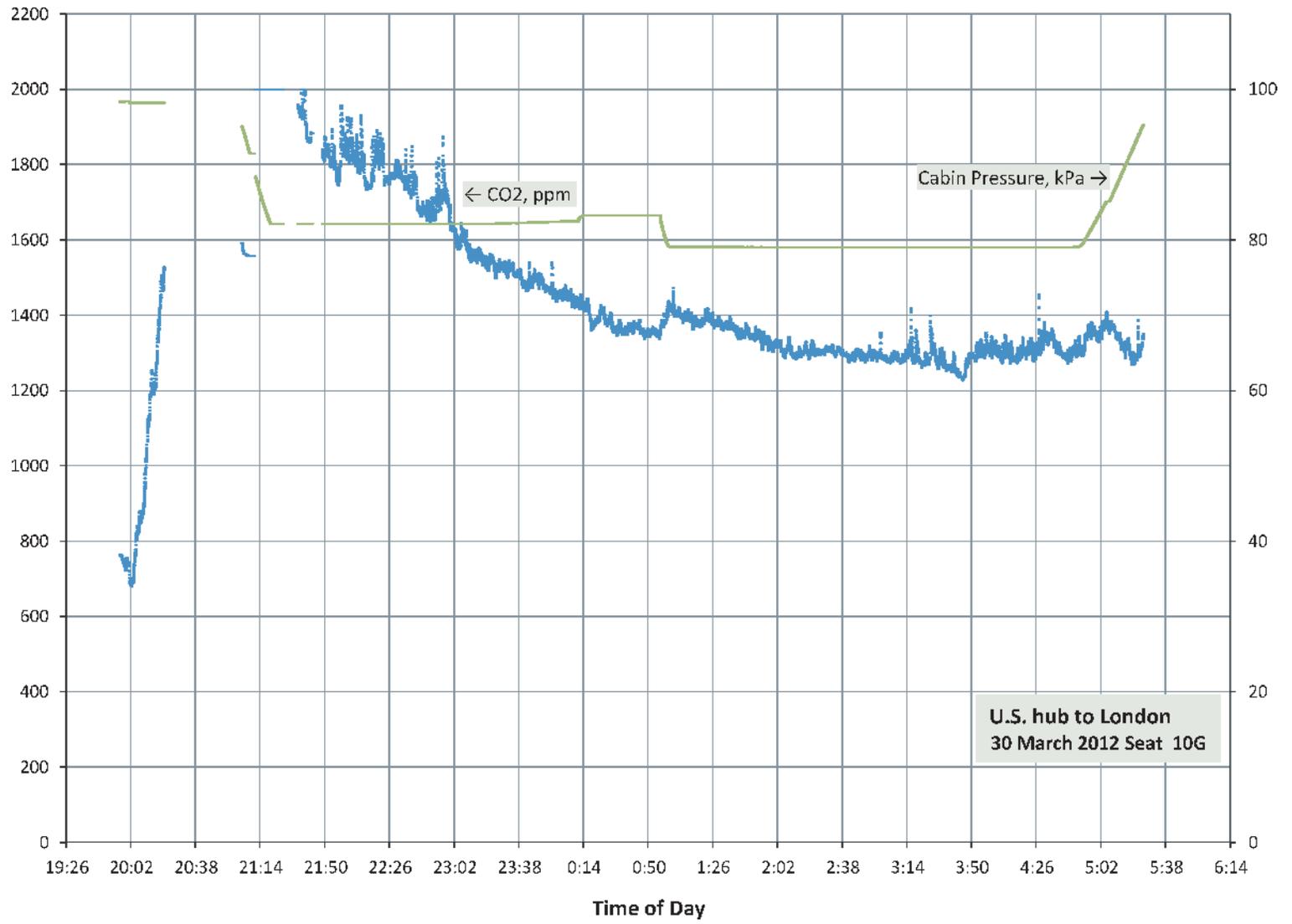


Figure 13. Cabin carbon dioxide concentration on outbound flight.

