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Aviation Research Division
Atlantic City International Airport
New Jersey 08405

# An Evaluation of Parameters Pertinent to Dry Ice Sublimation

October 2024

Final report

U.S. Department of Transportation
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16. Abstract

As a result of the COVID-19 (SARS-CoV-2) pandemic, over 12.7 billion vaccine doses were shipped and administered across 184 countries. Transportation via aircraft was a significant contributor in this effort. Many of the COVID-19 vaccines need to be stored at extremely low temperatures to maintain efficacy, therefore, dry ice has been used as a method to keep vaccines refrigerated throughout air shipments. Dry ice is categorized as a Class 9 (Miscellaneous) Dangerous Good. Dry ice undergoes a process called sublimation at normal pressure and temperatures, in which the solidified form transitions directly to gaseous CO2. This process can create an oxygen deficient environment in confined areas (including aircraft), which can produce shortness of breath, unconsciousness, or death if exposed over prolonged periods of time.

An assessment was conducted by the Federal Aviation Administration (FAA) to identify parameters pertinent to dry ice sublimation throughout air shipment. This study was motivated by minor sublimation rates (<1% per hour) claimed from container manufacturers. This has important safety implications as decreases in sublimation rates allow for exponential increases in permitted dry ice cargo. Further analysis was needed. Specifically, this study evaluated the following parameters' impact: temperature, pressure, humidity, dry ice pellet size, container design and durability. Results indicate that dry ice pellet size, container design, and durability had a clear impact on sublimation rate. Sublimation rates differed significantly between the three containers evaluated within this study and were observed to increase as containers were reused. Furthermore, dry ice pellets with smaller nominal diameters were noted to sublimate at a higher rate than those with a larger diameter. Other evaluated parameters within this study produced no clear correlation. Although sublimation was observed to be affected by numerous parameters, data suggests a conservative approach to this subject is prudent. While some external conditions may produce only minor differences in sublimation rates, it would have a major impact on the allowable quantity of dry ice shipped.

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## Acronyms

| Acronym | Definition |
|---|---|
| AC | Advisory Circular |
| CAMI | Civil Aerospace Medical Institute |
| DOT | Department of Transportation |
| FAA | Federal Aviation Administration |
| FAR | Federal Aviation Regulation |
| IATA | International Air Transport Association |
| OSHA | Occupational Safety and Health Administration |
| PEL | Permissible Exposure Limit |
| PPE | Personal Protective Equipment |

## Executive summary

During the COVID-19 (SARS-CoV-2) pandemic, over 12.7 billion doses of the COVID-19 vaccine were distributed and administered across 184 countries, in which shipment via aircraft was a major contributor. Many of the vaccines, such as those developed by Pfizer-BioNTech, must be stored at temperatures below -60°C (-76°F) to maintain its efficacy. As a solution to this problem, dry ice was used as a coolant in the bulk shipment of COVID-19 vaccines. Dry ice undergoes a process called sublimation at normal atmospheric pressure when exposed to temperatures above -78.5°C ( -109.3°F), releasing gaseous $CO_2$ into the nearby atmosphere. Substantial quantities can produce an oxygen deficient environment, especially in confined spaces such as within an aircraft. Overexposure of high $CO_2$ concentrations can cause shortness of breath, unconsciousness, or even death to occupants over prolonged periods of time. Although the hazards of dry ice are properly understood, the factors which affect sublimation during air shipment needed to be explored. This study was motivated by minor sublimation rates (<1% per hour) claimed from container manufacturers. This has important safety implications as decreases in sublimation rates allow for exponential increases in permitted dry ice cargo. Further analysis was needed.

An assessment was conducted by the Federal Aviation Administration (FAA) to identify important factors in dry ice sublimation during air shipment and to determine their respective impact. Within this analysis, the following parameters were evaluated: temperature, pressure, humidity, dry ice pellet size, container design, and container durability. Testing was first performed to evaluate how ambient pressure impacted sublimation rate, comparing sublimation of aircraft cruising altitude pressure (10.9 psia) to sea level pressure (14.7 psia). Subsequently, a flight profile test series was conducted to evaluate the effect of varying pressure (representative of ascent, cruise, and descent phases of flight) on sublimation. Additional testing was performed in a temperature and humidity-controlled chamber to evaluate how various temperatures and humidity levels affected sublimation. Results indicate that dry ice pellet size, container design, and durability had a clear impact on sublimation rate. Sublimation rates differed significantly between the three evaluated containers and were observed to increase as containers were reused. Furthermore, dry ice pellets with smaller nominal diameters were noted to sublimate at a higher rate than those with a larger diameter. Other evaluated parameters within this study produced no clear correlation in data. Although sublimation was observed to be affected by numerous parameters, data suggests a conservative approach to this subject is prudent. While some external conditions may produce only minor differences in sublimation rates, it would have a major impact on the allowable quantity of dry ice shipped.

# 1 Introduction

## 1.1 Background

Solidified carbon dioxide ($CO_2$), often referred to as “dry ice”, is a common coolant used to keep shipped goods at low temperatures throughout transport. Dry ice has historically been used to keep perishable items such as food cool during shipment. However, due to the emergence of the COVID-19 (SARS-CoV-2) pandemic, dry ice has seen increased use as a coolant in the transport of vaccines. Many vaccines must be stored at temperatures below -60°C (-76°F) to maintain its efficacy (Pfizer Inc., 2023). Since dry ice is an inexpensive and readily available compound, it is viewed as a practical solution to refrigerate bulk shipments of these vaccines. As of October 2022, it was estimated that more than 12.7 billion doses of the COVID-19 vaccine were administered across 184 countries (Bloomberg, 2022). Air shipment was a prominent part of this distribution.

However, there are risks involved in the transport of dry ice. Dry ice is classified by the Department of Transportation (DOT) and International Air Transport Association (IATA) as a Class 9 (Miscellaneous) Dangerous Good (ICAO, 2020). This classification is primarily due to three different factors. Firstly, dry ice is a cryogenic compound that can cause burns and frostbite to skin when directly exposed over prolonged periods of time. Therefore, it is necessary to wear personal protective equipment (PPE) such as gloves and a laboratory coat during handling (University of Washington, 2020). Furthermore, dry ice is an explosion hazard. Dry ice undergoes a process called sublimation at normal atmospheric pressure when exposed to temperatures above -78.5°C (109.3°F) and will transition directly from the solid phase into a gas. The $CO_2$ gas can accumulate in a sealed container, causing the pressure to increase beyond the container’s limit, resulting in an explosion. Lastly, dry ice is an asphyxiation hazard. As a result of the $CO_2$ gas produced during sublimation, dry ice can create an oxygen deficient environment, especially in confined spaces. $CO_2$ produced from dry ice can displace the oxygen within air, causing difficulty breathing for people within close proximity. This can lead to unconsciousness or even death when exposed over prolonged periods of time.

The asphyxiation hazard as a result of dry ice sublimation is particularly prominent for air transport. Bulk shipments of dry ice cargo may produce dangerous conditions to aircraft occupants if not sufficiently controlled. Limitations on the allowable amount of $CO_2$ have been implemented to account for this problem. According to DOT Advisory Circular (AC) 91-76A, “exposures to $CO_2$ in aircraft should not exceed a sea level equivalent to 0.5% $CO_2$ (5,000 parts of $CO_2$ per million parts of air or 5,000 ppm)”. This limit is also used as by the Department of

Labor, Occupational Safety and Health Administration (OSHA) as an 8-hour time weighted average permissible exposure limit (PEL) in general industries (Federal Aviation Administration, 2009).

