Dry Ice Tests to Support Safe Shipment of SARS-CoV-2 Vaccines:

Preliminary Results

January 2021

Disclaimer

- **This document describes tests performed by the Fire Safety Branch of the William J. Hughes Technical Center at the Atlantic City International Airport in New Jersey ("Technical Center") in November and December of 2020 in support of the FAA's effort to aid in the safe shipment of SARS-CoV-2 vaccines.**
- **The FAA notes the contents of this document do not have the force and effect of law and are not meant to bind the public in any way. This document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.**
- **The tests were performed with high urgency due to the COVID-19 public health emergency, which did not allow for the time necessary to define a formal research program.**
- **The results and observations presented here should therefore be considered preliminary because:**
  - Strict control of initial conditions was not possible due to the state and availability of the laboratory equipment at the time of testing and the difficulty in obtaining large quantities of dry ice as it was in high demand and supplies were limited.
  - A rigorous experimental design protocol was not followed due to the urgent need for test results.

Disclaimer (cont.)

- As additional tests are performed, the FAA will publish updated results and observations, as appropriate.
- The results and observations presented here should be considered together with other available information, including the specific details of particular operations. They do not relieve regulated parties of their independent obligations to analyze and appropriately manage safety risks to their operations.
- The sample vaccine thermal container that the FAA used to conduct these tests is just one example of COVID-19 vaccine packaging; different packaging may affect dry ice sublimation differently.

Objectives

1. **Sublimation of Dry Ice Tests**
   - Tests were performed to evaluate the impact of certain parameters on the rate of carbon dioxide gas evolution from dry ice in packages for air shipment.
   - Several parameters were varied, including:
     - Specific Packaging (sample vaccine thermal container vs. generic box).
     - Dry Ice Pellet Size (the diameter of the pellet).
     - Altitude (the ambient air pressure).

2. **Cargo Compartment CO_2 Evacuation Tests**
   - Tests were performed to evaluate the time required to achieve a safe concentration of carbon dioxide gas near the exterior of a lower deck cargo compartment door.
   - Several parameters were varied, including:
     - Cargo compartment loading (space occupied by cargo).
     - Initial volumetric concentration of CO_2.
     - Use of exhaust fan to expedite evacuation.

Objective 1 – Sublimation Tests

- **Tests were performed to evaluate the impact of certain parameters on the rate of carbon dioxide gas evolution from dry ice in packages for air shipment.**
- **Several parameters were varied, including:**
  - Specific Packaging (sample vaccine thermal container vs. generic box).
  - Dry Ice Pellet Size (the diameter of the pellet).
  - Altitude (the ambient air pressure).

- **Procedure**
  - An empty test container was placed on a scale, and the scale was zeroed.
  - Dry ice of specific pellet size was added to the test container.
  - The weight of the dry ice was recorded over extended periods (up to 18 hours).
  - For simulated altitude tests, the test container and scale were placed within a cylindrical pressure vessel, which was evacuated to achieve a pressure of 10.9 psia, roughly equivalent to 8,000’ altitude.
  - The mass loss rate and sublimation rate were calculated over the duration of each test.

Sublimation Test Parameters

- **2 test containers were tested**
  - SARS-CoV-2 vaccine thermal container.
  - Generic dry ice container typical of frozen meat shipments.
- **2 ambient pressure scenarios were tested**
  - Sea level (14.7 psia).
  - Simulated 8,000’ cabin altitude (10.9 psia) in reduced pressure in vacuum chamber.
- **3 dry ice pellet sizes were tested**
  - ¼” (6.35 mm) nominal diameter.
  - ½” (12.70 mm) nominal diameter.
  - ⅝” (15.88 mm) nominal diameter (*vaccine thermal container only due to limited availability of dry ice).*
  - *Note: The ½” pellets ordered for the generic box tests were not uniformly ½”. A random measurement with calipers revealed some pellets measuring a pellet size of nearly ¾”. The uniformity of the pellet size for all tests performed or the accuracy of the actual diameter to the nominal diameter was not confirmed.*

Vaccine Thermal Container

Sample Vaccine Thermal Container.