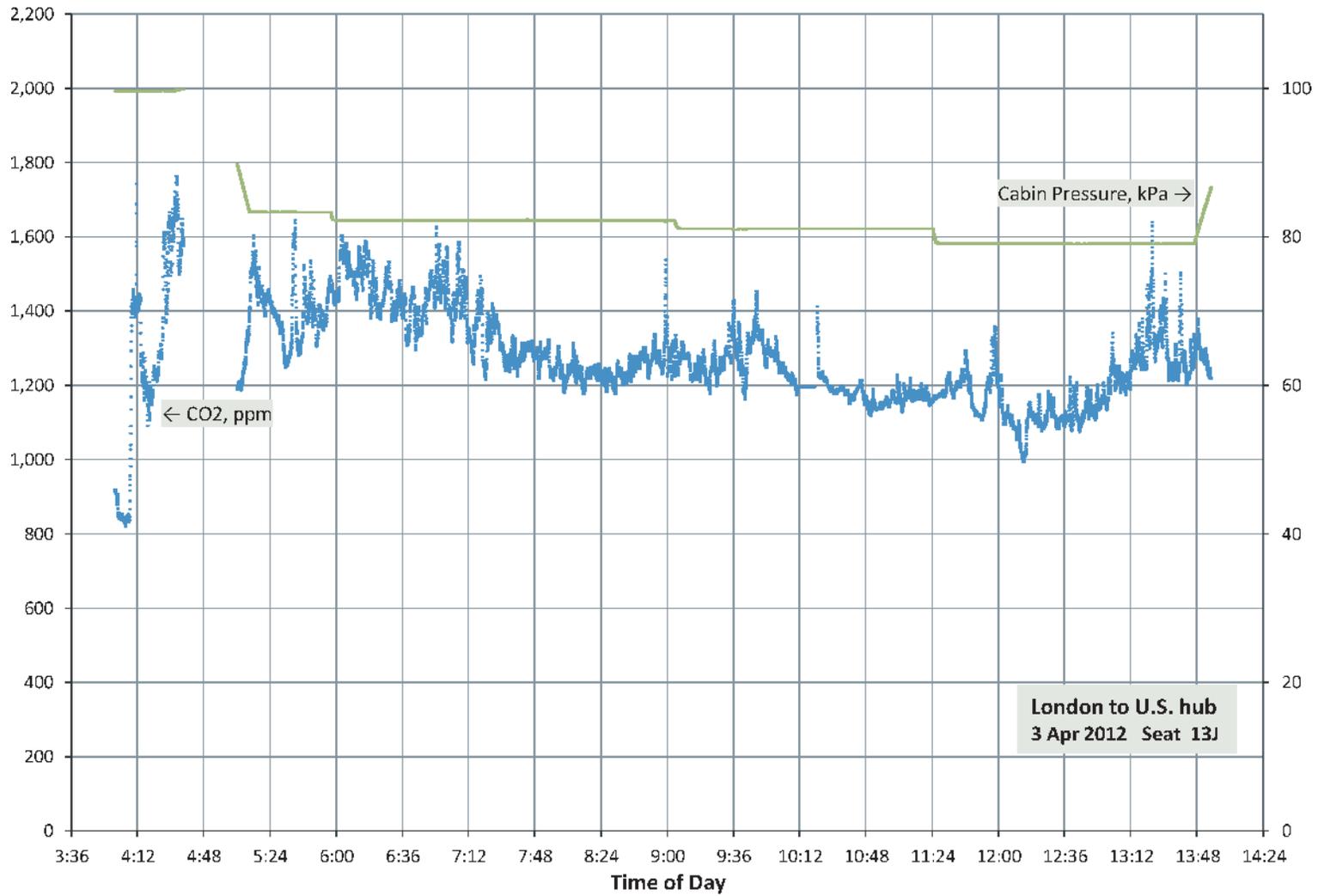
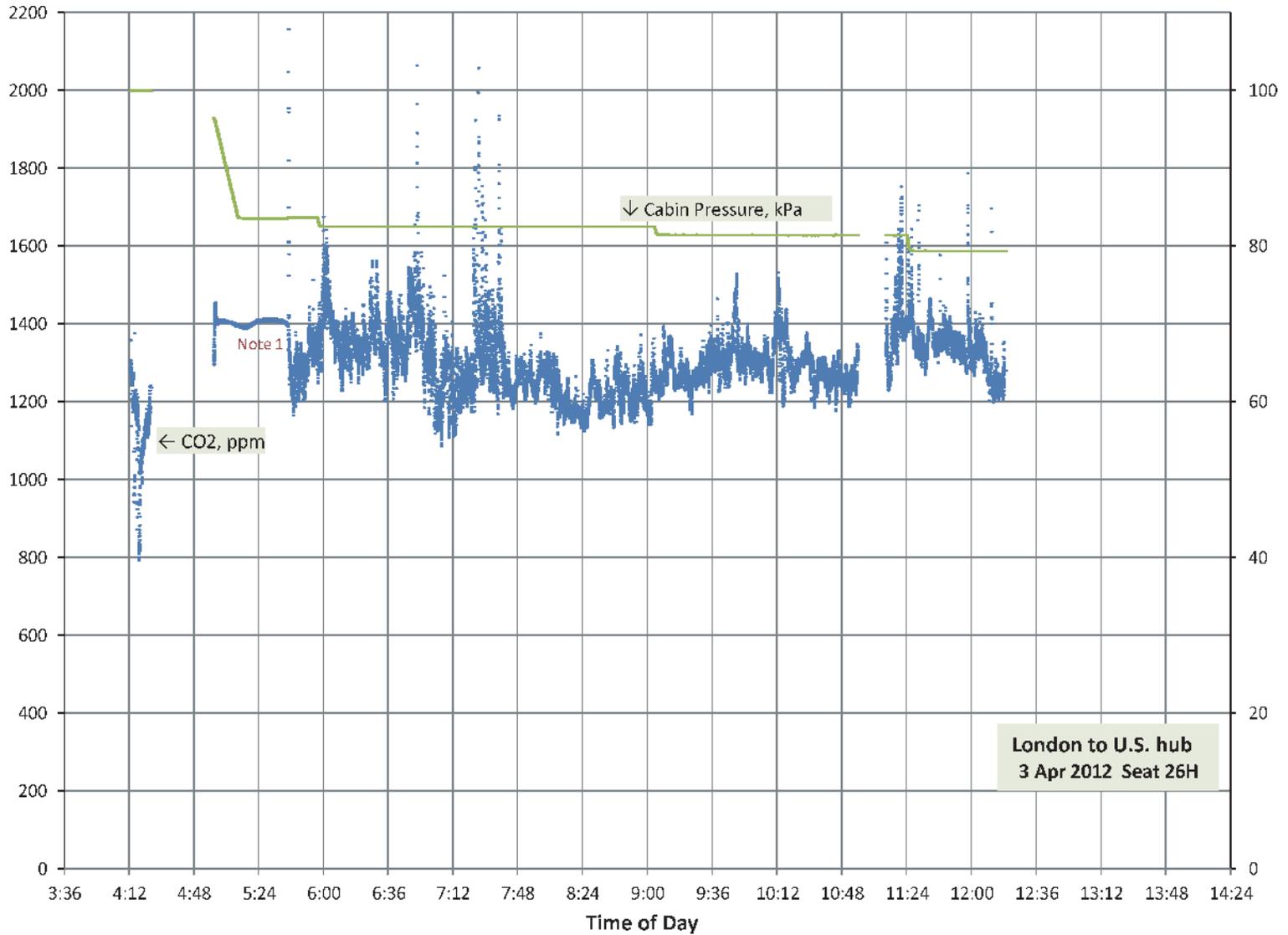


Figure 14. Cabin carbon dioxide concentration on return flight, location 1.



Note 1: The sample tube became disconnected and air was not entering the analyzer cell during this period.

Figure 15. Cabin carbon dioxide concentration on return flight, location 2.

Table 9. Relative importance of carbon dioxide sources on transatlantic flight.

