Transporting and Storing COVID-19 Vaccines

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Differing storage temperature requirements are not the only concern for COVID-19 vaccines. The entire vaccination process—from the original manufacturing to final vaccine administration—involves various refrigerated transportation and storage systems. This article describes various vaccine refrigerated transportation and storage technologies and systems recommendations for the general public and vaccine transport-related professionals.

The article is a product of the ASHRAE Refrigeration Technology Committee for Comfort, Process, and Cold Chain, which formed a group in February 2021 to provide "practical guidance for COVID-19 vaccine refrigerated transportation and storage" to assist stakeholders in the vaccine distribution process from the equipment point of view.

General Recommendations

The CDC has produced a Vaccine Storage and Handling Toolkit,[1] which provides general recommendations from "minimal actions" to "best practices" for the various steps of the immunization supply chain. *Table 1* provides the summary of the general temperature classes and common systems used in vaccine transportation and storage. The range of suitable and purpose-built products essentially spans three distinct temperature bands commonly associated with specific vaccines: medium-temperature refrigeration (2°C to 8°C [35.6°F to 46.4°F]), low-temperature refrigeration (–50°C to –15°C [–58°F to 5°F]), and ultralow-temperature refrigeration (–80°C to –60°C [–112°F to –76°F]).

Vaccines typically also require storage at different temperatures during the different stages of their transportation and handling (although refreezing is strictly prohibited in most instances) and do not usually remain within only one of the temperature bands. Products used for vaccine transportation and storage should, therefore, be both suitable and purpose-built to a pharmaceutical grade. Some of the products listed in

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TABLE 1 General temperature classes and common systems used in vaccine transportation and storage.

TEMPERATURE CLASS	TYPICAL RANGE[a]	COMMON VACCINES STORED AT TEMPERATURE	COMMON STORAGE SYSTEMS	COMMON TRANSPORT SYSTEMS
Medium-Temperature Refrigeration	2°C to 8°C[b]	Janssen COVID-19, Inactivated Vaccines, LAIV	Purpose-Built Vapor Compression Refrigerators and Cold Rooms	Purpose-Built Unit Load Devices (Air), Refrigerated Containers (Sea, Rail, Road), Qualified Containers And Pack-Outs, and Passive Cooling Devices
Low-Temperature Refrigeration	–50°C to –15°C	Moderna COVID-19, Varicella, MMRV, Zoster	Purpose-Built Vapor Compression Freezers and Freezer Rooms	Purpose-Built Refrigerated Containers (Sea, Rail, Road), Qualified Containers and Pack-Outs, and Passive Cooling Devices
Ultralow-Temperature Refrigeration	–80°C to –60°C	Pfizer-BioNTech COVID-19, Ervebo	Purpose-Built Vapor Compression Cascade and Auto-Cascades	Purpose-Built Refrigerated Containers (Sea, Rail, Road), and Passive Cooling Devices

[a]These are general "temperature classes" and not any one vaccine's specific limits, as specified by the CDC. Also review each manufacturer's instructions for specific storage temperatures.

[b]Special attention is always given to avoid the risk of freezing and especially refreezing.

the CDC Toolkit as suitable for vaccine transport include refrigerators and freezers, qualified containers and pack-outs, conditioned water bottle transport systems and the manufacturer's original shipping containers. Products listed as unsuitable include food and beverage coolers for transport (either off-site or emergency), and bar-style refrigerators/freezers for storage.[1]

Notwithstanding references to distinct temperature bands, each vaccine is also defined by its own, unique requirements. This may necessitate tighter temperature control or present stricter allowances for excursions, in addition to the specific temperature constraints placed on the various diluents used alongside vaccines. Given these unique features of each vaccine, the CDC, therefore, also publishes more detailed guidance.

The CDC recommends various vaccine storage methods after the shipment arrives in its controlled low-temperature state and before administering as follows:

- The Pfizer-BioNTech's COVID-19 vaccines can be sorted in ultralow-temperature freezers between –80°C and –60°C (–112°F to –76°F) until the expiration date, low-temperature freezers between –25°C and –15°C (–13°F and 5°F) for up to two weeks or refrigerators between 2°C and 8°C (35.6°F to 46.4°F) for up to five days.
- Moderna's COVID-19 vaccine can be stored in low-temperature freezers between –25°C and –15°C (–13°F and 5°F) until the expiration date or refrigerators between 2°C and 8°C (35.6°F to 46.4°F) for up to 30 days.
- The Janssen COVID-19 vaccine can be stored in low-temperature freezers between –25°C and –15°C (–13°F and 5°F) until the expiration date or refrigerators between 2°C and 8°C (35.6°F to 46.4°F) until the expiration date.