Vaccine Thermal Container – Internal View.

Dry ice pellets filled around the internal payload area.

Dry ice pellets held in bag above the internal payload area.

Dry ice bag closed, Thermal Container sealed by closing the lid.

Generic Box

Generic Box – Pre-Test

Generic Box – Prior to Closing

Generic Box on Scale

Generic Box – Post-Test

Reduced Pressure Chamber

Vaccine Thermal Container in Reduced Pressure Chamber

Calculated Values

- **Mass Loss Rate**

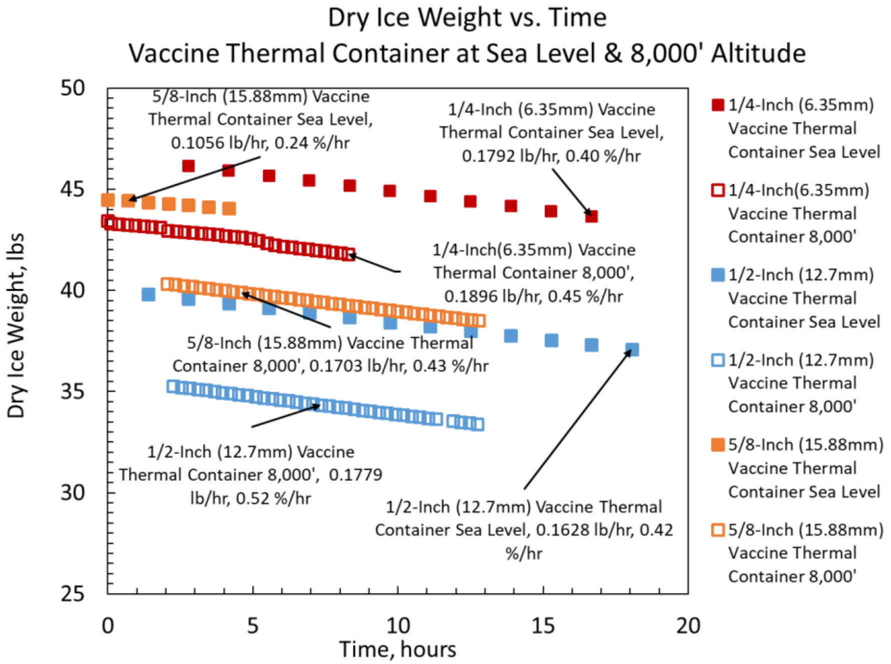
$$\frac{(m_2 - m_1)}{(t_2 - t_1)} = \frac{\text{pounds}}{\text{hour}}$$

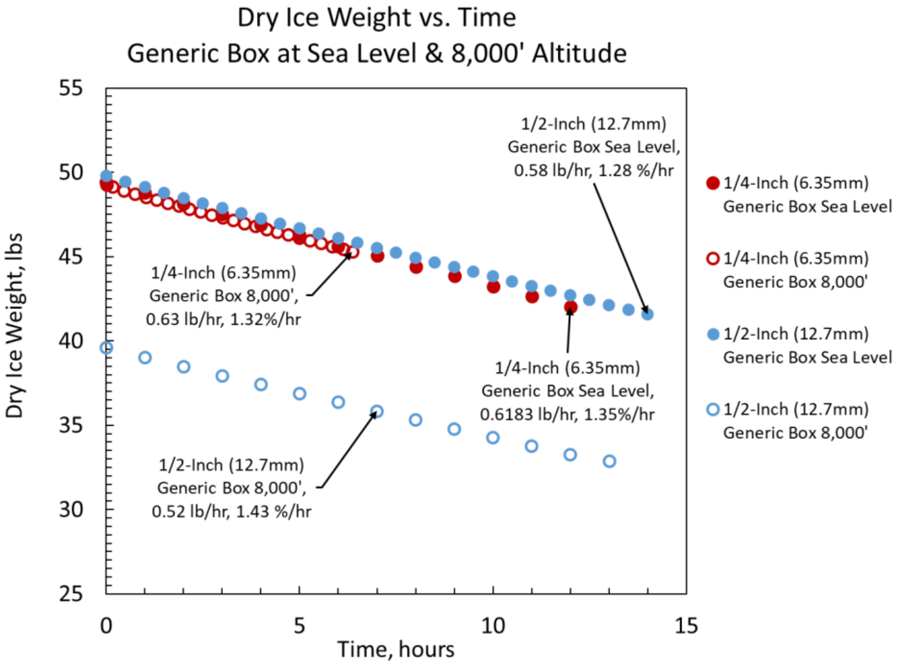
$$m_1 = \text{initial weight of dry ice, lb}$$
$$m_2 = \text{final weight of dry ice, lb}$$
$$t_1 = \text{time at which } m_1 \text{ was observed}$$
$$t_2 = \text{time at which } \mathrm{m}_2 \text{ was observed}$$