Carbon Dioxide (CO ₂) Source	Estimated CO ₂ Production Rate, kg/hr	Percent of Total	Percent Added CO ₂	Calculated ppm CO ₂ , Outbound	Calculated ppm CO ₂ , Return
People	14	56	74	689	699
Ventilation air	6	24	—	390	390
Food service	4	16	21	303	241
Dry ice in cargo ^a	1 ^a	4	16	55	0
Totals	25	100	100	1,427	1,321

^a The amount of air leakage from the cargo compartment to the passenger compartment is not known. However, if more than 10% of the carbon dioxide produced from dry ice in the cargo compartment entered the passenger cabin, the leakage would have been detected by measuring the difference in carbon dioxide concentration during the outbound flight, which had 680 kg of dry ice in the cargo hold, and the concentration during the return flight with no dry ice in the cargo hold. It is not suggested that such in-leakage occurs; it is included only to compare magnitudes of possible sources. Boeing does note that “carriage of animals or other odiferous cargo in the forward cargo compartment may result in odors in the main cabin and flight deck.”⁶⁰ This indicates that some small amount of air flow from this cargo compartment into the cabin is possible.

The overall levels of carbon dioxide were somewhat higher on the outbound flight, particularly near the beginning of the flight. While the difference in the steady-state concentration between the outbound and return flight might not be statistically significant, the 50 ppm difference in steady-state values, as well as the higher levels observed at the beginning of the outbound flight, could be attributed to (a) differences in the numbers of passengers (the return flight had four more passengers), (b) differences in the food service (the outbound flight began with a dinner service; the return flight started with a smaller lunch service), or (c) infiltration of carbon dioxide from the dry ice carried on the outbound flight into the passenger cabin from the cargo hold. The likelihood and importance of these possible sources are discussed in the following.

Analysis of the Relative Importance of Carbon Dioxide Sources

The sources of carbon dioxide include (a) the outside air, (b) the passengers and crew, (c) any dry ice used for cooling food and beverages to be served on board, and (d) carbon dioxide that may have originated from dry ice in the cargo compartments and subsequently entered the passenger cabin. In order to place these carbon dioxide sources in perspective, calculations were performed using some very simple assumptions.

The results of the calculations are presented in Table 9; the assumptions are discussed in more detail in the following.

Carbon Dioxide from Passengers and Cabin Crew

The amount of carbon dioxide generated by the passengers and cabin crew depends on their metabolic activity level,

stated in METS. Inasmuch as the passengers are mainly at rest, we assume an activity level for the passengers of 1.0 MET.* Based on literature values, the airline flight attendant activity level was assumed to be 3.0 MET.⁶¹ The air carrier supplied both passenger counts and crew staffing levels for the test flights.

The total people-generated carbon dioxide was estimated using parameters from ASHRAE and the method described by Murphy.⁶² For the test flights, this source of carbon dioxide amounted to about 9 to 10 kg/hr.

Carbon Dioxide from Ventilation Air

Information on the actual ventilation rate for the test flight was not available. However, the body of published work, as well as available data from aircraft manufacturers, indicates that typical aircraft ventilation rates range from 10 to 20 ACH. Based on published information on aircraft specifications, the cabin volume of the Boeing 777-200 aircraft was estimated to be 480 m³, and, based on data for other wide body aircraft, the air change rate was assumed to be 14.7 ACH. Assuming that the ventilation air contains 390 ppm of carbon dioxide* and using the ventilation rate data supplied by Boeing for their 777 aircraft, about 6 kg/hr of carbon dioxide enters with the ventilation air.

*People at rest have an activity level of 1.0 MET. Various activities are considered as multiples of the resting value; the sleeping level is 0.9 MET; jogging is about 7 MET.

*Information from NOAA and from NASA test flights shows that, at altitude, the concentration of carbon dioxide in the air does not vary more than ±3 ppm from this value.

Carbon Dioxide from Dry Ice Used for Food and Beverage Cooling

Some airlines use dry ice for keeping food and beverages cold that will be served on board. The amount of carbon dioxide from this source varies widely and is dependent on the type of meal service provided, the length of the flight, and the way that the dry ice is used. Dry ice was used for food and beverage cooling on the flights that we surveyed. It is estimated that the amount of carbon dioxide generated from this source could be from 1 to 5 kg/hr.

Carbon Dioxide from Sublimation of Dry Ice in Cargo Compartment

As part of this test, on the outbound flight, 680 kg[†] of dry ice blocks was placed on a wood pallet in an uninsulated ULD and loaded into the Boeing 777 cargo compartment. Based on the actual weights of this ULD at the beginning and end of the flight, the estimated carbon dioxide production rate from the dry ice in the cargo compartment[‡] was 7.3 kg/hr.

Figure 9 is a schematic of the air flow on a typical airplane. Based on this diagram, all of the carbon dioxide produced from the presence of dry ice in the cargo compartment would be expected to be exhausted from the aircraft via the outflow valve. However, some of this carbon dioxide might enter the passenger cabin, either from leakage through the cabin floor or through intermixing of the various exhaust streams with recirculated air just prior to the outflow valve. Assuming that the amount of carbon dioxide that enters the passenger cabin amounts to 10% of the total amount formed in the cargo compartment, the estimated amount of carbon dioxide entering the passenger cabin is 0.73 kg/hr.

Ventilation Model for Onboard Test

Based on the carbon dioxide generation rates (discussed previously), the volume of the passenger cabin, and the ventilation rate (obtained from Boeing), the expected increase in carbon dioxide concentration above the 390-ppm natural background for each of these sources has been calculated

[†]This is the airline's limit for dry ice carriage on this type of aircraft.

[‡]The dry ice in this ULD was the only dry ice in cargo on this particular flight.

using an estimated cabin volume of 482 m³ (17,030 ft³), and a ventilation rate of 14.7 air changes per hour.[§]

Based on these data and assumptions, the total carbon dioxide concentration and the contributions of each of the carbon dioxide sources to the total are shown in Table 9.