The low-temperature freezer temperature range, between –25°C and –15°C (–13°F and 5°F), is a slightly tighter temperature range than other vaccines routinely stored at these temperatures and, therefore, necessitates that suitable adjustments are made to the freezer. These ultralow-temperature and low-temperature freezers and refrigerators should also be supplied with both a digital data logger (DDL) and probe designed specifically for the referred temperature conditions (e.g., buffered with glycol, glass beads, sand or Teflon) and preferably display both minimum and maximum temperatures for daily observation and recording.[1,2] The CDC recommends measuring and recording temperatures at least every 30 minutes.[1]

The recommendation to use ultralow-temperature freezers may be applied more broadly to vaccines with similar storage temperature requirements, although "thermal shipping containers" supplied with dry-ice are not recommended by the CDC for any vaccine other than the Pfizer-BioNTech's COVID-19 vaccine[1] and may present an asphyxiation risk.

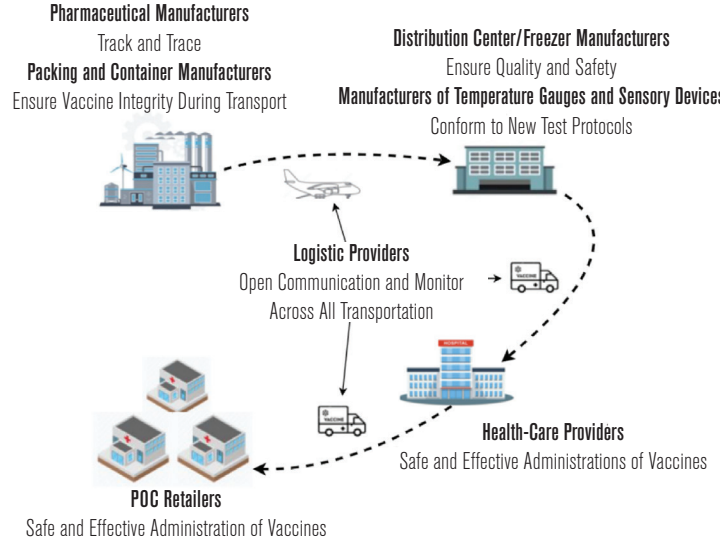
It is evident, therefore, that although suitable vaccine transportation and storage products can be broadly classified, special attention must also be given to any specific requirements. This may include specific requirements for storage temperatures or temperature limits, suitable transportation or storage products, temperature monitoring and/or data logging devices, types of probes, product quality and associated standards.

Refrigerated Vaccine Distribution Process

While there has been a major success in the U.S. for overall vaccine distribution, the process has faced some major challenges in several sectors.[3] The same is the case

for the rest of the world. The mass distribution of any vaccine has historically been a challenge. According to the International Air Transport Association (IATA), about a quarter of the vaccine cargo is delayed due to oversights, and the distribution infrastructure can be improved to avoid such lapses. It also has been reported that about 5% to 20% of the temperature-sensitive vaccine shipments have deteriorated during transportation, but there are no confirmed statistics.[4]

FIGURE 1 Cold chain logistics for effective distribution of vaccine.



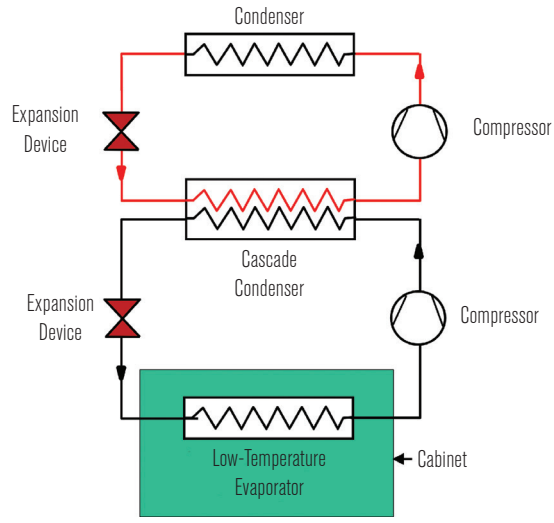
Therefore, strong vaccine logistics management is critical for the vaccine distribution to ensure the packaging, transport and delivery of vaccines without compromising the safety, security and effectiveness. This requires comprehensive coordination and communication among vaccine manufacturers, federal and local governments, freezer manufacturers, logistics providers and health-care providers. As governments, industries and other entities continue COVID-19 vaccine distribution efforts worldwide, cold chain management has emerged as a crucial factor for ensuring an effective and safe vaccine distribution framework.

