National Transportation Safety Board
Office of Research and Engineering
Washington, D.C. 20594

Dry Ice Sublimation Study

Specialist Report
Marie Moler

A. ACCIDENT

Location:	Bakersfield, California
Date:	November 23, 2018
Time:	1733 PST
Airplane:	Cessna 208, N781FE
NTSB Number:	WPR19IA030

B. GROUP

No group was formed.

C. SUMMARY

On November 23, 2018, about 1733 Pacific standard time, the pilot of a Cessna 208B, N781FE, became incapacitated after he reached the airport run-up area at Meadows Field Airport (BFL), Bakersfield, California. The airline transport pilot received minor injuries and the airplane was not damaged. The airplane was owned by FedEx Corporation and operated by Westair, Inc. under the provisions of Title 14 Code of Federal Regulations Part 135 as an on-demand, scheduled cargo flight. Visual meteorological conditions (VMC) prevailed, and an instrument flight rules flight plan was filed for the cross-country flight that was destined for Ontario, California.

D. DRY ICE SUBLIMATION STUDY

The purpose of this Study is to determine the possible amount of gaseous CO_2 produced in the airplane by the dry ice on board. The pilot reported that he closed the door and started the engine at 1729 PST. Due to the perceived cold air temperature, the vents had been closed to outdoor air. The Fire Captain who responded to the pilot incapacitation call reported that he opened the door at 1806 PST. According to these reports, the airplane's doors and air vents were closed for 37 minutes.

The operator reported the amount of pellet form dry ice that was aboard the airplane at the time of the incident was 36.9 kg (81 lbs) distributed through 41 boxes. However, the individual packing the boxes with dry ice that day was not a normal packer and misunderstood the equivalency between the number of scoops of pellets to pounds of dry ice, and inadvertently overfilled each box. Within twenty-four hours after the incident, the Federal Aviation Administration (FAA) weighed the cargo after most of the dry ice had sublimated and only 2.8 kg (6 lbs) remained. Accounting for the remaining dry ice, FAA calculations showed that the actual dry ice load was closer to 76.6 kg (169 lbs).

Weather Observations

The Meteorological Terminal Aviation Routine Weather Report (METAR) data at 1754 PST was temperature of 57°F (14°C), dew point of 54°F (12°C), pressure of 29.7 inHg, and winds from the southwest at 4 kts with light rain.

Dry Ice Sublimation Literature

Dry Ice is the solid state of carbon dioxide (CO_2) and is used to keep cargo in a frozen or chilled condition. It sublimates (changes from a solid to a gas with no intervening liquid form) at temperatures above -109°F (-78°C) under normal atmospheric pressure. As dry ice sublimates in a closed environment, the percentage of gaseous CO_2 increases in the air, reducing the amount of oxygen available to the crew. The Occupational Safety and Health Administration (OSHA) has set an 8-hour Time Weighted Average Permissible Exposure Limit (PEL) to be 5000 ppm (5000 parts of CO_2 per million parts of air) or 0.5% CO_2. The FAA Advisory Circular 91-76A (AC 91-76A) states that CO_2 exposure in aircraft should not exceed 0.5%.

FAA Advisory Circular 103-4, Hazard Associated with Sublimation of Solid Carbon Dioxide (Dry Ice) Aboard Aircraft, was issued in 1974 and presented the following equation to calculate the allowable amount of dry ice for a given aircraft volume and air exchange rate

$$Dry\ ice\ loading\ (lbs) = \frac{(CO_2 concentration)(Aircraft\ volume, ft^3)(complete\ air\ exchanges\ per\ hour)}{(sublimation\ rate)}$$

The 1974 AC used a sublimation rate of 1% (by weight) per hour. In 2004, AC 91-76 replaced the older AC 103-4 (with the same title) and updated the dry ice sublimation rates. For dry ice loads greater than 100 lbs it was recommended the 1%/hour sublimation rate be used. For loads less than 100 lbs, a sublimation rate of 2%/hour should be used for calculations. However, testing has shown that the sublimation rate of dry ice varies based on the amount, the type of ice (block, pellet, etc), packaging, ambient air temperature and pressure, and other factors and can vary considerably [1]. AC 91-76 was updated by AC 91-76A in 2009. The volume of gaseous CO_2 produced by one pound of dry ice was updated from 8.5 ft^3 to 8.8 ft^3. The 8.8 ft^3 value will be used in this report.

All three ACs stress the importance of ventilation to the safe transportation of dry ice. AC 91-76A states "maintaining adequate input and circulation of fresh air is the single most important precaution that must be taken when dry ice is transported" and "In the absence of ventilation, it would take a small amount of dry ice to produce an unacceptable level of CO_2 in the aircraft."