Comments on Dry Ice Sublimation Rate

Using the weights of the ULDs containing the dry ice, and the known initial weight of dry ice prior to placing it on the ULD of a 680-kg test load of dry ice and the measured area of the stack of dry ice blocks, the area-normalized loss rate was about 1,600 g/m² · hr. Using the measured surface area of the LD3 container (a standard type of container used on 777 and other aircraft), the estimated area-normalized loss rate was about 400 g/m² · hr. Comparing these numbers with the results summarized in Figure 8, it can be seen that the lack of insulation results in a much higher sublimation rate, as expected. Note also that the rate of carbon dioxide production for the test load was the equivalent of perhaps 80 insulated cartons like the one shown in Figure 2.

This discussion points to the need for a packaging standard that specifies a minimum heat transfer resistance. Without that standard, packages with vastly different sublimation rates could be presented by shippers for carriage on airplanes.

Importance of Various Sources

- Looking at these estimates and comparing them to the observed results, it is clear that a small fraction of the carbon dioxide produced from the dry ice in the cargo compartment enters the passenger cabin, and the fraction that does enter is small compared to the carbon dioxide from other sources.
- Given the magnitude of the carbon dioxide produced by human metabolism of the passengers and crew, a 10% or 20% change in the assumed activity level of the passengers and crew would likely be more significant than the carbon dioxide derived from assuming some leakage of carbon dioxide produced by dry ice in the cargo compartment.
- Dry ice used for food and beverages is an important source and likely to be more important than dry ice carried in the cargo compartments.

[§]However, it is noted that a paper by Hocking gives a Boeing 777 (model not specified) passenger cabin volume of 620 m³ and a ventilation rate of 10.4 ACH. Hocking states in his paper that this information was confirmed by Boeing.

CHAPTER 11

Development of Dry Ice Limit Guidelines

The project task assignment called for constructing a decision tool that would allow air carriers to determine the maximum amounts of dry ice that can be safely carried* and for explaining and justifying the amounts of dry ice that the decision tool would recommend.

The first section of this chapter provides a step-by-step listing of the decision tool; the tool uses an area limit to establish the maximum number and size of dry ice packages that can be placed on an airplane. This is followed by a more detailed discussion of the technical considerations for developing the decision tool and recommendations for shipping guidelines that would need to be developed to implement area-based dry ice limits.

Summary of Steps to Determine the Quantity of Dry Ice Packages Allowed in an Airplane

The proposed limits for determining the allowable quantity of dry ice packages[†] are derived from a six-step process:

1. Establish a concentration limit for carbon dioxide in cargo holds. This document suggests that 30,000 ppm is consistent with the ACGIH STEL and Boeing guidelines.
2. Establish a dry ice sublimation rate. This document suggests an area-based rate of 250 g/m² · hr. This rate assumes that the carrier requires the use of insulated packages with a thermal resistance equivalent to 38 mm (1.5 in.) of EPS.
3. Consider the ventilation flow rates in any cargo compartment containing dry ice packages. If the flow rate is not known, the airframe manufacturer can provide it. If the

cargo hold is unventilated, then the void volume[‡] and maximum flight duration (perhaps based on the amount of fuel loaded on the plane) must be estimated in order to verify that the concentration limit established in Step 1 is not exceeded during the flight.

4. Calculate the total surface area of the packages that could be placed on the airplane and still not exceed the maximum allowable carbon dioxide concentration in the cargo compartment.
5. Compare the total surface area of the dry ice packages being shipped with the surface area limit calculated in Step 4.
6. If the total dimensional area of the dry ice packages being shipped is less than the limit established in Step 4, then the concentration limit established in Step 1 will not be exceeded.*

If the cargo compartment is unventilated, then the procedure is somewhat different. The first two steps are the same, but for Step 3 and Step 4 the calculation differs:

3. Estimate the total free volume of the cargo compartment, and from the flight data, estimate the duration of the flight. A void fraction of 50% is suggested if no other data are available. It is also suggested that the flight duration be based on the duration assumed when calculating the fuel loading.

*This work is not intended to make or propose regulations.

[†]In this context, the term “packages” includes insulated ULDs and pallets as well as cardboard cartons.

[‡]The void volume is the total compartment volume less the volume of the cargo. In the case of tightly packed cargo compartments or those with multiple ULDs, the void volume may be much less than the compartment volume.

*If there are also live animals in the compartment, the calculation of dry ice package limits must take into account the carbon dioxide produced by the animals. This additional calculation is beyond the scope of this report.

4. Estimate the total surface area of the dry ice packages that would produce a concentration in the free volume of the cargo compartment that equals the concentration limit used in Step 1.
5. Same as previous Step 5.
6. Same as previous Step 6.

These steps can be applied to both passenger and cargo airplanes. The steps shown will be examined in greater detail in the guidelines section that follows.

Development of Guidelines for Establishing Dry Ice Limits on Airplanes

Selection of Target Carbon Dioxide Concentration Limit

For areas “normally occupied by passengers or crew members” [14 CFR 25.831(b)(2)], the target carbon dioxide concentration is specified by the FAA as 5,000 ppm. However, cargo compartments do not fall in the “normally occupied” category.

Referring back to Figure 9, it can be seen that the ventilation for the cargo compartment’s air flows from the passenger cabin (or from the main deck in the case of an all-freight aircraft) to the cargo compartments and that exhaust air from the cargo compartments is then dumped overboard. Thus, carbon dioxide generated in the below-deck cargo compartments should have no effect on concentrations in the flight deck or the passenger cabin/main deck. (On the other hand, air that is exhausted from the passenger compartment already contains elevated amounts of carbon dioxide; this level would become the baseline for any increase in carbon dioxide concentration from dry ice cargo in ventilated cargo compartments.)

However, there are additional considerations. The first is cargo compartment safety during loading and unloading. One approach would be to set a cargo compartment carbon dioxide concentration limit equal to the 30,000-ppm STEL for carbon dioxide that has been established by ACGIH. They define short-term as a 15-min average. Such a limit would offer protection during initial entry into the compartment. After initial entry, the carbon dioxide concentration in the compartment would be reduced through flow through the open cargo compartment door.