A major requirement in this regard is the maintenance of necessary refrigeration levels for highly temperature-sensitive coronavirus vaccines across manufacturing, storage, transportation and distribution processes. Effective vaccine cold chain management will require varying degrees of coordination and cooperation among multiple, distinct stakeholders (*Figure 1*).

The general practices for primary operations of vaccine distribution are:

- **Reception of Vaccine, Personal Protective Equipment (PPE) and Ancillary Products:** For effective distribution and to maintain an uninterrupted supply chain, the World Health Organization (WHO) defines the tasks to be completed by the cold chain.[5] Major tasks include pre-arrival, customs clearance and transport to national storage, an inspection of shipment, stocking of shipment, reporting of problems and follow-up actions.
- **Storage of Vaccines and Ancillary Products:** Storage of the COVID-19 vaccine and temperature monitoring depends on the country's supply chain infrastructure, the government's cold chain storage and equipment capacity, availability of cold chain storage in the private market and the characteristics and thermostability requirements of the vaccines. More details of vaccine storage are described in the Vaccine Storage section later in this article.
- **Preparation of Vaccine Shipment:** Repackaging vaccines and ancillary items and production or purchase of coolant packs are critical components at this stage. Since most COVID-19 vaccines will necessitate cold chain transport of 2°C to 8°C (35.6°F to 46.4°F) and some of them require ultracold temperature transport, e.g., –80°C to –60°C (–112°F to –76°F) for Pfizer vaccines and –25°C to –15°C (–13°F and 5°F) for Moderna vaccines, a combination of refrigerated vehicles and vehicles supporting refrigerated containers are required. For vaccines requiring ultracold temperature transport, fixed COVID-19 vaccine administration sites are recommended rather than mobile sites, and repackaging is not recommended. If internal transport within the same facility is required, specialized containers, phase change material (PCM) or a thermal shipper containing dry ice should be used. *Table 1* has details on temperature requirements.
- **Transportation of Vaccines:** Vaccine and ancillary products can be transported to all sites by land, air or sea. Data loggers are the preferred option for monitoring the temperature during transportation. For the data loggers installed inside the containers, temperatures are

FIGURE 2 Simple cascade system.[6]



checked at the beginning and end of each trip to avoid exposing the vaccines by frequent container openings for accessing data loggers. For data loggers with an outside reader, temperatures are checked at least twice during the trip. More details of vaccine transport are described in Refrigerated Vaccine Transportation later in this article.

Vaccine Storage

Deep Freezer

Guidance from both the CDC and the National Science Foundation (NSF) Joint Committee on Vaccine Storage recommend the use of medical grade, purpose-built cold storage products for use in the vaccine supply chain. Medical grade storage is separated into ultralow-temperature (–80°C to –60°C [–112°F to –76°F]), low-temperature (–30°C to –15°C [–22°F to 5°F]), and medium-temperature (2°C to 8°C [35.6°F to 46.4°F]) refrigeration categories. Viability and storage time for a given vaccine varies by storage temperature category.

Ultralow-temperature (ULT) storage freezers are generally defined with a temperature range from –80°C to –60°C (–112°F to –76°F). When approved, vaccines can typically be stored in ULT temperatures for much longer periods of time due to increased stability and reduced speed of chemical reactions as compared to higher temperature ranges. A traditional ULT design includes a cascade arrangement in the refrigeration system (*Figure 2*), where heat load from the cabinet is transferred to:

- A high-pressure low stage refrigerant, typically either R-508B or R-170 (ethane), via a cold wall evaporator design.
- Then to the high stage refrigerant, typically either R-404A or R-290 (propane), via an inter-stage cascade condenser.
- Then to the ambient environment through a traditional air-cooled or water-cooled condenser.

ULTs are designed with either thick-walled traditional blown foam or advanced insulation technology such as vacuum panels to minimize the heat load during operation and provide extended warm-up time in the event of a power failure. Many ULT designs include a cold wall configuration and do not incorporate forced air convection due to difficulty in fan operation at ULT temperatures.[7]

Another type of system architecture that is used to operate in the temperature range of –80°C to –60°C (–112°F to –76°F) is so-called auto-cascades or mixed-refrigerant cascades. While auto-cascades are normally used in applications requiring temperatures below the glass transition temperature of water (–137°C [–215°F]), some variants exist in the –80°C to –60°C (–112°F to –76°F) range featuring this design.

In auto-cascades, the low temperature is achieved through the use of a mixture of refrigerants with very different normal boiling points, forming blends with very strong zeotropic behavior. After achieving partial condensation in the condenser, vapor and liquid are separated. The liquid phase has a higher concentration in the less volatile mixture components. This liquid is subsequently expanded and absorbs, through another heat exchanger, heat from the vapor that was separated earlier, leading to condensation of the more volatile components. Meanwhile, the vapor generated in that second heat exchanger is sent back to the compressor. The newly formed liquid phase is then expanded and reaches even lower temperatures than the preceding expansion stage.

This combination of subsequent condensation and expansion processes can be performed in one or several stages, depending on the boiling point that is targeted in the evaporator and the mixture constituents. For example, mixtures of four different refrigerants with normal boiling points of approximately –130°C, –80°C, –10°C, and +15°C (–202°F, –112°F, 14°F and 59°F) could be

used to reach product temperatures that are as low as –80°C (–112°F).

When compared with conventional cascades that were described earlier, auto-cascades require only one compressor, i.e., there are only two pressure levels throughout the entire system. Other potential advantages of auto-cascades are seen in better lubricant oil return because the oil stays with the liquid and never (at least theoretically) reaches the system components operating at the lowest temperature. Increased oil viscosity-associated problems with oil return can be a serious concern in conventional cascade systems, often requiring other measures to ensure flowability of the oil in the coldest sections of the system.

To achieve full redundancy, two fully independent refrigeration circuits are often used in modern auto-cascade systems. This certainly increases system reliability by avoiding situations that could result in total loss of cooling in case of one compressor failure or leakage from one circuit. On the other hand, auto-cascades often have reduced energy efficiency compared to conventional cascade systems. Other challenges that equally affect both system types are frost accumulation on the inside walls in case of frequent door openings as well as the limited possibility to operate the freezer at much higher setpoints than the design temperature.

CDC guidance for medical grade refrigerators and freezers typically includes microprocessor-based temperature control, digital temperature sensors, temperature data logging including minimum and maximum temperatures, forced air convection to promote temperature uniformity and recovery and safeguards like self-closing hinges and door alarms to protect stored products. Medical grade refrigerators and freezers typically use traditional refrigeration systems. Design goals typically focus on:

- Tight temperature uniformity and stability, which may include incorporation of variable speed compressor control;
- Tight evaporator temperature control to minimize the potential for freezing in refrigerator applications;
- Fast temperature recovery during inventory and product loading;
- Energy efficiency, which may include refrigerant selection, intelligent compressor and fan control, improved insulation and robust gasketing strategies;
- Low ambient noise generation;
- High reliability to minimize downtime and interruption of product storage.

Refrigerated Vaccine Transportation

The cold chain, or refrigerated supply chain, is a critical aspect in the transportation of vaccines from the production site to the endpoint of use. Vaccines must be maintained within the manufacturer's prescribed temperature range throughout the delivery and storage process to ensure product quality and potency. There are multiple types of transport refrigeration products that are used within the cold chain to accomplish this, spanning transport via air, ship, rail and roadways. Each of these products can play a key role depending on the geographic shipping requirements. In addition to temperature control, products often incorporate remote temperature sensing and vehicle GPS tracking through cellular or satellite telematics devices to monitor performance and ensure security and quality compliance. An overview of the various types of products available in the market will be provided.

Air Transport Products

Unit load devices (ULD) are small (typically up to 5 m^3 [177 ft^3] volume) insulated containers used on aircraft for a variety of products that require temperature control. *Figure 3* shows an example of an air transport insulated container with refrigeration unit. These are often classified as either passive or active systems. Passive systems use onboard thermal storage through the use of phase change materials to provide product cooling. Active systems incorporate a vapor compression refrigeration circuit that can be powered either through standby electrical power, before loading on the aircraft, or battery power during air transit.