Data provided in AC 91-76 from 1963 indicates a sublimation rate of 1%/hour per one-hundred pounds of dry ice, and more recent data yields 2%/hour sublimation rate for small, insulated shipping containers carrying 4.6 to 5.3 pounds of dry ice. In addition, a rule-of-thumb for dry ice loading in relation to aircraft volume and air circulation is provided in Equation 1 as follows:

$$X = \frac{(CO_2\ concentration)(Aircraft\ Volume, ft^3)(Complete\ Air\ Exchanges\ per\ Hour)}{(sublimation\ rate)} \qquad 1$$

In Equation 1, X is the estimated acceptable dry ice weight (lbs.) relative to the volume of air circulation. In wake of the increased aircraft shipments of dry ice necessary for proper transport of COVID-19 vaccines, additional research on dry ice sublimation rate with respect to vaccine shipping containers was needed to validate the recommendations within AC 91-76A for safe transport.

## 1.2 Objective

This study was motivated by minor sublimation rates (<1% per hour) claimed from container manufacturers. This has important safety implications as decreases in sublimation rates allow for exponential increases in permitted dry ice cargo. Further analysis was needed. The objective of this study was to evaluate the impact that specific parameters had on dry ice sublimation. The parameters included temperature, pressure, relative humidity, dry ice pellet size, container design, and container durability.

# 2 Sublimation variable testing

## 2.1 Experiment setup

Testing was conducted to determine how select parameters affect the rate at which dry ice sublimates into gaseous $CO_2$. Throughout this study, the following parameters were evaluated: temperature, pressure, relative humidity, dry ice pellet size, container design, and container durability. Many of these factors were identified during preliminary testing as parameters which could impact sublimation. Additional factors such as container durability and relative humidity were discovered throughout testing.

### 2.1.1 Dry ice pellets

Four different nominal diameter sizes of dry ice pellets were procured from two local vendors within proximity of the William J. Hughes Technical Center. Prior to testing, the diameter of thirty pellets from each batch was measured using calipers which measured to the nearest 0.001 inch. Minimal variation was observed in pellet diameter between batches. Pellet diameters were denoted and categorized as follows: 0.10” (0.25 cm), 0.20” (0.51 cm), 0.55” (1.40 cm), and 0.68” (1.73 cm). It was observed that the measured diameter of the dry ice pellets slightly differed from the nominal sizes ordered(e.g., pellets advertised as 0.50” (1.27 cm) by the vendor recorded an average diameter of 0.68”). To avoid confusion, the measured pellet sizes were used herein, rather than the advertised sizes offered by vendors. Figure 1 shows images of three of the pellet sizes.

As a result of supply chain shortages, local vendors were unable to produce 0.20” pellets throughout the course of testing. Therefore, only a limited amount of testing was performed for dry ice pellets of this diameter.

Figure 1. Dry ice pellets 0.10”, 0.55”, and 0.68” (left to right)

### 2.1.2 Vaccine thermal containers

Pellets were loaded into three different vaccine thermal containers and sealed according to manufacturer directions. The vaccine containers were denoted as follows: Large Thermal Container, Medium Type A, and Medium Type B. Each container was comprised of different materials and stored different quantities of dry ice. Figure 2 displays images of each of the vaccine containers evaluated within this study.

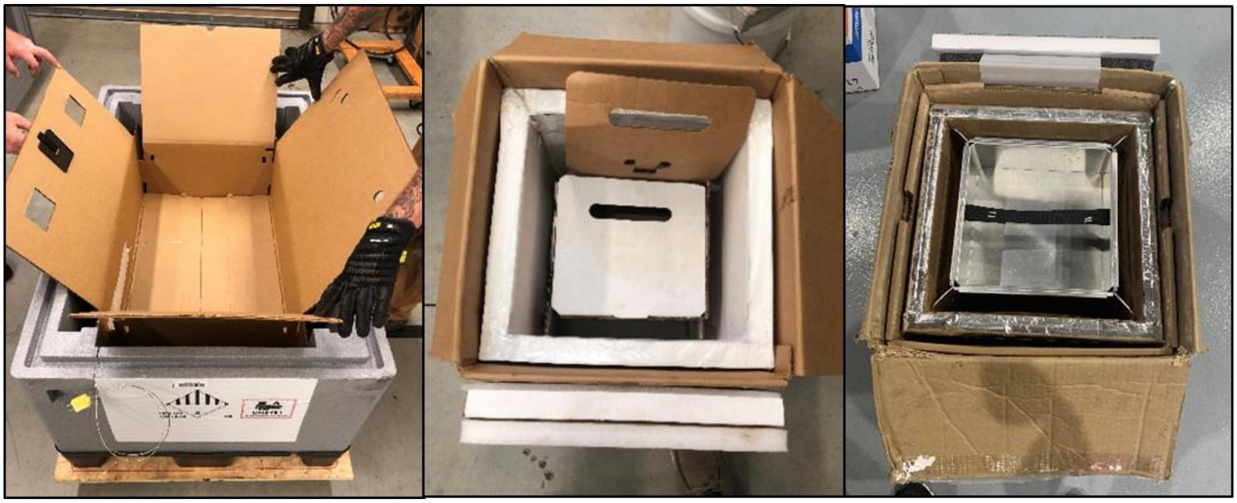

Figure 2. Large Thermal, Medium Type A, and Medium Type B containers (left to right)

### 2.1.3 Pressure vessels

Initial testing was conducted within two test environments. A pressure vessel with an interior volume of 10.8 $m^3$ (381.4 $ft^3$) was used to concurrently test the Large Thermal and Medium Type A vaccine containers. A 1.31 $m^3$ (46.3 $ft^3$) pressure vessel was used in testing for the Medium Type B vaccine container. Pictures of the two test chambers is shown below in Figure 3.

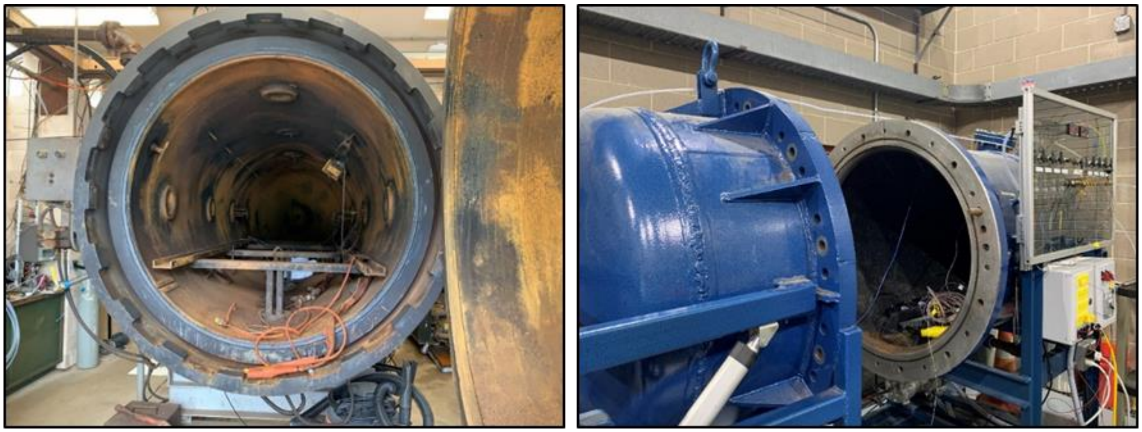

Figure 3. Pressure vessels 10.8 $m^3$ (left) and 1.31 $m^3$ (right)

Pressure within these chambers was controlled to simulate levels normally experienced within the interior of aircraft. Federal Aviation Regulation (FAR) 25.841 mandates that "Pressurized cabins and compartments to be occupied must be equipped to provide a cabin pressure altitude of not more than 8,000 feet (2,440 m) at the maximum operating altitude of the airplane under normal operating conditions" (National Archives and Records Administration, 2023). A pressure environment of 8,000 feet is equivalent to 10.9 psia. Therefore, aircraft cabin pressure can range from a maximum of 14.7 psia (101 kPa) to a minimum of 10.9 psia (75 kPA) under normal flight conditions. Testing was performed at both of these extrema to simulate a reduced pressure environment (10.9 psia) and a “normal” sea level altitude (14.7 psia). Pressure was kept constant throughout the entirety of the test.