The second consideration is that many airlines carry both live animals and dry-ice-cooled cargo, and therefore the limit must be chosen so that there is no conflict between the two. In a guidance document,⁶³ Boeing suggests a carbon dioxide concentration of a 30,000-ppm (3%) maximum for compartments in which there is live animal carriage. It is convenient that this limit is the same as the STEL suggested by ACGIH.

A further caution is the need to know the degree to which the cargo compartments are completely isolated from the

flight deck and the passenger cabin. Although the cargo compartments are to be maintained at a lower pressure so that during normal operation any leakage is into, rather than out of, the cargo compartment, abnormal conditions may occur. It is not certain that the cabin floor provides an airtight seal between the cabin and the cargo compartments, and there is a concern that off-normal conditions could cause carbon-dioxide-laden air from the cargo compartment to enter the passenger compartment or flight deck. Additional study of this issue is needed, and special procedures may be required to address these off-normal conditions.

Estimation of Sublimation Rates

As has been discussed, the sublimation rate is best estimated using the dimensional area of the package. Observed sublimation rates ranged from 120 g/m² · hr to 200 g/m² · hr, with an average of 170 g/m² · hr. Packages that were in a stack and had no air-exposed surfaces were at the lower end of the range. Based on these results, and including a safety factor of 1.5, a sublimation rate of 250 g/m² · hr is suggested. The sublimation rate used could be different, depending on safety factors used by the air carrier.

Consideration of Ventilation Air Flow

Information on the design amount of ventilation for a given compartment, as well as the compartment volume, is available from the aircraft manufacturer. However, the actual amount of ventilation may depend on how the aircraft systems are operated; for some newer aircraft there are even computerized ventilation control strategies that can adjust the amount of ventilation depending on the number of passengers.

Calculation of Maximum Allowable Dimensional Area

For a ventilated compartment, the maximum allowable package area may be calculated from the following formula:^{*}

$$\text{PkgArea} := \frac{\text{VentRate} \cdot (\text{CO2}_{\text{Limit}} - \text{CO2}_{\text{In}}) \cdot 10^{-6} \cdot \rho_{\text{CO2}}}{k_{\text{insul}} \cdot \frac{\Delta T}{\text{SubNum} \cdot t_{\text{insul}} \cdot \lambda_{\text{dryice}}}}$$

where[†]

PkgArea = total allowable dry ice package area, m²,
VentRate = ventilation rate, m³/s,

^{*}An Excel spreadsheet is available on the CD-ROM that accompanies this report that incorporates this formula and shows an example calculation.

[†]SI units are shown here, but any consistent set of units may be used, or appropriate conversion factors may be added.

CO_{2_Limit} = carbon dioxide ceiling concentration, ppm,
 CO_{2_In} = carbon dioxide concentration in the incoming air[‡], ppm,
 ρ_{CO_2} = density of carbon dioxide, kg/m³,
 ΔT = the temperature difference between the dry ice and the external environment, 100 K,
 SubNum = sublimation number, dimensionless,
 t_{insul} = insulation thickness, suggest 0.038 m, and
 λ_{dryice} = heat of sublimation of dry ice, 573 kJ/kg.

For an unventilated compartment:

$$PkgArea_{unvent} := \frac{\frac{CO_{2_Limit} - CO_{2_In}}{10^6} \cdot Vol_{compartment}}{SubRate \cdot FlightTime \cdot VoidFrac \cdot \rho_{CO_2}}$$

where the variables are same as the previous equation, except for:

$Vol_{compartment}$ = compartment volume, m³,
 $VoidFrac$ = fraction of compartment not occupied by cargo, dimensionless,
 $SubRate$ = area-based sublimation rate, kg/m² · hr, and
 $FlightTime$ = duration of flight, including a safety factor for delays, hr.

Guidelines for Implementation of Dry Ice Limits

Packaging

The development of dry ice quantity limits is predicated on the assumption that we know about the heat transfer to the dry ice. But, as of now, there is no standard that requires adequate insulation or even any insulation at all.

Insulation Standards for Packages

For packages, the following is suggested:

- Cardboard cartons could be dry ice certified. Dry-ice-certified cartons should have a minimum thickness of 35 mm of EPS foam protected by a cardboard carton. Note that currently there is no minimum amount of insulation specified or required. (Other packaging could be acceptable if the heat transfer performance could be shown to be equivalent or better according to the procedures of the ASTM D3103 standard.)

[‡]The carbon dioxide concentration in the incoming air can be assumed to be 390 ppm if outside air is used for ventilation. However, if air to the cargo compartment has previously been in the passenger cabin, a higher value, such as 2,000 ppm, should be used.

- It is also possible that less insulation could be accepted, but then the package should have an associated penalty factor that would increase the effective dimensional area of the package for the purpose of calculating dry ice package limits (and perhaps for calculating shipping costs as well).
- The heat transfer analysis suggested that the sublimation number could be used as a package design criterion if the package standard adopted does not specify a minimum EPS foam thickness, but more study is needed to validate the use of such a criterion and to assess its value in practice.

Insulation Standards for Insulated ULDs

For insulated ULDs:

- Specifications for insulated ULDs could require insulation and a maximum average U value of 0.35 W/m² K. Note that even though insulated ULDs from responsible vendors already meet this specification,* right now there is no insulation requirement.
- The information available on dry ice sublimation rates for insulated ULDs is still quite limited, and there are no data available from third-party tests. Tests with several types and brands of ULDs would provide increased confidence that their thermal performance can be bounded. Another issue is the degree to which the amount of dry ice added to an insulated ULD is actually accurately known—it is possible that some shippers just use a standard value for all shipments or just use the amount needed to fill the bunker that is found in the product literature. Actual measurements of carbon dioxide production rates would be helpful here.

Standards for Uninsulated ULDs

- Shippers using uninsulated ULDs (either with or without thermal blankets over the cargo) could be required to state the dry ice loss rates and to justify them based on actual third-party tests or on tests reviewed by a third party. The results of such tests could be used to develop an equivalent area-based dry ice loss rate. In the absence of such tests, uninsulated ULDs should be subjected to a much higher assumed dry ice loss rate.*

*If necessary, ASTM D3103, Standard Test Method for Thermal Insulation Quality of Packages, could be extended to cover the testing procedures.