Typical temperature control on ULDs ranges from 0°C to 25°C (32°F to 77°F), in ambient temperatures up to 50°C (122°F). Autonomous run time on battery power varies by product, typically ranging up to a maximum of 125 hours. Systems are also often equipped with telematics devices, which can provide data for GPS tracking, as well as continuous monitoring of internal box and/or product temperature. Given the temperature range of these systems (0°C to 25°C [32°F to 77°F]), care must be used in selecting which vaccines could be stored without supplemental cooling. Such devices could not be used to directly control vaccines requiring ultracold

FIGURE 3 Example of air transport insulated container with refrigeration unit.[8,9]

ULD Key Features

- Accurate Temperature Control
- Wide Ambient Range Including Extreme Conditions
- GDP Certified
- 1 Pallet or 4 EUR/5 U.S. Pallet Offering
- 3 Independent Refrigeration Redundancies
- Full Electric with NiMH Battery for Autonomy, 100+ Hours
- Fits Containers from 1.5 m^3 – 4.5 m^3 & 4.5 m^3 – 8.5 m^3

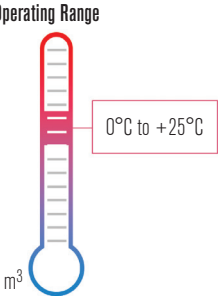
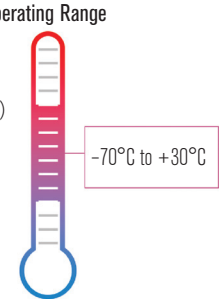


FIGURE 4 Examples of marine intermodal refrigerated containers.[8–10]

Container Key Features

- Accurate Temperature Control
- Wide Ambient Range
- Full Electric or Diesel Option (With Generator Set)
- Real-Time 24/7 Visibility
- ISO Standard for Containerized Shipping
- GDP Certified
- Fits Multiple Size Containers (3 m, 6 m, 12 m)



refrigeration but could be used in combination with vaccine packages containing dry ice or other thermal storage to extend life.

Ship Transport Products, Also Used for On-Site Storage

Container units are systems used on ships for refrigerated transport. *Figure 4* shows examples of marine intermodal refrigerated containers. Container size typically ranges from 3 m to 12 m (10 ft to 40 ft) in length. ISO standard boxes are well insulated to minimize heat load from conduction or solar radiation. Systems operate from electrical power input provided by the ship during transport. When the container box is unloaded, it can be connected to a diesel generator (genset) for portable power during transport to the final destination.

A wide range of product technologies are available, which could be used in the vaccine cold chain. Conventional systems are capable of maintaining box temperatures from –30°C to 30°C (–22°F to 86°F) in up to 50°C (122°F) ambient, making them suitable for the transport of many vaccines, aside from those requiring ultralow conditions. Additional products are available that provide storage temperatures down to –40°C (–40°F) as well.

For ultralow refrigeration, products are available using a dual compressor cascade refrigeration system capable of maintaining a –70°C (–94°F) in 3 m to 6 m (10 ft to 20 ft) special insulated containers. Such products are capable of direct storage of vaccines requiring ultralow refrigeration. Special care may be required to ensure proper temperature control and uniformity for direct storage without supplemental thermal storage/dry ice.

As these products are typically used for long-term transport, they are designed for optimum air distribution and temperature control of ±0.25°C (0.45°F). Units are down-flow, with conditioned air supplied through a T-bar floor system in the box to attain the most uniform temperature control possible. Systems also typically use automatic fresh air exchange for the management of air quality inside the container.

Systems are available with real-time telematics for performance monitoring and security. This includes GPS tracking, along with geofencing to monitor if the container has moved from a designated area. Real-time onboard data, including internal container temperature, product temperature sensors, along with temperature recording, can be remotely transmitted to a data server for monitoring. Systems may also use data

FIGURE 5 Examples of over-the-road trailer and truck transport refrigeration units.[8–10]

Trailer & Truck Key Features

- High Capacity for Fast Pulldown
- Wide Ambient Range
- Diesel Operation Independent from Main Vehicle
- Optional Electric Standby for Stationary Operation
- Real-Time 24/7 Visibility
- Fits Multiple Trailer & Box Sizes

Operating Range

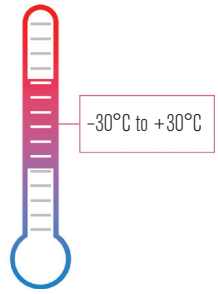
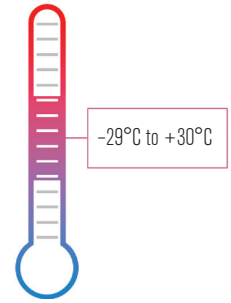


FIGURE 6 Example of small, refrigerated delivery vehicle.[10]

Delivery Vehicle Key Features

- Accurate Temperature Control
- Wide Ambient Range
- Real-Time 24/7 Visibility
- GDP & PIEK Certified in EMEA
- Full Electric Options with Battery Hold-Over
- Compatible with Multiple Makes/Models of Commerical Vehicles

Operating Range



diagnostics to assess the status of the refrigeration system and send automatic alerts to users if required.