### 2.1.4 Scales

Containers were placed within the pressure vessels on Pennsylvania Scale Company 6400 series heavy duty scales, and the weight was recorded throughout testing to the nearest 0.01 lbs. (4.54 g). Empty containers were tared prior to test start so the recorded weight equated to the amount of dry ice within each container.

### 2.1.5 Procedures

Each test had an approximate duration of eight hours. Type K thermocouples were placed in the interior of the vaccine containers and inside of the test chamber to record container and ambient temperatures. Thermocouples within the vaccine containers were oriented to prevent direct contact with dry ice pellets so that inner air temperature was measured. Upon test completion, the final weight of the filled container was recorded. Two values were calculated upon test completion. The dry ice’s average mass loss rate was calculated using Equation 2 below.

$$Average\ Mass\ Loss\ Rate = \frac{[m_f - m_i]}{(t_f - t_i)} \qquad 2$$

In Equation 2, $m_f$ and $m_i$ are the final and initial weights of the dry ice within the container, respectively. Furthermore, $t_f$ and $t_i$ are the test end and test start time, respectively. Therefore, this equation would yield the sublimated mass over a given period of time.

Although this equation provides useful information regarding the total quantity of $CO_2$ produced over a given time period, it does not account for the variations in initial amounts of dry ice stored within the containers. For example, the Large Thermal container stored approximately five times the amount of dry ice compared to the other two containers. Therefore, another metric called the average sublimation rate was calculated using Equation 3 to normalize the capacity variation.

$$Average\ Sublimation\ Rate = \frac{\left[\frac{m_f - m_i}{m_i}\right] * 100}{(t_f - t_i)} \qquad 3$$

## 2.2 Pressure vessel results

Analysis concluded that dry ice pellets with a smaller nominal diameter sublimate at a higher rate compared to larger pellets. Pellets with a smaller diameter have a higher surface area to volume ratio compared to large pellets and dry ice blocks. Smaller dry ice pellets can absorb heat over a larger area when compared to its total volume and thus sublimate quicker. Similar conclusions were observed in previous studies conducted by the Packaging Engineering Program at the University of Florida (Hafner, Welt, Pelletier, & Boz, 2023). Furthermore, a similar trend was noted in a study by the Civil Aerospace Medical Institute (CAMI), which determined that dry ice pellets sublimated at a higher rate compared to blocks of dry ice (Caldwell, Lewis, Shaffstall, & Johnson, 2006). Test results indicated that the measured dry ice pellet size was a pertinent factor in the sublimation of dry ice. Another clear determinant in dry ice sublimation rate was the container type. Differences in mass loss rate and sublimation rate data were observed between the various vaccine thermal containers. The Large Thermal container consistently had the highest total mass loss rate of all three evaluated containers. However, this container also stored approximately five times (200 lbs.) the amount of initial dry ice compared to the other two containers (approximately 40 lbs.). Conversely, this container also had the lowest average sublimation rate of all three containers. The full measured range and data averages of mass loss rate and sublimation data for each container, subject to both pressure environments and pellet sizes within this test series, can be found in Table 1.

Table 1: Pressure vessel tests sublimation data range

| **Pressure Vessel Testing - Sublimation Data** | | | |
|---|---|---|---|
| | | **Mass Loss Rate** | **Sublimation Rate** |
| **Container** | | **[lbs./hr]** | **[%/hr]** |
| Large Thermal | Min | 0.63 | 0.32 |
| | Median | 1.08 | 0.55 |
| | Average | 1.04 | 0.53 |
| | Max | 1.33 | 0.68 |
| Medium Type A | Min | 0.19 | 0.43 |
| | Median | 0.25 | 0.61 |
| | Average | 0.26 | 0.60 |
| | Max | 0.34 | 0.74 |
| Medium Type B | Min | 0.23 | 0.48 |
| | Median | 0.32 | 0.72 |
| | Average | 0.29 | 0.71 |
| | Max | 0.34 | 0.93 |

Sublimation data proved to be inconsistent when test chamber pressure was altered. Initially, dry ice was observed to sublimate at a higher rate at sea level pressure (14.7 psia) compared to reduced pressure environments (10.9 psia) for all evaluated containers. Eight tests in a reduced pressure environment and seven subsequent tests at sea level were performed. As the sea level test series progressed, severe degradation of the interior of the Large Thermal container was observed. As a result of this observation, experimentation was suspended until a new Large Thermal container was obtained. Upon arrival, three additional tests were performed with the new Large Thermal container. Sublimation results from these tests were much lower compared to previous testing for both the sea level and reduced pressure tests. Higher sublimation rates for the Medium Type A container were consistently observed at sea level pressure, even when a new container was used. Figure 4, Figure 5, and Figure 6 exhibit how alterations in pellet size, pressure and the container affected the measured sublimation rate data for all evaluated containers.