*Recall that the dry ice loss rate for the test flight described in Chapter 10 was over 400 g/m² · hr based on the area of the entire LD3 container and over 1,600 g/m² · hr based on the area of the dry ice blocks themselves, compared to values of 120 to 200 g/m² · hr for insulated packages and ULDs.

Dimension and Area Data

Basing the estimated sublimation rate on dimensional area should be feasible. Major freight carriers already collect package dimensions from customers in order to calculate a dimension weight, which is then compared with the actual weight to determine the shipping charge. Knowing the package dimensions, the calculation of package area is straightforward. For ULDs there are a few standard sizes, and their areas need to be determined only once. After that, the area associated with the type of ULD could even be stenciled on the ULD as the tare weight is now. We believe that for other cargo (e.g., pallets), it is reasonable to ask the shipper to provide this information.

Guidelines for Specific Locations and Situations

Guidelines are presented in the following for specific locations on the aircraft.

Guidelines for Passenger Compartment

For the passenger compartment: The decision tool could include a nominal limit for the number of packages containing dry ice based on the cabin volume, the ventilation rate, an estimate of the carbon dioxide emissions from the passenger cabin occupants based on the potential number of passengers and crew, and an estimate of the carbon dioxide sublimation rate from packages with dry ice based on a $300 \text{ g/m}^2 \cdot \text{hr}$ carbon dioxide emission rate. (This sublimation rate is higher to account for the possibility that some passengers may use substandard packaging.) The limit should also take into consideration that there may be some uncertainty in passengers' estimates of the amount of dry ice actually carried on board. In keeping with the discussion in Chapter 3, the guidelines could be based on a 5,000-ppm carbon dioxide concentration limit because the cabin is an occupied space.

However, given existing restrictions on the number and size of carry-on items that passengers may bring on board, the need for passengers to stow other luggage, and the overall lack of space for carry-on packages in the passenger cabin, the number of parcels with dry ice will be few, and it is likely that dry ice packages in the passenger compartment will never be an issue.

Guidelines for Ventilated Cargo Compartments

For a ventilated cargo compartment: The limit for dry ice carriage could be based on dimensional area of the cargo and a normalized dry ice loss rate, either $250 \text{ g/m}^2 \cdot \text{hr}$ or a higher value for an increased safety factor, as well as the cargo compartment volume, the ventilation rate, and a 30,000-ppm carbon dioxide concentration limit.

Guidelines for Unventilated Cargo Compartments

In the case of unventilated cargo compartments, the carbon dioxide concentration will continually increase with time, so the amount of dry ice that can be tolerated is smaller and must be strictly controlled so that the carbon dioxide concentration limit is not reached prior to the end of the flight. Airbus suggests that for unventilated cargo compartments, the total volume of carbon dioxide generated by the dry ice packages over the duration of the flight must be less than the volume of the cargo compartment times 0.005, which is equivalent to establishing a carbon dioxide concentration limit of 5,000 ppm. Considering that a good argument may be made for a 30,000-ppm limit, the Airbus limit might be too restrictive.

However, it should also be noted that much of the cargo compartment volume may be occupied by the volume of cargo or ULDs, and so the free volume of air to absorb the carbon dioxide may be considerably less than the volume of the empty compartment. It is this void volume that should be used for any calculation of expected carbon dioxide concentrations, not the volume of the empty compartment.

For an unventilated cargo compartment, what is proposed instead is that the limit be based on the effective cargo compartment volume, the maximum flight time, the carbon dioxide production rate in the cargo compartment (based on a sublimation rate of $250 \text{ g/m}^2 \cdot \text{hr}$), and a 30,000-ppm carbon dioxide concentration limit. The maximum flight time should be based on the actual expected flight time plus any possible extra flying time according to the amount of extra fuel carried on board; moreover, procedures should be in place to account for ground delays.

Guidelines for Regional Jets

No information was obtained on ventilation rates for regional jets. Nor did these manufacturers provide any information on air flow paths, ventilation control strategies, or ventilation rates.

In view of the lack of information on ventilation flow paths, compartment volumes, and ventilation rates for regional jets, there is no engineering basis for setting dry ice carriage limits. Without any engineering basis of estimate, carriage of dry ice on these aircraft cannot be recommended.

Some information on compartment volumes of regional jets may be obtained from published sources or the Internet. It is possible that a dry ice package with a very small area could be carried based on knowledge of the compartment volume alone, without assuming any ventilation. However, such capacity would be minimal.

Consider an Embraer 145 regional jet with a cargo compartment volume* of 9.2 m^3 (325 ft^3). Assuming no ventila-

*Regional jet compartment volumes can be found in various industry reference manuals and Internet sources.

tion,[†] a 1-hour maximum flight time, a 50% void volume, a 5,000-ppm concentration limit,[‡] and a sublimation rate of 250 g/m² · hr, the total surface area of dry ice packaging that could be placed in that cargo compartment would be 0.24 m². This is equivalent to one small package having dimensions of about 200 mm (about 8 in.) on a side. Note that for regional jets, because the cargo space is limited, the void volume could be considerably less than 50%, further limiting the allowable number of packages. A void volume of 25% would lower the allowable total surface area of dry ice packages to 0.12 m², implying that no dry ice shipments should be allowed on regional jets.

Summary of Implementation Steps

A summary of the dry ice implementation steps is presented in the following.

Prerequisites:

- Establish an allowable concentration limit for carbon dioxide in the compartment containing the dry ice packages.
- Develop specifications for the insulating ability of dry-ice-certified packaging.
- Develop specifications for the insulating ability of insulated ULDs.
- Ascertain aircraft compartment volumes and ventilation rates.

Is dry ice carried on board by passengers?

- Advise passengers of 2.5-kg limit.
- Advise passengers of need for dry-ice-certified packaging.
- Provide information on dry-ice-certified packaging.
- It is not believed that any other tracking is necessary inasmuch as it does not seem likely that more than a few passengers will have dry ice, and the packages will necessarily be of modest size. Perhaps use a nominal value of 0.15 kg/hr for each such package given that their size is necessarily limited. For 10 packages, this would be 1.5 kg/hr.