Truck, Trailer and Rail

A wide range of transport refrigeration products and capacity sizes are available for over-the-road and rail transportation. *Figure 5* shows examples of over-the-road trailer and truck transport refrigeration units. Truck systems are typically classified as those applied to box sizes in the 3.5 m to 9.5 m (11.5 ft to 31 ft) range. Trailer systems are applied to larger box sizes in the 12 m to 16 m (39 ft to 52 ft) range. Rail applications can be trailer units mounted directly to rail cars ranging in size up to 22 m (72 ft), or intermodal applications such as trailer or container units (with genset) on the flat car.

Refrigerated products for road or rail transportation use onboard power generation for autonomous operation. Diesel engines, equipped with independent fuel systems from the primary mover, provide power either directly to the refrigeration system, or through the use of an onboard generator. Direct systems will incorporate a compressor directly coupled to the engine, with fans powered through belts or the use of a small generator. Fully electric systems use a generator mounted to the engine, similar to a genset, which provides electrical power to all refrigeration components. Fully electric trailer systems, or direct systems equipped with a standby motor, are capable of using standby plug-in power when not in transport, which could make them effective for on-site storage. Smaller truck systems are also capable of standby operation through use of an electric standby motor and clutch for the compressor.

Typical temperature control ranges are from –30°C to 30°C (–22°F to 86°F) in up to 50°C (122°F) ambient, making them suitable for all but ultralow vaccine requirements. Units are up-flow, with conditioned air directed out of the top of the unit and return air from the bottom. Some applications use air chutes or other means of directing airflow to the back of the container to improve temperature distribution, depending on the product loading configuration. Telematic data capabilities are similar to that on container systems.

Small Scale Delivery Vehicles

Systems are also available for small delivery vehicles, typically used for local short-distance deliveries, with multiple configurations available. *Figure 6* shows an example of a small refrigerated delivery vehicle. Some systems use a compressor driven from the main vehicle, with refrigerant hoses connected to the refrigeration unit. Others use a generator driven from the vehicle, with electric power provided to the refrigeration unit. Thermal storage is also used in some applications. Temperature control ranges are from –29°C to 30°C (–20°F to 86°F) up to 50°C (122°F) ambient, also making them suitable for some vaccine storage conditions.

Small Scale Delivery Containers

Temperature-controlled portable transport containers are available for local distribution and on-site storage. *Figure 7* shows examples of refrigerated portable containers. These types of containers include an active refrigeration system with an onboard compressor and heat exchangers for cooling, freezing and heating. Such containers are designed to be arranged inside a delivery van, where they can draw power from an auxiliary port on the vehicle or operate autonomously off optional, integrated battery power. Once brought to their destination, these containers can be used to store the product at desired temperatures off conventional wall power.

Pharma-specific application volumes typically range from 140 L to 720 L (37 gallons to 190 gallons). Temperature control generally ranges from –21°C to 30°C (–5.8°F to 86°F), with some of the larger containers capable of –30°C (–22°F) setpoints in up to 50°C (122°F) ambient. Small, cooler-sized (typically 32 L to 82 L [8.5 gallons to 22 gallons) products are also available for smaller-scale distribution. Cooling capability ranges by size, from –24°C (–11°F) down to –31°C (–24°F).

Use of Refrigerated Transport To Assist Vaccine Thermal Storage Packages

Refrigerated transport systems can also be used in unison with insulated vaccine packages that incorporate either dry ice for ultralow-temperature applications or thermal storage for typical low-temperature applications. Storage of such vaccine packages in refrigerated containers at –30°C (–22°F) can effectively extend the life of dry ice by reducing sublimation rate vs. storage in room ambient conditions. This could enable less frequent reloading of dry ice or other thermal storage, reducing cost and logistics requirements, along with minimizing vaccine temperature variation from frequent package openings.

Portable Transportation (Passive Cooling)

For the vaccine transportation in a short distance travel time, portable transport systems can be used with passive cooling methods. Passive cooling portable devices must maintain the same temperatures as the CDC suggests.