Dry Ice Sublimation in Incident Aircraft

Calculations were done to determine the possible concentration of CO_2 in the incident airplane. As stated earlier, the pilot reported closing the airplane's vents, so CO_2 would have built up in the airplane as the dry ice sublimated. These calculations assume no air exchange with the air outside the airplane. Since the airplane is not perfectly airtight this is not strictly accurate, but it can be assumed that air transfer was minimal as the internal and external air pressures were likely the same. The amount of CO_2 produced by the dry ice was calculated as

$$gaseous\ dry\ ice\ CO_2 = initial\ weight\ of\ dry\ ice\ \times sublimation\ rate\ \times time\ unvented$$

The initial weight of the dry ice was determined to be 76.6 kg (169 lbs) and was distributed across 41 separate boxes. Since each individual box held significantly less than 100 lbs, the 2%/hour sublimation rate is used in this Study.

CO_2 is naturally present in the atmosphere at varying levels and a concentration of 390 ppm or 0.039% was used in this Study. Additionally, a sitting adult produces about 0.0043 L/s of CO_2. Naturally present atmospheric CO_2 and the CO_2 produced by a single individual are significantly less than the CO_2 from dry ice sublimation but are included in these calculations for accuracy. The total amount of CO_2 in the aircraft was calculated as

$$total\ CO_2 = atmospheric\ CO_2 + pilot\ produced\ CO_2\ + dry\ ice\ produced\ CO_2$$

The concentration of CO_2 was dependent on the volume of the aircraft that was air and not cargo. The volume of the interior of the airplane minus the known dimensions of the cargo aboard yielded an air volume of 239 ft^3. The calculation for the percentage of CO_2 in the airplane is

$$\%\ CO_2 = \frac{total\ CO_2\ volume}{air\ volume\ of\ airplane}$$

This calculated percentage of CO_2 assumes an averaged concentration across the entire interior of the airplane. However, the gaseous CO_2 from dry ice is heavier than air and tends to sink so the concentration was likely to vary across the air volume, being higher in some areas and lower in others.

Table 1. CO_2 concentrations after time unvented from incident airplane configuration.

Time with vents closed, minutes	Naturally occurring CO_2, ft^3	CO_2 produced by the pilot, ft^3	CO_2 from sublimating dry ice, ft^3	CO_2 concentration, %
5	0.09	0.05	2.48	1.09
15	0.09	0.14	7.44	3.21
30	0.09	0.27	14.8	6.37
45	0.09	0.41	22.3	9.54
60	0.09	0.54	29.7	12.7

These results assume an airtight fuselage and uniform distribution of CO_2 through the air volume, so they should be considered estimates of the concentration. After five minutes in the unvented airplane, the CO_2 concentration was calculated to be above 1%, twice the FAA and OSHA standards. By 30 minutes, the concentration was above 6% and by one hour it could be above 12%.

If the initially reported 36.9 kg of dry ice had been loaded on the airplane the CO_2 concentrations would have been about half that of the 76.6 kg load, as shown in Figure 1. The CO_2 concentration could have exceeded 1% in about 10 minutes of unvented time.