[†]The compartment is assumed to contain fresh air prior to loading.

[‡]Without knowing the ventilation air paths, we must assume that cargo compartment air may enter the passenger compartment.

Is dry ice carried in cargo compartments?

- Advise shippers of need for dry-ice-certified packaging or the use of insulated ULDs with an equivalent insulation value.
- Collect package dimension information.
- Compute the total dimension-based area of all packages with dry ice.
- Compute the total dimension-based area of all insulated ULDs with dry ice.

Is conditioned air supplied to the compartment?

- If yes, determine the aircraft ventilation rate in volume of air per time (e.g., cfm, m³/hr, L/s).
- Compute a total dimensional area limit for each compartment from the compartment volume, ventilation rate, allowable carbon dioxide concentration limit, and assumed normalized loss rate. If the ventilation rate does not change, this needs to be done only once for each aircraft type and configuration.
- Compare the total dimensional area of packages and insulated ULDs containing dry ice to the maximum allowable package area for a given aircraft ventilation rate.

If no conditioned air is supplied to the compartment:

- Find out the maximum flight duration, including a reserve for possible flight delays.
- Use the compartment volume, void fraction, and maximum flight duration to compute the maximum allowable package area.
- Compare the total dimensional area of packages containing dry ice to the maximum allowable dimensional area for a given aircraft situation.
- Develop procedures to trigger a warning if the assumed flight time is exceeded.
- Use special ventilation procedure upon unloading, such as: open hatch, insert canvas air supply hose, wait, then unload.

Note that the calculations used to estimate buildup of CO₂ in an unventilated compartment could also be used to establish a time limit for cargo handler activity during loading if a normally ventilated compartment was not actually being supplied with ventilation air.

CHAPTER 12

Recommendations for Future Work

This report suggests a technically based approach to specifying dry ice limits on aircraft. Because a new approach is proposed, the existing base of technical data, experience, and procedures will need to be augmented, and administrative changes may be required for implementation. Although these are beyond the scope of this project, they are described in the following.

Administrative Steps

At the present time, regulatory agencies provide general guidelines for dry ice carriage, and air carriers establish their own aircraft limits based on the guidelines. This division of responsibilities seems to have worked in the past, suggesting that the use of area-based limits does not need to change the responsibilities assigned to the regulator and the carrier. However, if an area-based limit were established, changes may be required to both the administrative procedures used by the airlines when establishing these limits and to the regulations.

The carriers would need to establish at least two new standards: (1) the maximum carbon dioxide concentration allowed in a cargo hold,* and (2) a minimum packaging standard for packages (or ULDs) containing dry ice.†

In the past, the FAA and PHMSA requirements for dry ice carriage on aircraft have been based on the mass of dry ice carried and on an assumed percent of the dry ice inventory per hour that sublimates. There are FAA circulars and even a NAS report for establishing an allowable quantity of dry ice that use a mass-based dry ice sublimation rate.

*In a previous section, a concentration of 30,000 ppm was suggested as a limit in cargo compartments.

†An amount of insulation equal to 38 mm (1.5 in.) of EPS would be consistent with current good practice.

The technical findings of this project show that establishing limits based on package area is more technically sound than the current dry ice inventory limits based on dry ice mass and on standard sublimation rates. However PHMSA, in Part 173, specifically bases its packaging, labeling, and documentation requirements on the mass of dry ice.

For carriers to implement these new procedures, PHMSA and FAA would need to revise their policies and regulations. Thus, one of the first steps would be to have discussions with the regulators, FAA and PHMSA (and for international shipments, ICAO and IATA).

Possible next steps include:

- A meeting with and presentation to the FAA to discuss how the new approach may be coordinated with existing FAA reports and circulars on dry ice limits.
- A workshop for aircraft manufacturers, air carriers, FAA, PHMSA, IATA, and other stakeholders to describe the work and the results and to identify any concerns or issues with implementation of dry ice packaging standards and utilization of the dimensional-area approach.
- Preparation of explanatory materials for various audiences.

Although some carriers already require shippers to collect information on package dimensions in order to calculate a dimensional weight, the need to have package dimensions available in order to calculate the package area may represent a change in data collection procedures for the air carrier and some shippers.

As mentioned previously, the amount of insulation is the most significant factor in determining the rate of sublimation, yet there are currently no requirements on the minimum amount of insulation for either packages or insulated ULDs. The development of industry standards and appropriate certification tests (probably based on ASTM standards) would be needed.

Recommended Future Technical Studies on Dry Ice Sublimation

Assessment of Sublimation Rates from Palletized Packages

Some packages may be palletized and act like a single large package or even like an insulated ULD in that the overall configuration limits the rate of heat gain.* How to reliably specify the heat transfer for this situation requires information on industry practices and the configurations of freight actually seen in the system. For example, packages that are all the same size may pack more efficiently than packages of mixed sizes. And packages secured with bands may be more tightly packed than those secured with shrink wrap or netting. Extensive firsthand observations of freight may be the only way to gain this knowledge.

Also, some vendors sell thermal blankets intended for use in covering shipments of cold cargo contained in an ordinary ULD; there is a lack of information about the heat transfer performance of this configuration.

Effect of Variation in Dry Ice Form

Most of the experimental studies of dry ice in cargo used a particular form of dry ice: blocks, slabs, or pellets. Generally, the most reasonable or most common form was tested. However, there is a lack of comparisons in which the only variable was the form of dry ice. For example, the FAA box tests used dry ice in the form of 10-mm × 20-mm pellets. It would be useful to have another test in which all variables were constant except for the size of the pellet* or the use of slabs or blocks instead of pellets.

Obtaining Further Technical Data on Aircraft Ventilation

Aircraft Ventilation System Configuration

There are many ways that the conditioned air system of an aircraft can be configured, and we have been able to consider only the most general aspects. Different configurations of cargo compartment ventilation can be specified when the aircraft is ordered. Additional information about the installation of air conditioning equipment on board the aircraft and the ways that freight can be configured would be helpful.