Phase Change Materials

Phase change materials (PCM) are latent heat storage materials. Passive cooling devices use PCM to keep the vaccines cool in qualified insulated containers and pack-outs. In general, the cooling energy may be stored in solid-liquid, liquid-to-gas, and solid-to gas PCM. The frozen solid-liquid PCM cools during melting. The cooling mechanism of liquid-to-gas PCM is vaporization. Cooling using sublimation transforms the PCM from solid to gas. Solid-liquid PCM, more commonly known as the melting-solidification cycle, is primarily used in thermal energy storage (TES) devices. Therefore, hereafter PCM means solid-liquid PCM. The melting-solidification process is shown in *Figure 8*.

The PCM must be cooled prior to use in portable devices. Point D to Point C is the process of sensible cooling liquid PCM, Point C to Point B is the solidification of the liquid PCM during latent heat release, and Point B to Point A is the sensible subcooling of the solid PCM. Point B is the saturated solid state, and Point C is the saturated liquid state at the solid region. The cooling source temperature must be below the lowest PCM temperature. The freezers recommended by CDC can be used to precool the PCM. During vaccine cooling, Point A to Point B is the sensible heating of the solid PCM, Point B to Point C is the melting of the solid PCM during latent heat absorption, and Point C to Point A is the sensible heating of the liquid PCM. Melting must be performed at temperatures below the vaccine temperature.

FIGURE 7 Examples of refrigerated portable containers.[8,9]

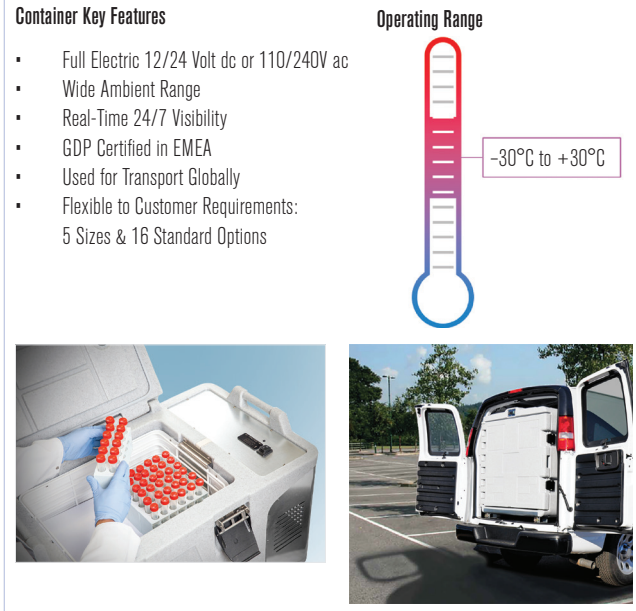


FIGURE 8 Melting-solidification process.

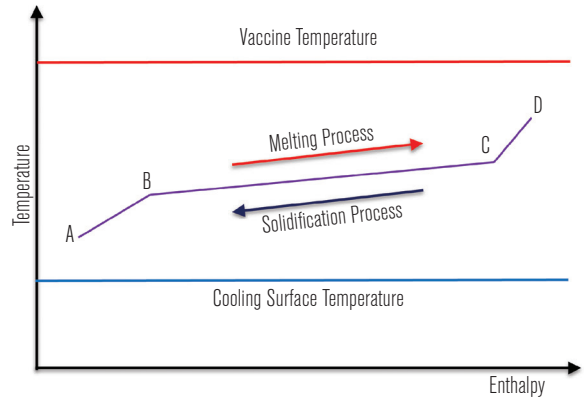
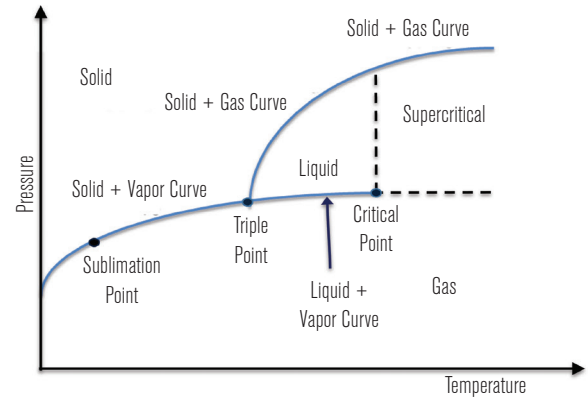


FIGURE 9 Phase diagram of carbon dioxide.



Fleisher[11] provides a very good overview of fundamentals and applications of TES using PCM. The melting point is the primary property in selecting PCM material. In general, use a PCM with the highest possible melting point that is still below the required vaccine temperature. This will enable using the cooling source with the highest possible temperature. The next important criterion is the heat of fusion, and the higher the latent heat, the better.

The other criteria are:

- Single-phase specific heat (high specific heat is preferred);
- Thermal conductivity (the higher conductivity is preferred);
- Solid and liquid density difference (has an impact on the containment structure due to contraction upon solidification;
- Chemical and physical stability over repeated thermal cycling with repeatable and consistent melting and solidification cycles;
- Compatibility with the casing material;
- Environmental safety;
- Nonflammable;
- Nontoxic;
- Cost-effective.

The PCM market is dominated by paraffin products. The Department of Agriculture and the National Science Foundation have sponsored research to investigate the potential for vegetable-derived compounds to become a significant factor in the PCM market.[12–14] The melting temperature of about 300 different fat- and vegetable-oil-based PCM ranges from minus –90°C to 150°C (–130°F to 302°F) with latent heats of fusion between 150 kJ/kg and 220 kJ/kg (64 Btu/lb and 95 Btu/lb) .

Dry Ice

Dry ice is the solid form of carbon dioxide (CO_2). Dry ice is used to passively cool frozen foods in portable transportation devices when the use of refrigeration systems is not cost-effective. Large quantities of dry ice are used for transportation of the COVID-19 vaccine. Packing the vaccine container with dry ice is the current passive cooling technology used in portable transportation devices and is applicable to the Pfizer vaccine.

Dry ice is colorless, odorless and nonflammable. It is not toxic, but is considered a hazardous material in the U.S. The U.S. Department of Transportation issued a Safety Alert for Operators in 2020 for dry ice.[15] High levels of gaseous CO_2 can degrade cognitive functions and present an asphyxiation hazard to persons subjected to it. It is extremely cold; skin contact with dry ice can lead to severe frostbite.

A phase diagram of CO_2 is shown in *Figure 9*. The figure demonstrates three thermodynamics phases: solid, liquid and gas. The critical point of carbon dioxide is 7,377 kPa (1070 psi) and 31°C (88°F). Usually, carbon dioxide states above the critical pressure and critical temperature are referred as to supercritical fluid; and the gaseous states below the critical pressure on the left of the liquid phase are referred as to vapor states. The phases are separated by the saturated curves: solid + liquid, solid + vapor, liquid + vapor, and solid + gas (top right). The dry ice triple point is 519.8 kPa (75.4 psi) and –56.4°C (–69.5°F). Heating dry ice at the states below the triple point turns it into vapor and this process is called

sublimation. Dry ice sublimates at –78.5°C (–109.3°F) at the sea-level atmospheric pressure and this is the sublimation point. The enthalpy of sublimation is 571 kJ/kg (246 Btu/lb). The density of dry ice is 1,550 kg/m^3 to 1,700 kg/m^3 (97 lb/ft^3 to 106 lb/ft^3). If the described above solid-liquid PCM implements a reversible melting-solidification cycle, dry ice is used to cool vaccine in a non-reversible sublimation cycle. In recent years, sublimation flow and heat transfer have been proposed and used in real applications.[16] According to Langebach, et al.,[17] sublimation heat transfer is much less effective compared with boiling—as a rule of thumb roughly at least one order of magnitude lower with respect to heat transfer coefficient.

Vacuum Insulation Panel (VIP)

A vacuum insulated panel (VIP) is a form of thermal insulation consisting of a gastight enclosure surrounding a rigid core, from which the air has been evacuated. According to Skulka, et al.,[18] an ultralow thermal conductivity of a VIP is almost five to 10 times smaller than the conventional insulations such as foams and fibers. Passive cooling systems may use VIPs as insulation for containers.

Conclusions

Since the COVID-19 outbreak in late 2019, multiple COVID-19 vaccines were developed swiftly. However, there are major challenges in storage and transportation of these vaccines that require different storage temperatures. ASHRAE's Refrigeration Technology Committee for Comfort, Process, and Cold Chain formed a task force to provide practical guidelines for COVID-19 vaccine refrigerated transportation and storage from the equipment point of view. This document describes various safe vaccine refrigerated transportation and storage technologies and systems recommendations for the general public and vaccine transport-related professionals.

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