- **Sublimation Rate**

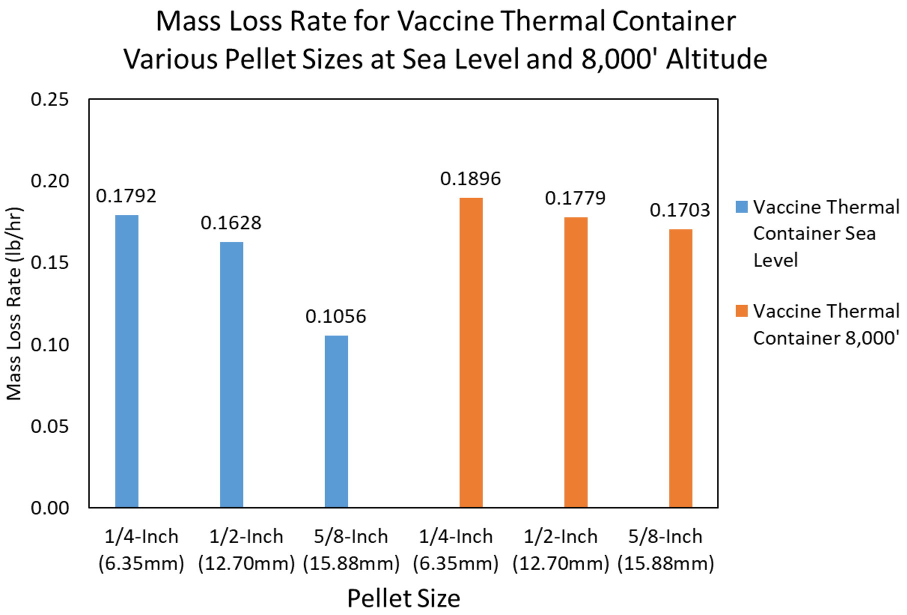
$$\frac{\left(\frac{(m_2 - m_1)}{m_1}\right) * 100}{(t_2 - t_1)} = \frac{\%\ \text{weight loss}}{\text{hour}}$$

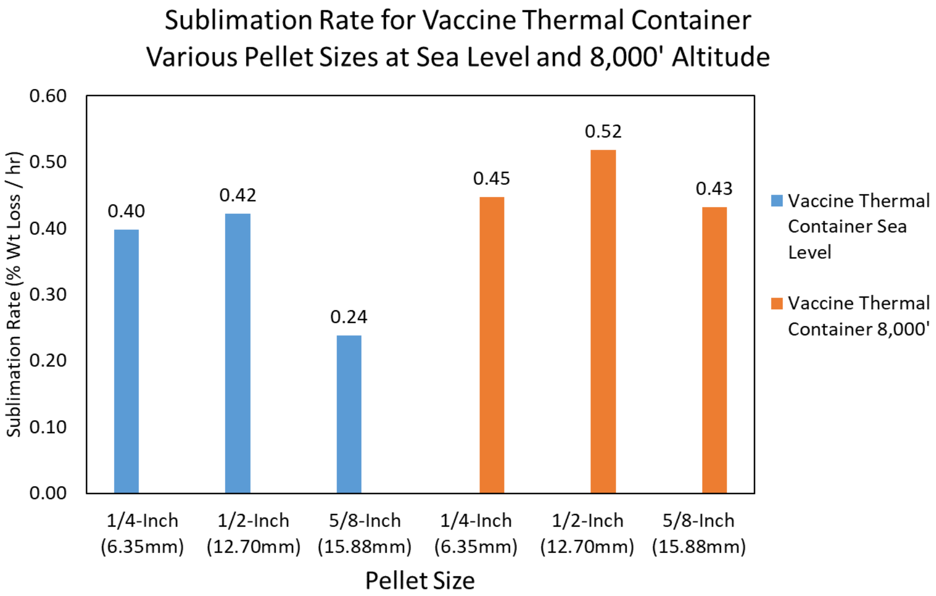
Results – Dry Ice Weight vs. Time



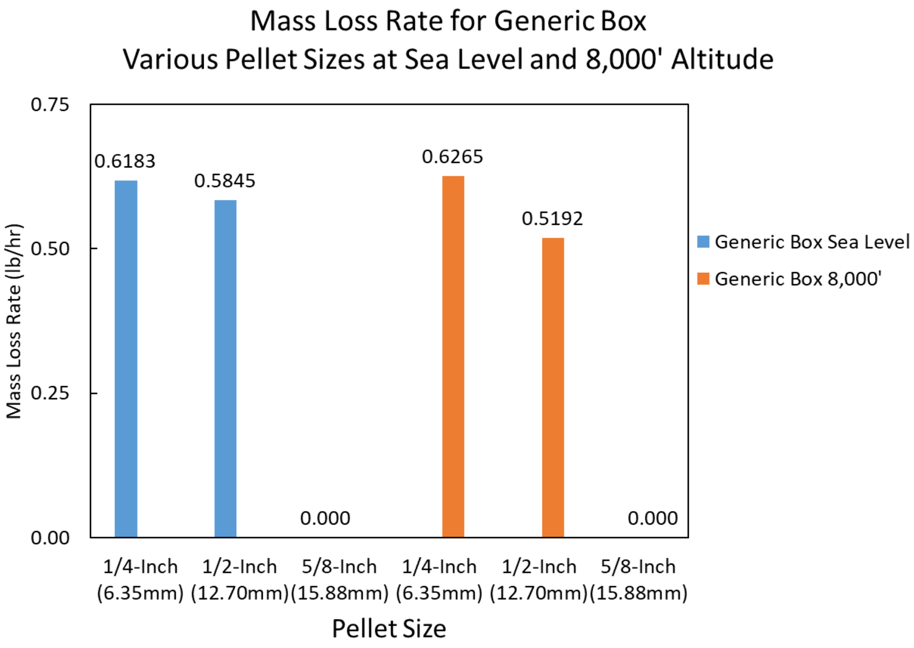


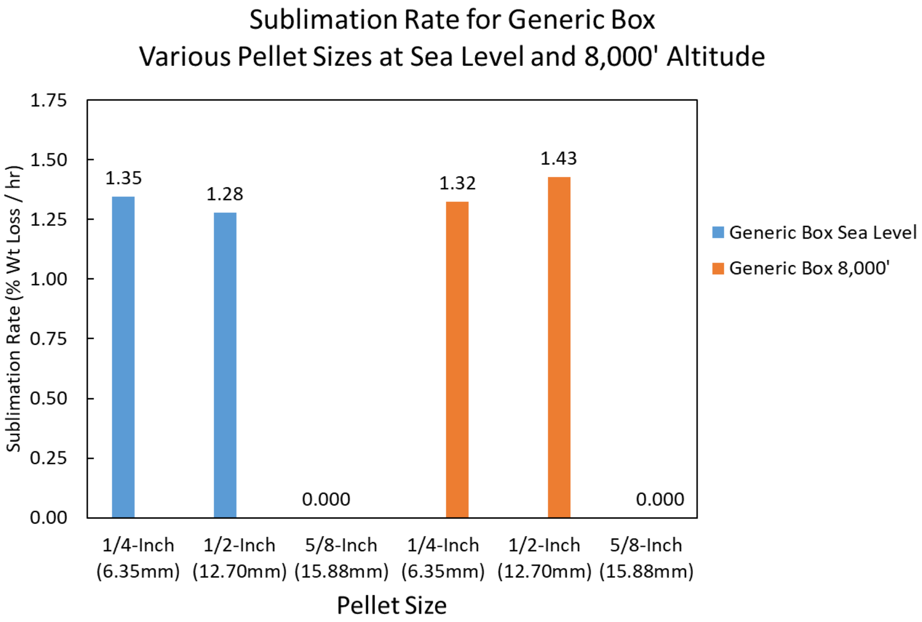
Results – Vaccine Thermal Container





Results – Generic Box





Measurement →		Pellet Diameter	Pellet Diameter	Dry Ice Initial Weight	Dry Ice Initial Weight	Dry Ice Final Weight	Dry Ice Final Weight	Elapsed Time	Average Mass Loss Rate	Average Mass Loss Rate	Average Sublimation Rate
Ambient Pressure	Package	in.	mm	lb.	kg	lb.	kg	hr	lb/hr	g/hr	% mass loss / hr
14.7 psia Sea Level	Vaccine Thermal Container	1/4	6.35	46.139	20.928	43.649	19.799	13.89	0.1792	81.300	0.40
		1/2	12.70	39.809	18.057	37.095	16.826	16.67	0.1628	73.852	0.42
		5/8	15.88	44.490	20.180	44.050	19.981	4.17	0.1056	47.899	0.24
	Generic Box	1/4	6.35	49.442	22.426	42.022	19.061	12.00	0.6183	280.471	1.35
		1/2	12.70	49.778	22.579	41.598	18.869	14.00	0.5845	265.108	1.28
		5/8	15.88	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
10.9 psia 8,000' Altitude (Simulated in Pressure Vessel)	Vaccine Thermal Container	1/4	6.35	43.452	19.709	41.79	18.957	8.27	0.1896	85.983	0.45
		1/2	12.70	35.264	15.995	33.400	15.150	10.48	0.1779	80.713	0.52
		5/8	15.88	40.330	18.293	38.502	17.464	10.73	0.1703	77.266	0.43
	Generic Box	1/4	6.35	49.256	22.342	45.292	20.544	6.36	0.6265	284.167	1.32
		1/2	12.70	39.632	17.977	32.884	14.916	13.00	0.5192	235.515	1.43
		5/8	15.88	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Observations

- The generic box loses carbon dioxide mass at a higher rate than the vaccine thermal container.

- Smaller diameter dry ice pellets sublimate faster than larger diameter pellets.

- Reduced ambient pressure can increase the mass loss rate, but it was not observed to be consistent across all tests performed in this study.
  - This could be due to combined effects of varying initial conditions and uncontrolled parameters in this initial investigation.

- Mass loss rate (lb / hr) was observed to be highly linear in all tests over the time intervals tested.

- Sublimation rate (% mass loss per hour) is mathematically dependent upon the initial weight of dry ice over the time interval considered.
  - Physical effects of starting each test with the same weight of dry ice were not determined in this study but could have an impact on sublimation rate.

Observations

- **The vaccine thermal container, under the conditions tested, was observed to have the following values for:**
  - Mass loss rate
    - Min 0.1056 lb/hr
    - Max 0.1896 lb/hr
    - Avg 0.1642 lb/hr
  - Sublimation rate
    - Min 0.24 %/hr
    - Max 0.52 %/hr
    - Avg 0.41 %/hr
- **The generic box, under the conditions tested, was observed to have the following values for:**
  - Mass loss rate
    - Min 0.5192 lb/hr
    - Max 0.6265 lb/hr
    - Avg 0.5871 lb/hr
  - Sublimation Rate
    - Min 1.28 %/hr
    - Max 1.43 %/hr
    - Avg 1.34 %/hr

	Vaccine Thermal Container		Generic Box	
	lb/hr	% mass loss / hr	lb/hr	% mass loss / hr
Min	0.1056	0.24	0.5192	1.28
Max	0.1896	0.52	0.6265	1.43
Avg	0.1642	0.41	0.5871	1.34

Recommendations

- **A fixed sublimation rate for a dry ice container should not be considered a constant property of the container, as the sublimation rate provided by container manufacturers may have been determined under known and fixed environmental conditions. Users should–**
  - Be aware of the conditions the container manufacturer used in determining the sublimation rate, and compare to the range of conditions that the shipment may experience in transit.
  - Consider applying a conservative safety factor to the manufacturer-provided sublimation rate when determining maximum allowable dry ice amounts.
- **The mass loss rate may be the more useful parameter than the sublimation rate since:**
  - Mass loss rate is independent of initial weight of dry ice.
  - Mass loss rate is highly linear.
- **Ultimately it is the total amount of carbon dioxide released into the airplane that is of interest. This is determined with knowledge of the mass loss rate of a specific container, the number of containers, and the duration of time in transit.**

Sublimation Tests – Potential Impacts to Results

- All tests were performed with no contents in the containers aside from the dry ice load.
- The ½” pellets ordered for the generic box tests were not uniformly ½”. A random measurement with calipers revealed some pellets measuring a pellet size of nearly ¾”.
  - Measurements were not performed for the other tests, so the deviation of the actual diameter from the nominal diameter is unknown.
- The ¼” generic box test was the only test performed in which additional dry ice was added at the conclusion of the 8,000’ altitude test prior to starting the sea level test.
- The ⅝” vaccine thermal container sea level test was accidentally terminated early due to a forced operating system update on the data acquisition PC.

Objective 2 – Cargo Compartment CO_2 Evacuation Tests

- **Tests were performed to evaluate the time required to achieve a safe concentration of carbon dioxide gas near the exterior of a lower deck cargo compartment door**
- **Several parameters were varied, including:**
  - Cargo compartment loading (space occupied by cargo).
  - Initial volumetric concentration of CO_2.
  - Use of exhaust fan to expedite CO_2 evacuation.

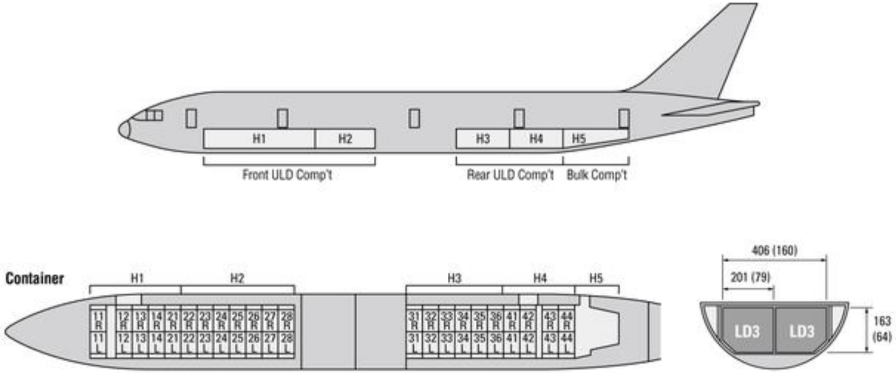
- **Test Setup**
  - Tests were performed in and around the aft cargo compartment of the FAA Technical Center's DC-10 fire test fuselage.
  - Carbon dioxide gas was plumbed into the compartment from an external liquid carbon dioxide tank.
  - Gas analyzers were used to measure the volumetric concentration of carbon dioxide gas at several locations inside the compartment and outside the cargo compartment door.

CO_2 Evacuation Test Parameters

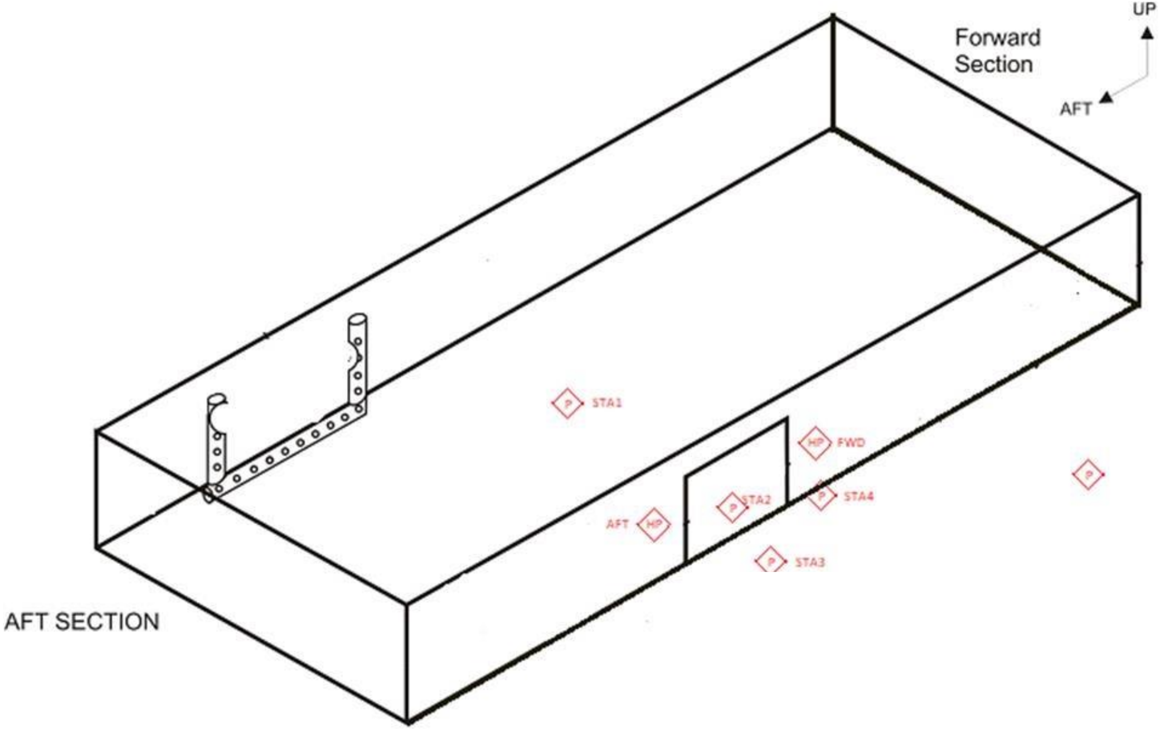
- **2 Loading Configurations were tested**
  - 93% (6 LD3 Containers filled with cardboard boxes, and 140 cardboard boxes to fill the rest of the compartment).
  - 37% (3 LD3 Containers filled with cardboard boxes).
- **3 Initial CO_2 concentrations were tested**
  - 5% CO_2.
  - 20% CO_2.
  - 50% CO_2.
- **2 Fan Configurations were tested**
  - Fan Off.
  - Fan On.

Typical Cargo Loading of a Lower Deck Cargo Compartment

LD3 Container



Lower Cargo Compartments



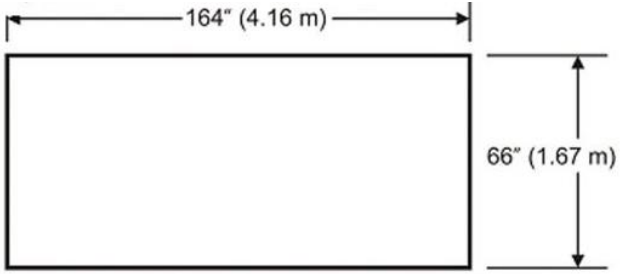
Gas Probes

Handheld Probes

STA 1-4 = CO_2 Sampling Station 1-4

AFT = toward the tail end of the fuselage

FWD = towards the forward end of the fuselage



Front View

Compartment Volume:
2000 cubic feet (56.64 cubic meters)

Test Compartment and CO_2 Gas Sampling Locations

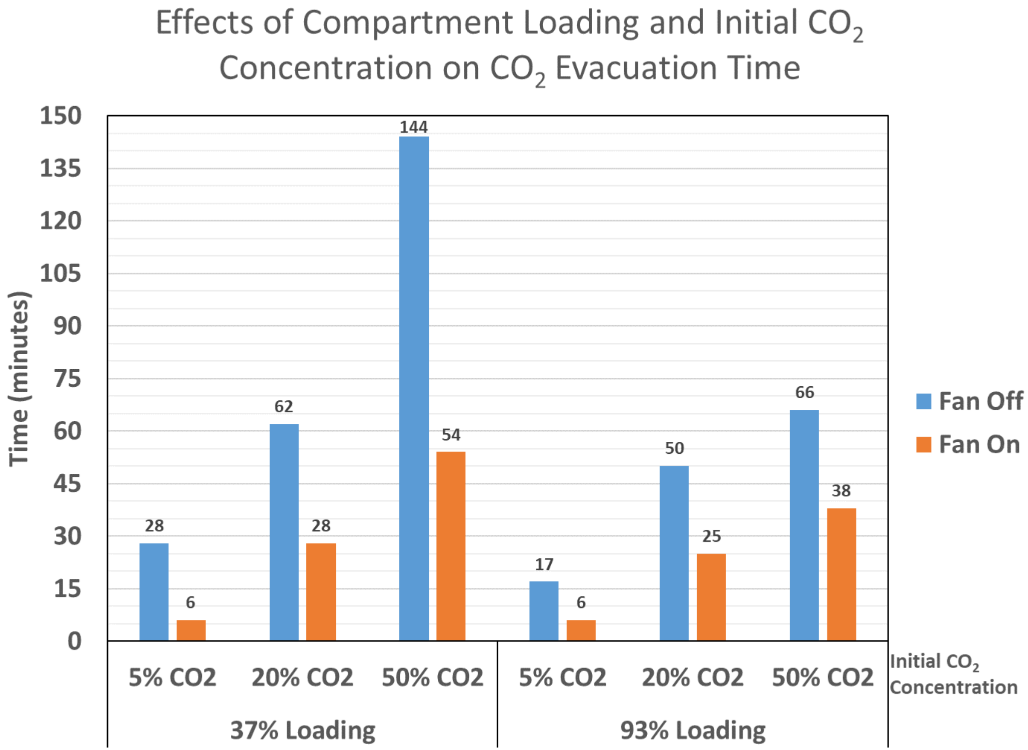
Test Compartment Loaded with LD3 Containers and Fan Located AFT of the Cargo Door

93% Cargo Loading

CO_2 Evacuation Test Procedures

- **Compartment is filled with the target CO_2 concentration with the door closed.**
- **Fan is turned on for designated tests.**
- **Door is opened.**
- **Test is conducted until the concentration in the compartment reaches 0.5%.**
  - 0.5% is the FAA regulatory limit for transport category aircraft (14 CFR § 25.831) and Occupational Safety and Health Administration (OSHA) occupational exposure limit (29 CFR § 1910.1000 Table Z-1).

Results – CO_2 Evacuation Testing



Observations

- The compartment takes longer to evacuate CO_2 as the initial concentration increases.
- Utilizing a fan to circulate air away from the door reduces the CO_2 evacuation time.
- Increase in the amount of cargo in the compartment reduces the CO_2 evacuation time.
  - Increase in loading percentage leads to reduction in free volume.
  - Because of the smaller free volume, less CO_2 is needed to reach target concentration.

Observations

- Amount of CO_2 needed to reach 5% initial concentration in each loading configuration:
  - 7ft^3 – 93% Loading.
  - 67ft^3 – 37% Loading.
- Greater amounts of CO_2 require more time to evacuate the compartment.

Recommendations

- At the end of a flight, compartments containing dry ice will tend to have a high CO_2 concentration that will take time to dissipate. When the cargo door is opened, the areas immediately outside the door also experience a high CO_2 concentration temporarily. How long it will take for these high CO_2 concentrations to dissipate depends upon a variety of factors and should be assessed based upon the specific details of particular operations.
  - Prior to removing cargo, wait for the compartment and containers to air out upon opening.
  - Use a fan to circulate fresh air around the ground crew personnel and to reduce the concentration of CO_2.
  - Use CO_2 monitors to be aware of hazardous quantities/concentrations of CO_2.
  - Beware of the potential for hazardous concentrations of CO_2 to be present under the aircraft, since CO_2 is heavier than air and tends to accumulate near the ground.