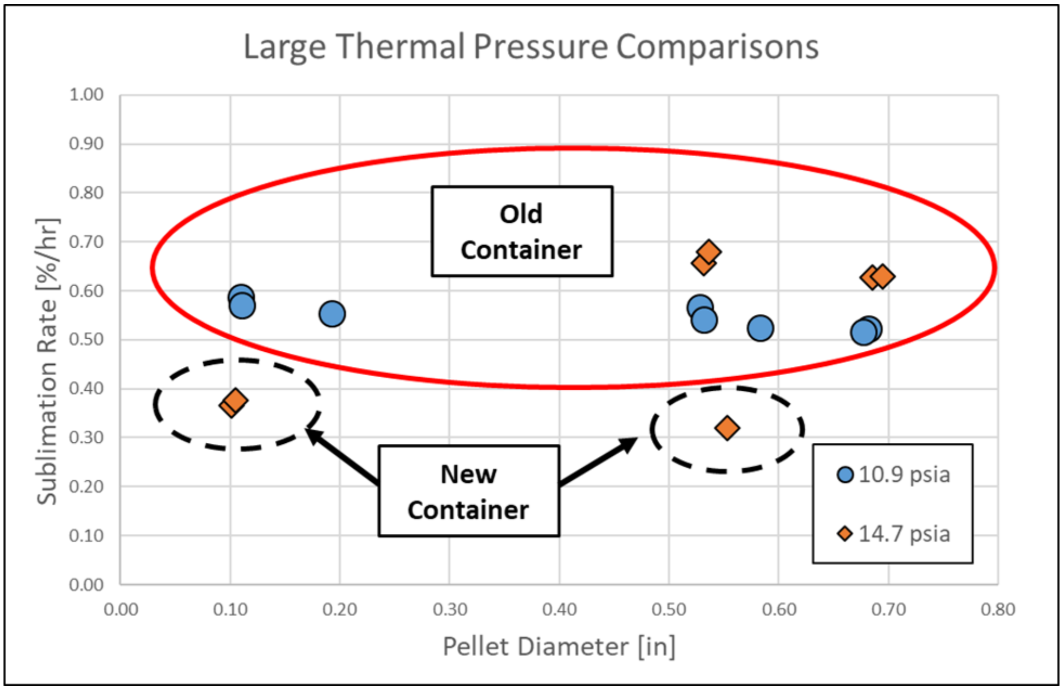

Figure 4. Large Thermal container pressure comparisons

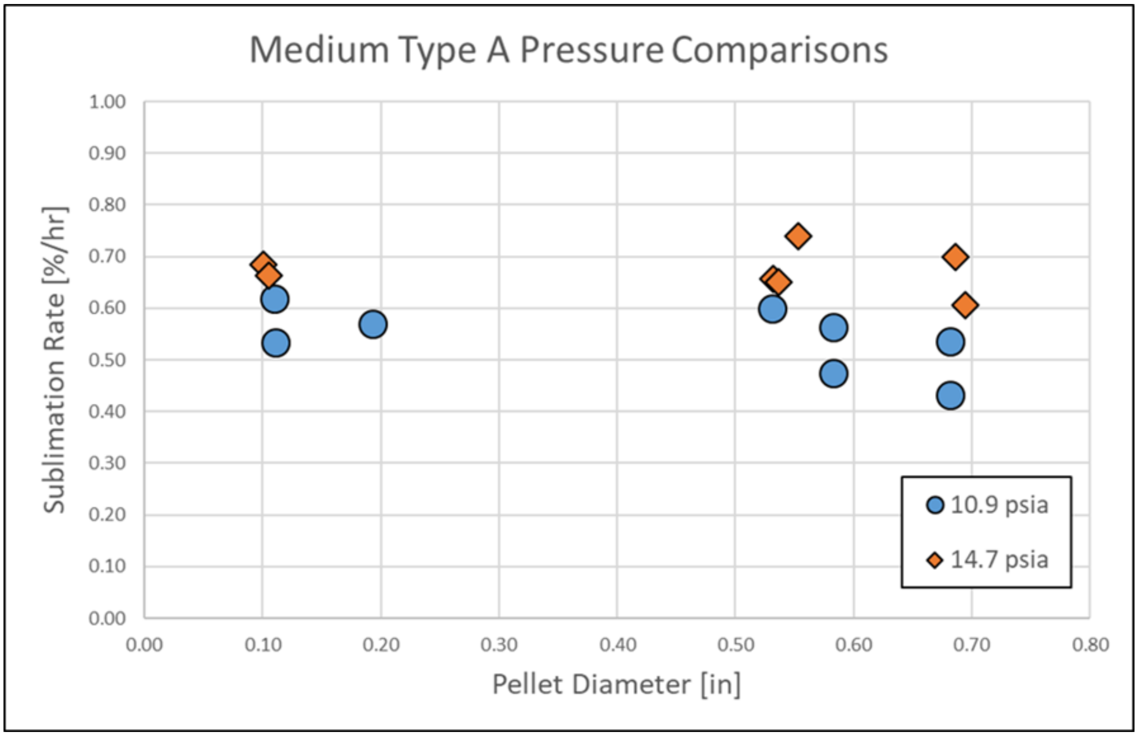

Figure 5. Medium Type A pressure comparisons

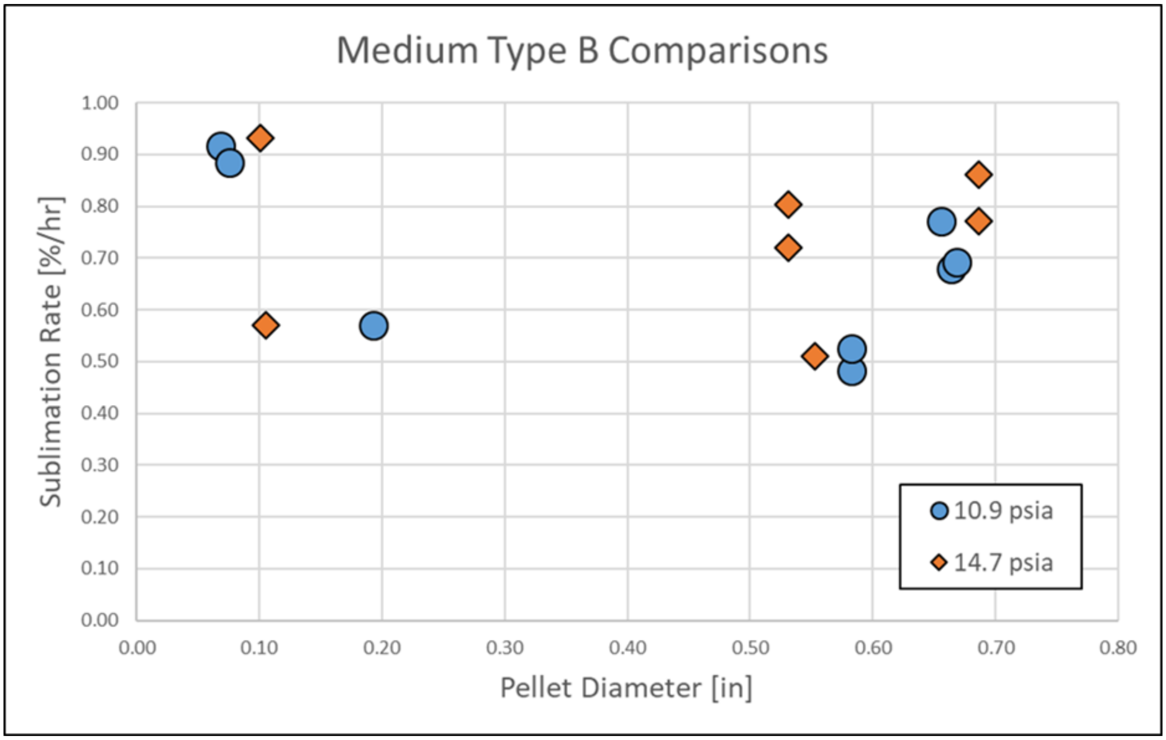

Figure 6. Medium Type B pressure comparisons

Degradation of container durability was also observed to be a major factor in dry ice sublimation. Significant signs of damage were observed within the interior of the containers after numerous uses. Chunks of styrofoam had fallen out from the interior side walling of the Large Thermal container. Additionally, the flat cardboard cover placed atop the dry ice warped after multiple uses. This warping made it more difficult to get a complete seal on the top molded styrofoam lid after dry ice packing.

Evidence of damage to the Medium Type A container was also observed after moderate use. A “dry ice pod” made up of woven fabric was placed on top of the payload carton prior to sealing the container. However, after multiple tests, this bag partially ripped, potentially providing a means for external heat to enter the interior of the container.

The performance of the Medium Type B container also suffered from repeated use. The medium Type B had a thinner insulation barrier than the Medium Type A and was constructed with cardboard layers that had warped easily as its moisture content flexed overtime with the condensation produced from the sublimation. The Medium Type B retained a significant amount of moisture in its outer cardboard layer in comparison to Medium Type A, and because of that, the box became less rigid and was prone to cracks in the cardboard, gaps at the corners, and rips at the handle grips. The cyclical swelling degradation increased the sublimation rate after repeated use. Pictures of the damage within each container is shown below in Figure 7, Figure 8, and Figure 9, respectively.

Figure 7. Large Thermal container damage

Figure 8. Medium Type A “dry ice pod” tear

Figure 9. Medium Type B container damages

Figure 10, Figure 11, and Figure 12 display the relationship between container degradation and sublimation rate for all three containers within this test series. A clear increase in sublimation rate was observed as vaccine containers were reused.

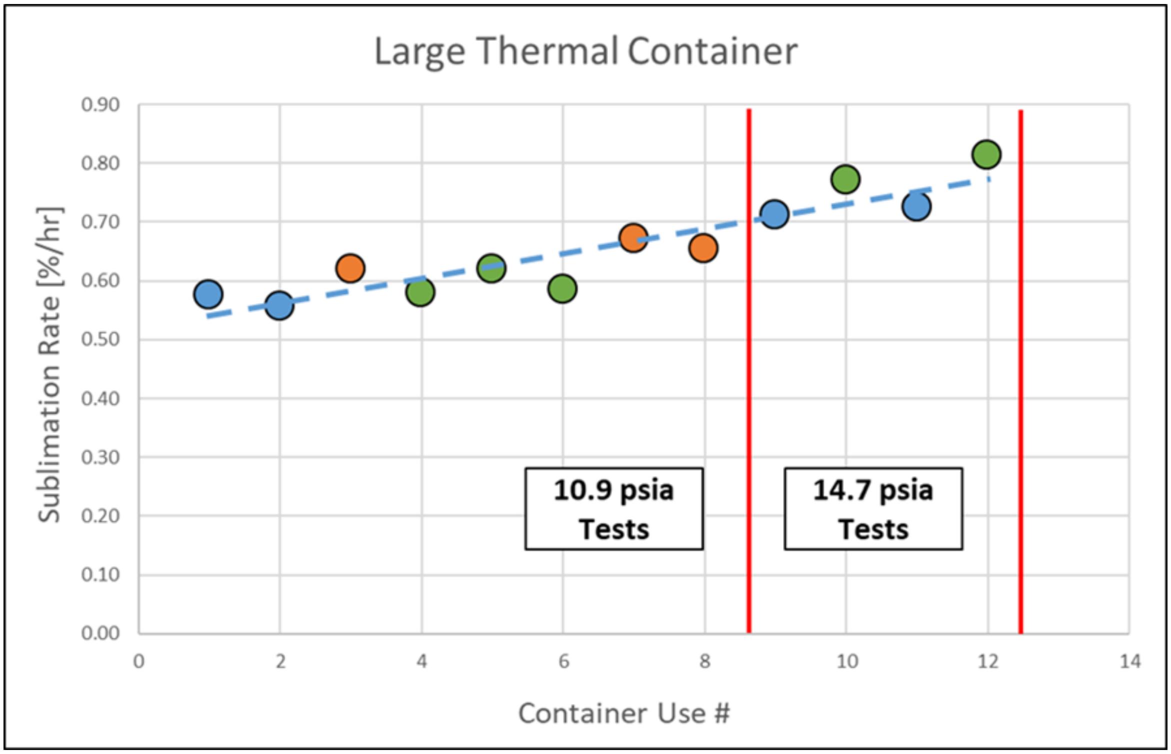

Figure 10. Large Thermal container degradation

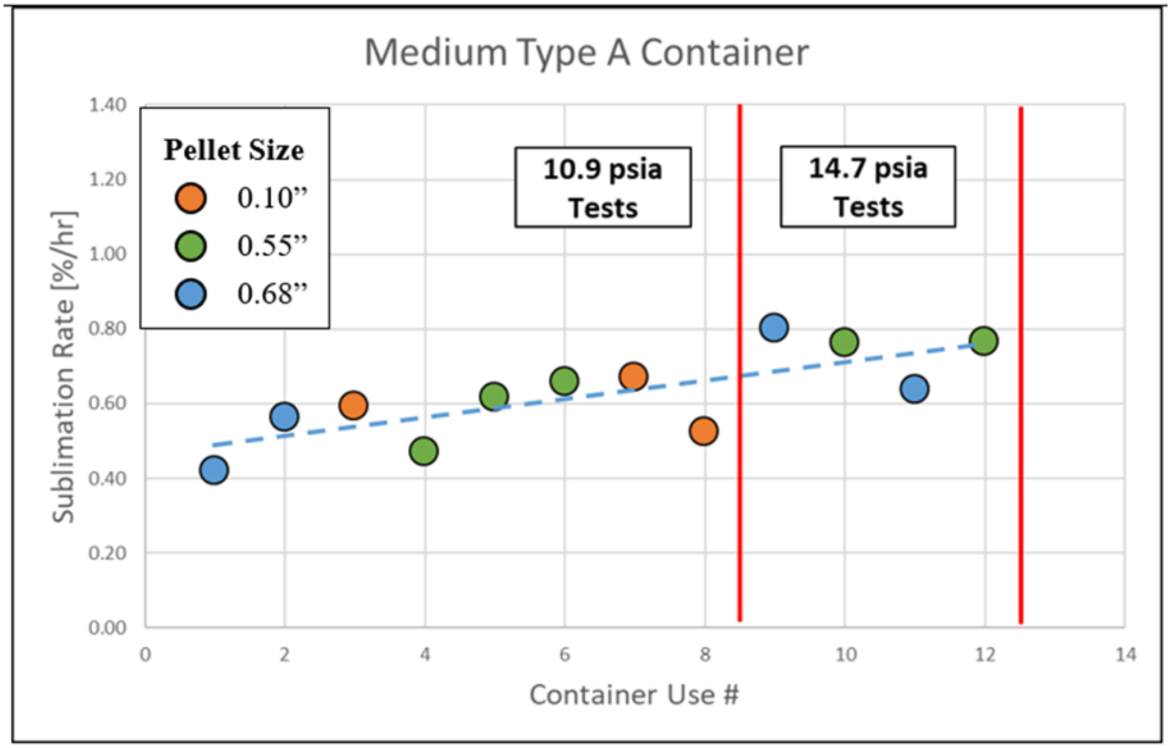

Figure 11. Medium Type A container degradation

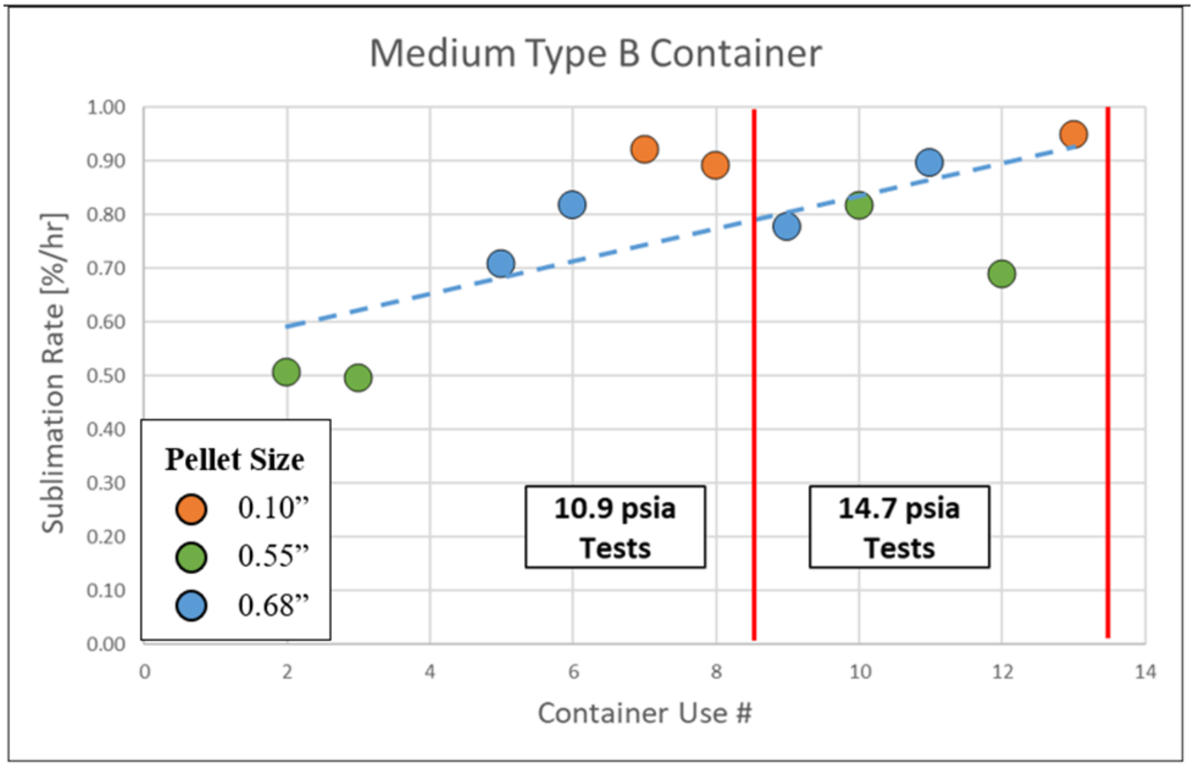

Figure 12. Medium Type B container degradation

## 2.3 Flight profile tests

Supplementary testing was performed to replicate an environment more realistic to aircraft dry ice transportation. Pressure within an aircraft interior fluctuates under normal flight conditions. Pressure fluctuations were replicated rather than being kept constant as done in the previous test series. It was unknown how changes in ambient pressure would affect the sublimation of dry ice. Therefore, a test setup was created to simulate a flight profile of an aircraft in which the climb, cruise, and descent phases were accounted for.

During normal operations, the rate of change in cabin pressure altitude is limited to not more than 5 meters/second (approximately 1,000 feet/minute) during ascent or a rate of 2.3 meters/second (450 feet/minute) during descent (National Research Council (US) Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002). A simulated ascent and descent rate of 500 feet/minute was selected for testing.

Each test within this series had a duration of approximately four hours. A graph showing the relationship between pressure chamber and total pellet weight for one of the tests is shown below in Figure 13.

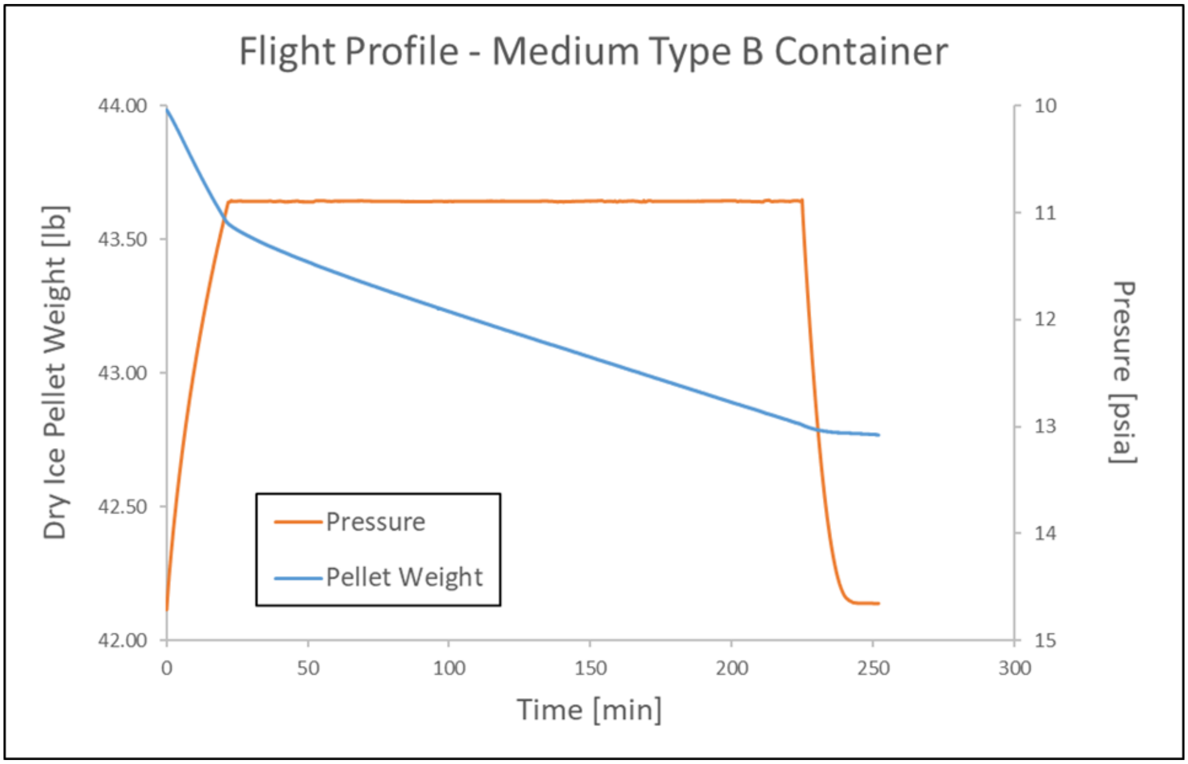

Figure 13. Medium Type B flight profile test

Data suggests that the highest rate of dry ice sublimation occurred during ascent. The average sublimation rate during ascent for all tests was calculated to be 1.77%/hour. Conversely, average sublimation rates for the in-flight and descent time intervals were measured to be 0.49%/hour and 0.41%/hour, respectively. Full sublimation data of the different time intervals for all tests can be found in Table 2, Table 3, and Table 4. These tables only include data from tests with 0.68" pellets.

Table 2: Ascent sublimation data

| **Container** | **Iteration** | **Ascent Test Duration** | **Ascent Mass Loss Rate** | **Ascent Sublimation Rate** |
|---|---|---|---|---|
| | | **[min]** | **[lb/hr]** | **[%/hr]** |
| Large Thermal | 1 | 17.20 | 1.14 | 0.57 |
| | 2 | 18.45 | 1.47 | 0.74 |
| Medium Type A | 1 | 17.20 | 0.70 | 1.65 |
| | 2 | 18.45 | 1.24 | 2.68 |
| Medium Type B | 1 | 21.54 | 1.00 | 2.33 |
| | 2 | 21.86 | 1.17 | 2.66 |

Table 3: In-flight sublimation data

| Container | Iteration | In-Flight Duration | In-Flight Mass Loss Rate | In-Flight Sublimation Rate |
|---|---|---|---|---|
| | | [min] | [lb/hr] | [%/hr] |
| Large Thermal | 1 | 206.65 | 0.75 | 0.37 |
| | 2 | 207.45 | 0.77 | 0.39 |
| Medium Type A | 1 | 206.65 | 0.24 | 0.57 |
| | 2 | 207.45 | 0.26 | 0.57 |
| Medium Type B | 1 | 204.59 | 0.22 | 0.51 |
| | 2 | 203.08 | 0.22 | 0.51 |

Table 4: Descent sublimation data

| Container | Iteration | Descent Duration | Descent Mass Loss Rate | Descent Sublimation Rate |
|---|---|---|---|---|
| | | [min] | [lb/hr] | [%/hr] |
| Large Thermal | 1 | 16.15 | 0.63 | 0.32 |
| | 2 | 18.73 | 0.57 | 0.29 |
| Medium Type A | 1 | 16.15 | 0.22 | 0.54 |
| | 2 | 18.73 | 0.32 | 0.71 |
| Medium Type B | 1 | 15.31 | 0.14 | 0.34 |
| | 2 | 18.75 | 0.10 | 0.24 |

Although the ascent phase recorded the highest sublimation rate of all three phases of flight, this may be attributed to the high sublimation rates typically observed in the beginning of the testing. Even in previous test series in which pressure was kept constant, higher sublimation rates were noted to occur during the first hour of testing, as the interior of the container needed time to acclimate.

An example of this phenomena can be seen below in Figure 14, which displays data from the previous test series in which external pressure (14.7 psia) was kept constant throughout. Data from this test was divided into four subsections of equal time intervals (approximately 120 minutes each) and the sublimation rate of each was calculated. Analysis determined that a significant amount of time was needed for the interior of the container to reach a consistent temperature. During this transitionary period, sublimation rate was noted to be highest, as compared to the end of the test in which the container temperature had equilibrated. Furthermore, preliminary testing determined that a pressure differential between the container's interior and exterior would compound the rate at which $CO_2$ gas was drawn out from the container.

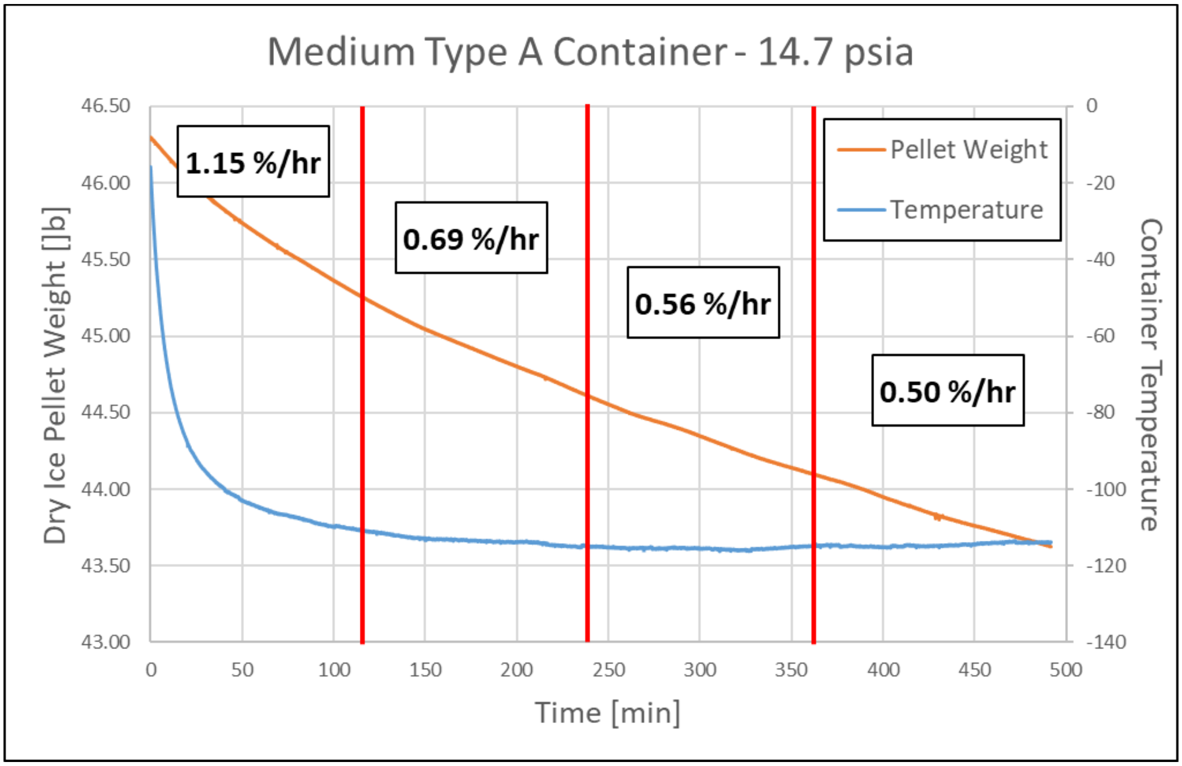

Figure 14. Sublimation rate and inner container temperature compared to test duration

## 2.4 Environmental chamber results

Although testing within the pressure vessels could adequately control the pressure within the test chamber, it could not control the temperature or relative humidity. This was predominantly problematic for the 10.8 $m^3$ pressure vessel, as it was contained within a non-air-conditioned facility. Differences in daily weather were believed to produce undesirable variation in recorded data. This variance was assumed to create inconsistencies in data comparisons between tests, especially as changes due to seasonal weather occurred.

To account for this problem, all vaccine containers were moved into an environmental chamber with inner dimensions of 72" x 71" x 93" (1.83 m x 1.80 m x 2.36 m) and an interior volume of 275 $ft^3$ (7.79 $m^3$). Within this chamber, the pressure, relative humidity and temperature could be controlled. Figure 15 displays the interior of the environmental chamber with the three scales within.

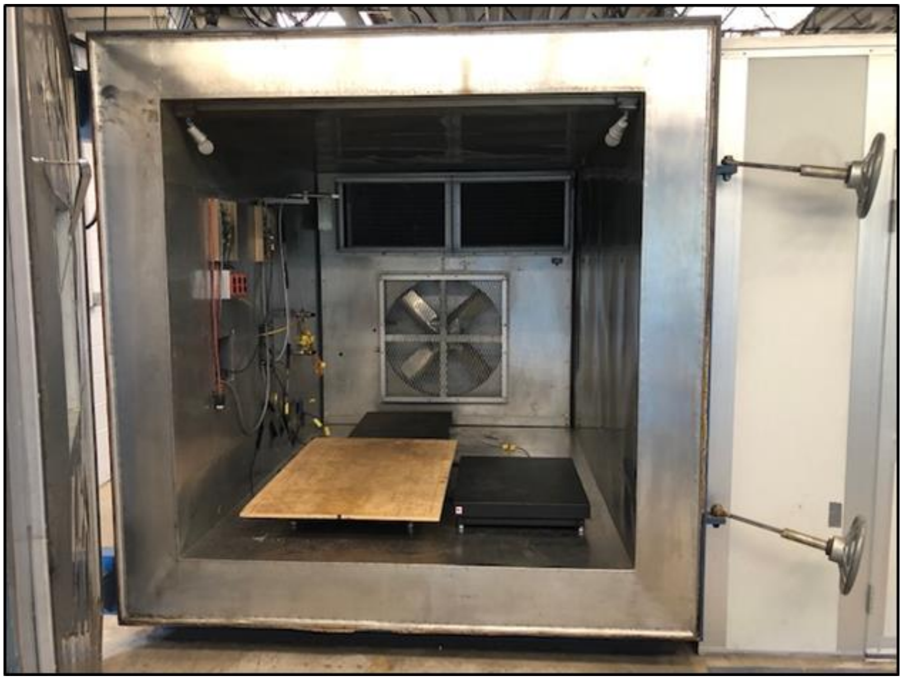

Figure 15. Environmental chamber with an inner volume of 7.79 m3 (275 ft3)

The objective of testing within the environmental chamber was to determine the effect that ambient temperature and relative humidity had on dry ice sublimation. Pressure was kept constant at a sea level pressure of 14.7 psia for all tests within this series. Temperature and humidity were altered to three levels; low, medium, and high, in which different combinations of these levels were evaluated. Each test level combination was replicated at least twice. Table 5 shows the selected variable levels for both temperature and humidity.

Table 5: Environmental chamber variable levels

| **Variable** | **Level** | **Value** |
|---|---|---|
| Temperature [°F] | Low | 40° |
|  | Medium | 60° |
|  | High | 80° |
| Relative Humidity [%] | Low | 40% |
|  | Medium | 60% |
|  | High | 80% |

Data indicates that test chamber humidity produced a limited impact on results. Little to no changes in sublimation rate was observed as humidity was altered for both the Large Thermal and Medium Type B containers. There was a more pronounced change observed in the Medium Type A container, as higher humidity environments were found to produce a lower sublimation rate. Figure 16 shows the relationship between sublimation data and changes in humidity for all containers as ambient temperature was kept constant.

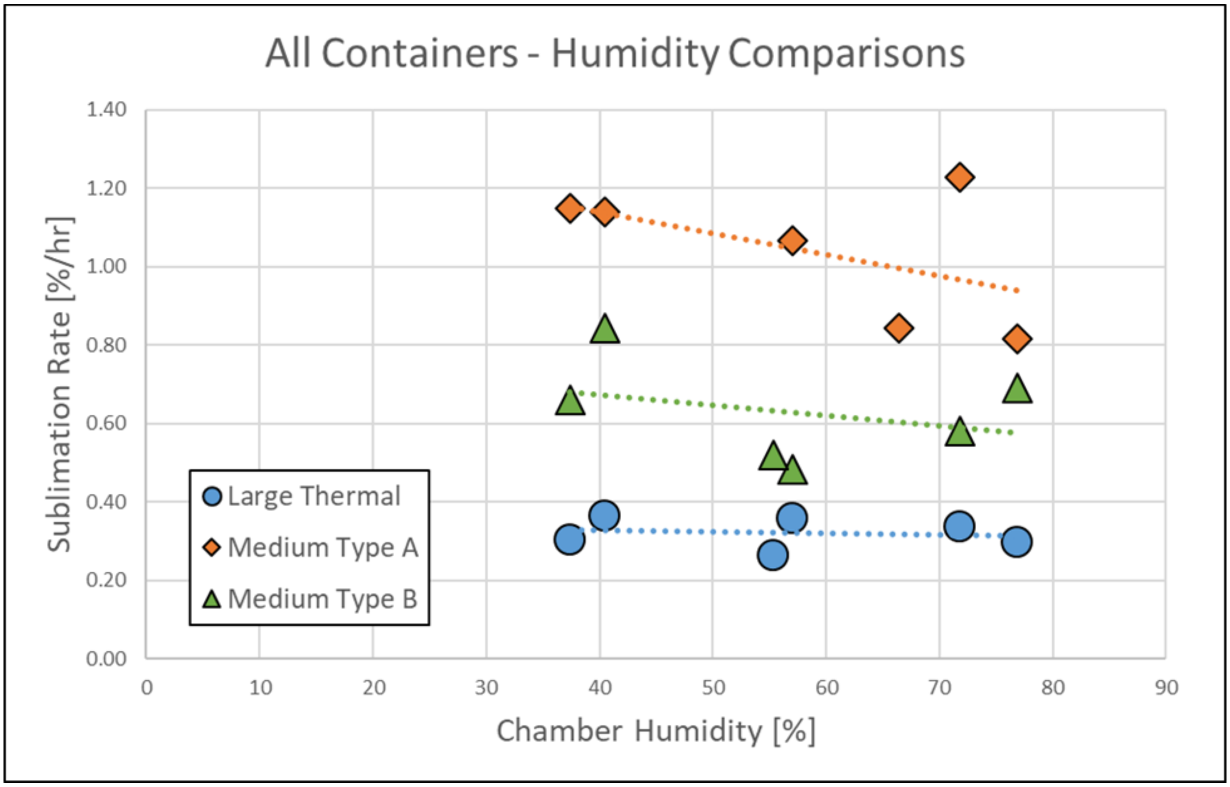

Figure 16. All containers humidity comparisons

Identically to the humidity tests, alterations in ambient temperature were found to have a minor effect on sublimation rates for both the Large Thermal and Medium Type B containers. However, contradictory to common logic, trends suggested that increases in ambient temperature decreased sublimation for the Medium Type A container. Figure 17 displays a chart of the correlation between sublimation rates and ambient temperature for all three containers.

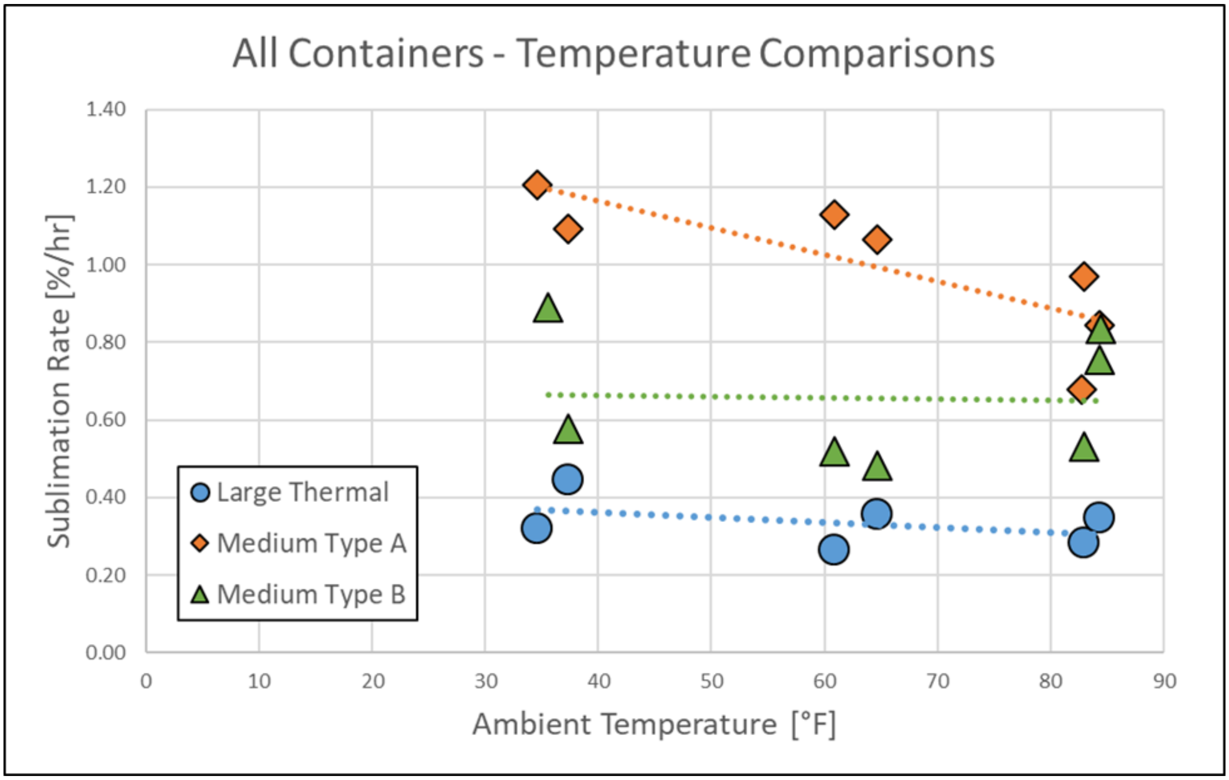

Figure 17. All containers temperature comparisons

Despite changes made to the test chamber ambient temperature, no significant differences in internal container temperature were observed as outside temperatures were altered. Table 6 displays the average inner container test temperatures for each ambient temperature level.

Table 6: Average inner container temperatures [°F] for each ambient temperature level

| | **Low [~40°F]** | **Medium [60°F]** | **High [80°F]** |
|---|---|---|---|
| Large Thermal | -111.5 | -108.9 | -108.3 |
| Medium Type A | -113.2 | -111.5 | -107.9 |
| Medium Type B | -108.6 | -104.6 | -104.0 |

Throughout this test series, average internal temperatures ranged between -100°F (-73°C) to -116°F (-82°C). As the test chamber temperature was altered, only small changes in the internal container temperatures were observed. For example, average internal temperatures of the Large Thermal container were calculated to be -111.5°F (-79.7°C), -108.9°F (-78°C) and -108.3°F (-78°C), for the low, medium and high levels, respectively. This observation suggests that despite external conditions, the containers did an exceptional job in preventing exterior heat from entering the interior once sealed. Exterior environment temperature was determined to not to be much of a factor in sublimation rate for the containers evaluated within this study given the insulated nature of the designed containers.

# 3 Conclusions

Testing indicates that some of the evaluated external parameters clearly impacted dry ice sublimation. The vaccine container itself was determined to be an important factor in sublimation. A significant difference in recorded mass loss rate and sublimation rate was observed between each of the evaluated containers as all three evaluated containers were comprised of different materials and stored different quantities of dry ice. In addition to the variations caused among the containers, container sublimation rate was observed to increase after repeated use. Significant damages caused from weathering and dry ice loading occurred. Cardboard within the container was observed to warp due to humidity and mechanical stress. Furthermore, styrofoam within the Large Thermal container was noted to fall out in chunks after repeated use.

Pellet size was determined to be another clear determinant in dry ice sublimation. Dry ice pellets with a smaller diameter were observed to sublimate at a higher rate than larger pellets. Pellets with a smaller diameter have a higher surface area to volume ratio and thus can absorb heat more quickly compared to larger dry ice pellets and dry ice blocks.

Alterations in ambient pressure produced mixed results. Within the initial test series, pressure was kept constant throughout the entirety of the experiment. Early results indicated that sea level pressure environments (14.7 psia) produced higher sublimation rates than lower pressure environments (10.9 psia). However, containers were replaced midway through the test due to considerable signs of interior damage. Sea level pressure test results from the “new” Large Thermal container produced lower sublimation rates than the reduced pressure tests.

Additional comparisons were conducted within the flight profile test series, in which pressure was altered to replicate the flight path of a typical aircraft. Results indicated that sublimation rate is highest during ascent and lowest during descent. However, this observation may not have been a result of changes in ambient pressure, as dry ice consistently sublimated at a higher rate in the beginning of tests, even when pressure was kept constant in previous test series.

In the environmental chamber tests, ambient temperature and humidity were observed to have a limited impact on sublimation. Testing was conducted at three different levels for both of these parameters. Despite alterations in external temperature and relative humidity, minimal differences in sublimation rates were observed in both the Large Thermal and Medium Type B containers. Results showed that average inner container temperatures remained relatively consistent despite external environment conditions. A more pronounced change in sublimation rate for the Medium Type A container was observed as these levels were changed.

Test analysis confirmed that pellet size, container design, and durability greatly affect performance. Whereas alterations in parameters such as ambient pressure, temperature and relative humidity yielded inconclusive results. Although sublimation was observed to be affected by numerous parameters, data suggests a conservative approach to this subject is prudent. While some external conditions may produce only minor differences in sublimation rates, it would have a major impact on the allowable quantity of dry ice shipped.

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