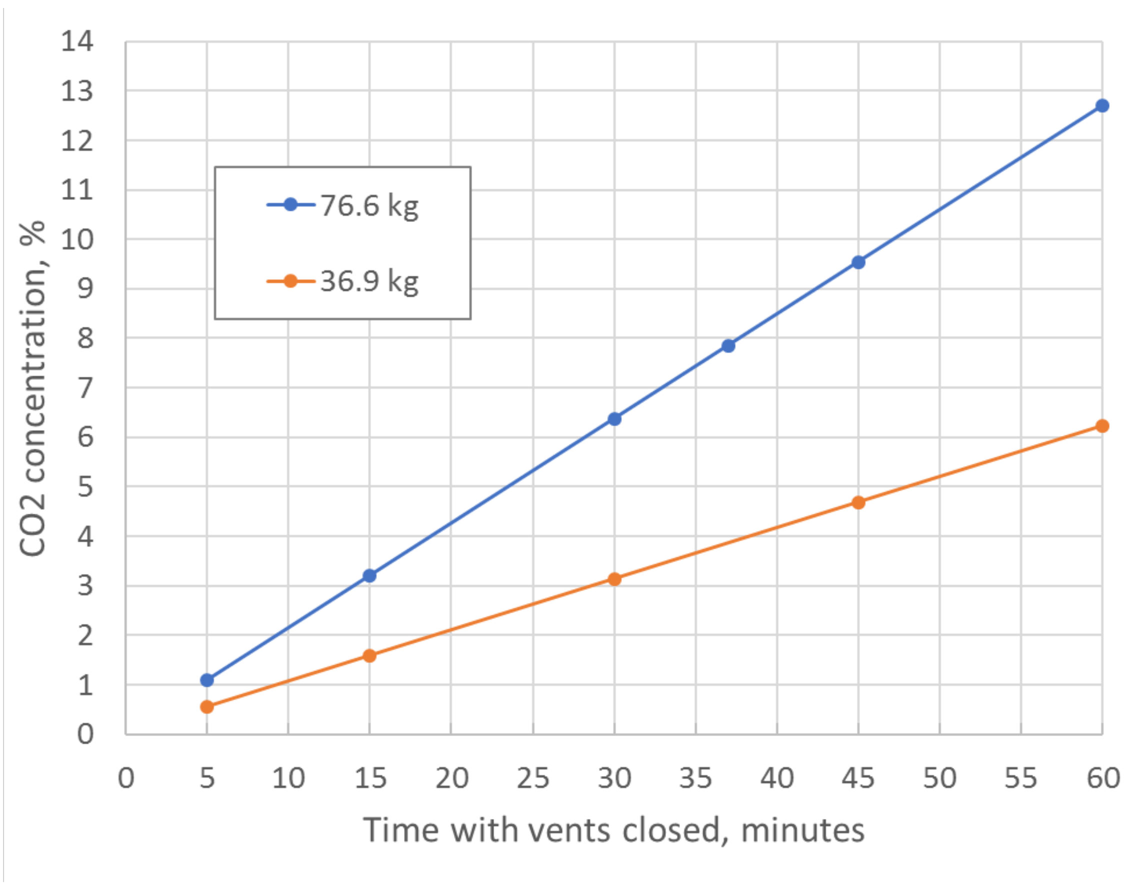

Figure 1. CO_2 concentrations versus time unvented from incident airplane configuration.

Necessary Ventilation for Dry Ice

Of interest was the amount of ventilation needed to safely carry the quantity of dry ice that was aboard. The relevant advisory circular presents the following equation to calculate dry ice loading (in pounds, lbs), X, as

$$X = \frac{(CO_2 concentration)(Aircraft\ volume, ft^3)(complete\ air\ exchanges\ per\ hour)}{sublimation\ rate}$$

The ventilation is communicated as "complete air exchanges per hour" because larger airplanes recycle a portion of the air in the cabin and cargo areas. Table 2 shows the results of using the equation above to determine the required air exchanges to keep CO_2 levels at or below 0.5%. Exchanges of air per hour is dependent on the aircraft volume and is therefore specific to the incident airplane configuration. Volumetric flow rate, reported in cubic feet per minute (cfm), however, is consistent for all volumes of airplane.

Table 2. Required air exchange rate and volumetric flow rate to keep CO_2 below 0.5% concentration.

Weight of ice, lbs	Sublimation rate, %/hr	Exchanges of air per hour	Volumetric flow rate, cfm
36.9 kg (81 lbs)	2	12	48
76.6 kg (169 lbs)	2	25	99

Cessna provided FedEx (then Federal Express) cabin ventilation and heater flow rates for the Cessna 208A in a memo from 1985 [2]. Ventilation rates at two airspeeds for two forward overhead vents and two forward side vents were provided. Volumetric flow rates through all vents increased with increased airspeed. Additionally, the volumetric flow rate of the bleed heat at full hot was provided at two altitudes. The flow rates could be as low as 23 cfm for only a single small vent opened or as much as 243 cfm when all vents were opened (bleed heat flow rates fell between 90-140 cfm). This translates to possible dry ice loading amounts between 17 kg (39 lbs) and 375 kg (830 lbs)[1]. The ventilation system of a Cessna 208 could adequately vent the CO_2 produced by 76.6 kg of dry ice while in flight with sufficient vents open. Ventilation information for a stationary airplane on the ground was not available.

[1] The low value reflects a 2% sublimation rate and the smallest vent open at a lower airspeed. The highest value represents a 1% sublimation rate, all the vents open, and a high airspeed.

E. CONCLUSIONS

Without adequate ventilation, the amount of CO_2 produced by the sublimation of dry ice can quickly become dangerous in an aircraft. The incident airplane, a Cessna 208, was loaded with an estimated 76.6 kg of dry ice when the pilot closed the airplane's external vents to maintain heat in the cabin. Assuming there was no exchange of air with the outside and that the 76.6 kg of ice was sublimating at a rate of 2%/hour, the concentration of CO_2 in the cabin would have exceeded the OSHA and FAA limit in less than five minutes. After 30 minutes, the concentration would have exceeded 6% CO_2.

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F. REFERENCES

1. Murphy M and McSweeney T. Technical Assessment of Dry Ice Limits on Aircraft. Hazardous Materials Cooperative Research Program Report 11, Transportation Research Board 2013.
2. "Cabin Heater & Ventilation Flow Rates – Model 208A" Memo from B. Bergman at Cessna to P. Hedrick and E. Brady at Federal Express, 1 January 1985.