*Because only the packages on the outside of the stack are exposed to ambient temperatures, those in the interior may experience little or no heat gain.

*Dry ice pellets come in different sizes.

Moreover, aircraft manufacturers are continually making changes to aircraft and/or ventilation configurations. The effects of such changes should be monitored to determine the possible effect on dry ice carriage limits. For example, some Boeing 777 aircraft have been modified to place crew rest quarters below the main deck.

Also, if a large part of the volume of the compartment is occupied by cargo, the volume of free space available to absorb the carbon dioxide emissions may be limited, and the nominal cargo compartment volume may not be the appropriate volume to use in ventilation calculations. In the case of aircraft that carry only freight, virtually the entire compartment volume may be occupied by ULDs, with only a small clearance volume on the periphery. This situation needs more study.

Finally, additional information is needed about the amount of leakage of air from the cargo compartment to the passenger compartment or even the flight deck. Even though these areas are separated by interior partitions, it is not known how airtight these partitions are. This is particularly important in the case of unventilated cargo compartments. Without a forced air flow through the compartment, the path followed by the carbon dioxide produced by the sublimation of dry ice is uncertain.

Aircraft Ventilation System Operation

Questions arise from the use of both manual and computer controls of conditioned air systems for aircraft. With manual control, we may not know all the circumstances when a pilot may change or disable the operation of the conditioned air packs, or in the case of conditioned cargo compartments, what temperature set points are used. And likewise with computer control, we may not know all the inputs and algorithms that control the operation. This lack of knowledge introduces uncertainty into the assumptions about ventilation rates.

Off-Normal Operation

Additional study is needed on ways aircraft ventilation systems may be subject to off-normal operation, particularly during ground delays and when there are unexpected maintenance issues.

Regional Jets

We do not have reliable information on the compartment volumes, ventilation strategies, and ventilation rates of either the cabins or the cargo compartments of regional jets. Until such information is provided, the safety of shipping dry ice packages on such flights cannot be assessed.

Obtaining Further Technical Data on Aircraft Operations

Dry Ice in Passenger Cabin from Carry-On Packages

Additional information on the number of passengers that carry packages containing dry ice on board with them would be helpful. Although this mode is not believed to be a significant source of carbon dioxide, actual survey data on the number of such packages would increase the certainty of the estimates used to come to this conclusion.

Aircraft Loading and Unloading Procedures

Because aircraft compartments may vary in their dry ice load and ventilation rate, loading and unloading procedures may need to vary as well. Special procedures may be needed for:

- Identifying compartments without a ventilation air supply. This could consist of a marking or placard for baggage/freight handlers. It would be desirable for this marking to be standardized.
- Loading and unloading compartments known to have large amounts of dry ice. This would be particularly important if there has been a delay in loading or unloading without full ventilation system operation.

Use of Dry Ice for Food and Beverage Cooling

Some airlines use dry ice for food and beverage cooling on some routes. The impact of such use on carbon dioxide concentrations in the cabin is in need of further study: data collected through this project indicate that this can be a significant source of carbon dioxide.

Obtaining Further Technical Data on Carbon Dioxide Measurements on Board Aircraft

A key question concerns the ability of the decision tool to accurately predict actual carbon dioxide concentration levels in aircraft cargo spaces. This question can only be addressed with a comparison of predicted carbon dioxide concentrations based on predicted sublimation rates (using the dimensional-area method) with the actual carbon dioxide concentrations observed during onboard measurements.

Onboard Measurements in Passenger Cabin

Clearly the number of flights tested in this study (two) was limited, and measurements on additional flights (particularly

flights with different model aircraft or flights operated by different carriers) would be valuable.

Onboard Measurements of Carbon Dioxide in Cargo Compartments

Among the original objectives of this project were plans to determine typical carbon dioxide concentrations in the cargo compartments of aircraft carrying substantial amounts of dry ice and to use these measurements to validate proposed dry ice carriage guidelines. These measurements were also intended to help verify the feasibility of applying the proposed guidelines to actual cargo shipments containing dry ice. Several air carriers expressed interest in such measurements at the beginning of the project and also as the project progressed.

In order to support this plan, Battelle selected and tested a carbon dioxide monitor capable of making and storing measurements of carbon dioxide concentration as well as temperature, humidity, and ambient pressure. In order to protect the monitor, reduce emissions of electromagnetic radiation,* and provide for increased battery life,† Battelle designed and constructed an instrument package. The exterior dimensions of the package were about 12 in. × 9 in. × 5 in. Using four alkaline D cells, the monitor was capable of operating without attention for a period of 3 days—long enough to allow for deploying it on round-trip flights to international destinations. Figure 16 shows exterior and interior views of one of these packages.

However, none of the candidate host air carriers could obtain a commitment from their management to support the use of this equipment for cargo compartment tests during the time the HMCRP Project 09 study was active.

We believe, however, that with additional dialogue on technical requirements and with additional testing, an acceptable instrument package could be developed that would allow cargo compartment measurements during flight. There is precedent for electronic equipment being used in cargo compartments during flight, a prime example being active insulated ULDs that have fans, electronic temperature measurement, and data loggers, all operating unattended under computerized control.*

*Even without the increased shielding, the instrument met Boeing's EMI standards for use during all phases of flight.

†In the standard configuration as supplied by the vendor, the monitor uses four AA alkaline cells. This provides an expected battery life of 8 to 12 hours.

*One such insulated ULD uses 14 D cells as a power source for the fans and associated computer control system and contains a data logging system.



Battelle photos

Figure 16. Exterior and interior views of portable CO₂ monitor.

Improving Precision for the Decision Tool

As additional technical data become available, it is likely that the proposed decision tool itself could be refined. For example, independent third-party measurements of the dry ice loss rates of insulated ULDs are presently not available. Also, experimental data are not available for non-insulated

ULDs that are completely filled with packages containing dry ice. Additional data may also become available for a wider variety of package sizes and aspect ratios.

Additional data would allow more accurate estimation of error bounds, and therefore greater confidence could be placed in the predicted results. This could allow for the use of a lower safety factor or even support the use of different sublimation rates for different classes of cargo or packaging.

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation