Practical Guidance for Vaccine Refrigerated Transportation and Storage

Abstract

As COVID-19 vaccines available require different storage temperatures and the entire vaccination process from the original manufacturing to final vaccine administration involve various refrigerated transportation and storage systems, the Refrigeration Technology Committee of the ASHRAE formed a task force in February 2021 for providing a “Practical guidance for COVID-19 vaccine refrigerated transportation and storage” to assist stakeholders in the vaccine distribution process from the equipment point of view. This document describes various safe vaccine refrigerated transportation and storage technologies and systems and makes general recommendations.

1. Introduction

Since COVID-19 emerged in 2020, its rapid spread around the world resulted in over 3.14 million casualties worldwide and more than 0.57 million casualties in the United States (U.S.) alone [1] and caused far-reaching economic damage. In order to stop the COVID-19 pandemic, several organizations successfully developed COVID-19 vaccines and seven different vaccines have been distributed with more than 60 in clinical development [2]. Since the FDA issued an Emergency Use Authorization (EUA) for the Pfizer-BioNTech COVID-19 Vaccine and the Moderna COVID-19 vaccine in December 2020, and the Janssen COVID-19 Vaccine in February 2021, the Centers for Disease Control and Prevention (CDC) authorized and recommended for their use in the U.S., and provided details of vaccination [3]. Moreover, the CDC recommended the Pfizer-BioNTech COVID-19 vaccine for use in 12- through 15-year-old adolescents in May 2021 [3]. As the CDC is preparing for wider vaccinations through federally qualified health centers and retail pharmacies, 143 million people received at least one does (43%) and 98 million people (29.5%) are fully vaccinated as of the writing of this report [1, 2].

In order to provide practical equipment guidance for safe refrigerated transportation and storage of COVID-19 vaccines requiring different storage temperatures, the task force team of the Refrigeration Technology Committee (REF-CPCC) prepared this document describing various safe vaccine refrigerated transportation and storage technologies and systems, and makes general recommendations.

2. General Recommendations

The CDC has produced a Vaccine Storage and Handling Toolkit [3] 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), low temperature refrigeration (-50°C to -15°C) and ultra-low temperature refrigeration (-80°C to -60°C). Vaccines typically also require storage at different temperatures during the different stages of their transportation and handling (although re-freezing is strictly prohibited in most instances) and do not usually remain

within only one of the following 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 the CDC Toolkit as suitable for vaccine transport include refrigerators and freezers, qualified containers and packouts, 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 [3].

Table 1: General temperature classes and common systems used in vaccine transportation and storage

Temperature Class	Typical Range*	Common Vaccines Stored at Temperature	Common Storage Systems	Common Transport Systems
Medium Temperature Refrigeration	2°C to 8°C†	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 packouts, 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 packouts, and passive cooling devices.
Ultra-Low 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.

** 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.*
† Special attention always given to avoid the risk of freezing and especially re-freezing.

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. For example, the recommended storage of Pfizer-BioNTech's and Moderna's COVID-19 vaccines should be by way of freezers that operate between -25°C and -15°C [3], which 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 freezers should also be supplied with both a digital data logger (DDL) and probe designed specifically for these conditions (e.g., buffered with glycol, glass beads, sand, or Teflon) and preferably display both minimum and maximum temperatures for daily observation and recording. From the freezer, Moderna's COVID-19 vaccines is removed and thawed in a refrigerator between 2°C and 8°C for up to 30 days [3]. The CDC's recommended vaccine storage methods for Pfizer-BioNTech's COVID-19 vaccine are ultra-low temperature freezers and 'thermal shipping containers' (of the variety

supplied with dry-ice) [3]. The recommendation to use ultra-low 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 other vaccine [3] and present a toxicity risk. From the ultra-low temperature freezers, Pfizer-BioNTech's COVID-19 vaccines are removed and thawed in a refrigerator between 2°C and 8°C for up to 5 days before mixing with a diluent. These ultra-cold freezers should operate between -80°C and -60°C and be supplied with both a DDL and probe designed specifically for these ultra-low temperature conditions [3,4]. The CDC's recommended vaccine storage methods for Janssen COVID-19 vaccine are pharmaceutical refrigerators between 2°C and 8°C until the expiration date [3].

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.

3. 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. 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 [7]. 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, which requires comprehensive coordination and communication among vaccine manufacturers, federal and local governments, freezer manufacturers, logistics provider, and healthcare providers. As governments, industries, and other entities begin 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 as illustrated in Figure 1.

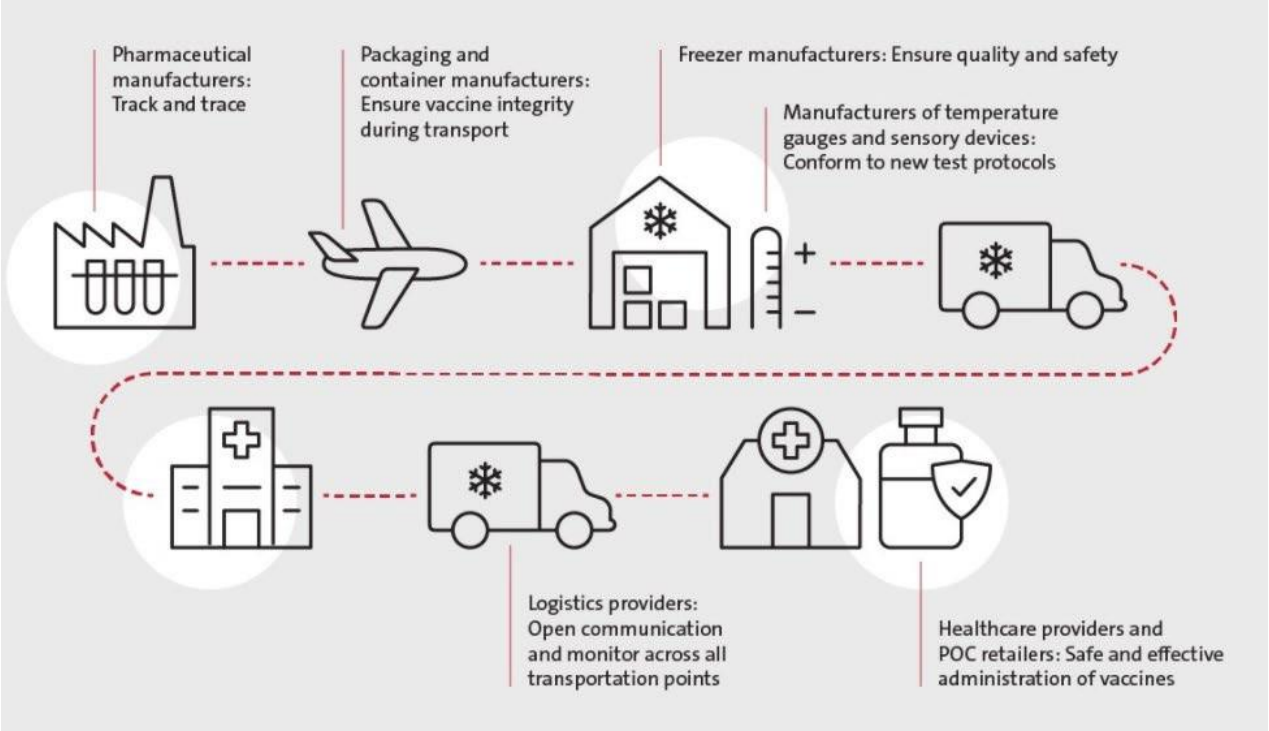

Figure 1: Cold chain logistics for effective distribution of vaccine.

The primary operations of vaccine distribution are:

Reception of vaccine, 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. Major tasks include pre-arrival, customs clearance and transport to national store, an inspection of shipment, stocking of shipment, reporting of problems, and follow-up actions.

Storage of vaccines and ancillary products: The storage of COVID-19 vaccine and temperature monitoring depends on the country's supply chain infrastructure, 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 section 4.

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 2°C to 8°C, some of them require ultra-cold temperature transport, e.g. -80°C to -60ºC for Pfizer vaccines, -25ºC to -15ºC for Moderna vaccines, refrigerated vehicles are required. For vaccines requiring ultra-cold temperature transport, fixed COVID-19 vaccines administration sites are recommended without requiring repackaging. If internal transport is required, specialized containers, such as Arktek, phase change material (PCM), or a thermal shipper containing dry ice, should be used. Please see Table 1 for 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 data loggers inside the container, temperatures are checked at the beginning and end of the trip to avoid exposing vaccines through frequent openings. For data loggers with an outside reader, temperatures are checked at least twice during the trip. More details of vaccine transport are described in section 5.

4. Vaccine Storage

4.1 Local Care Storage (Deep freezer)

Guidance from both the Centers for Disease Control and Prevention (CDC) and the National Science Foundation (NSF) Joint Committee on Vaccine Storage recommends the use of Medical Grade, Purpose-Built cold storage products for use in the vaccine supply chain. Medical Grade storage is separated into ultra-low temperature (-80°C to -60°C), low temperature (-30°C to -15°C), and medium temperature (2°C to 8°C) refrigeration categories. Viability and storage time for a given vaccine varies by storage temperature category. Ultra-low temperature (ULT) storage freezers are generally defined with a temperature range from -80°C to -60°C. 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.

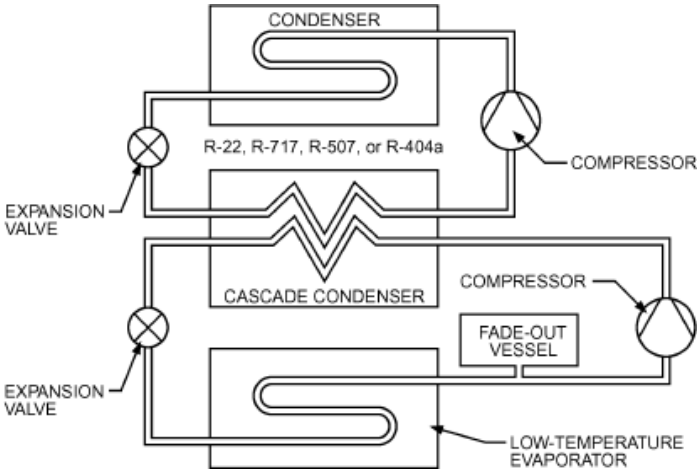

Figure 2: Simple cascade system [9]

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.

Another type of system architecture that is used to operate in the temperature range of -80°C to -60°C 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), some variants exist in the -80°C to -60°C 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, thereby 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. In the temperature range of interest, mixtures of four different refrigerants with normal boiling points of approximately -130°C, -80°C, -10°C, and +15°C are used to reach product temperatures that are as low as -80°C.

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-cades are seen in better 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. Due to the fact that conventional cascades require two compressors to keep the different refrigerant circuits separated, modern auto-cades also utilize two compressors. However, this is done to achieve full redundancy through the use of two fully independent auto-cascade circuits. 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 cooler at much higher set points 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.

5. 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 utilized 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 on the market will be provided.

5.1 Air Transport Products

Unit Load Devices (ULD) are small (up to 5 m^3 volume) insulated containers utilized on aircraft for a variety of products that require temperature control. Figure 3 shows an example of air transport insulated container with refrigeration unit. These are often classified as either passive or active systems. Passive systems utilize 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, in ambient temperatures up to 50°C. 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), 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 ultra-cold refrigeration, but could be used in combination with vaccine packages containing dry ice or other thermal storage to extend life.

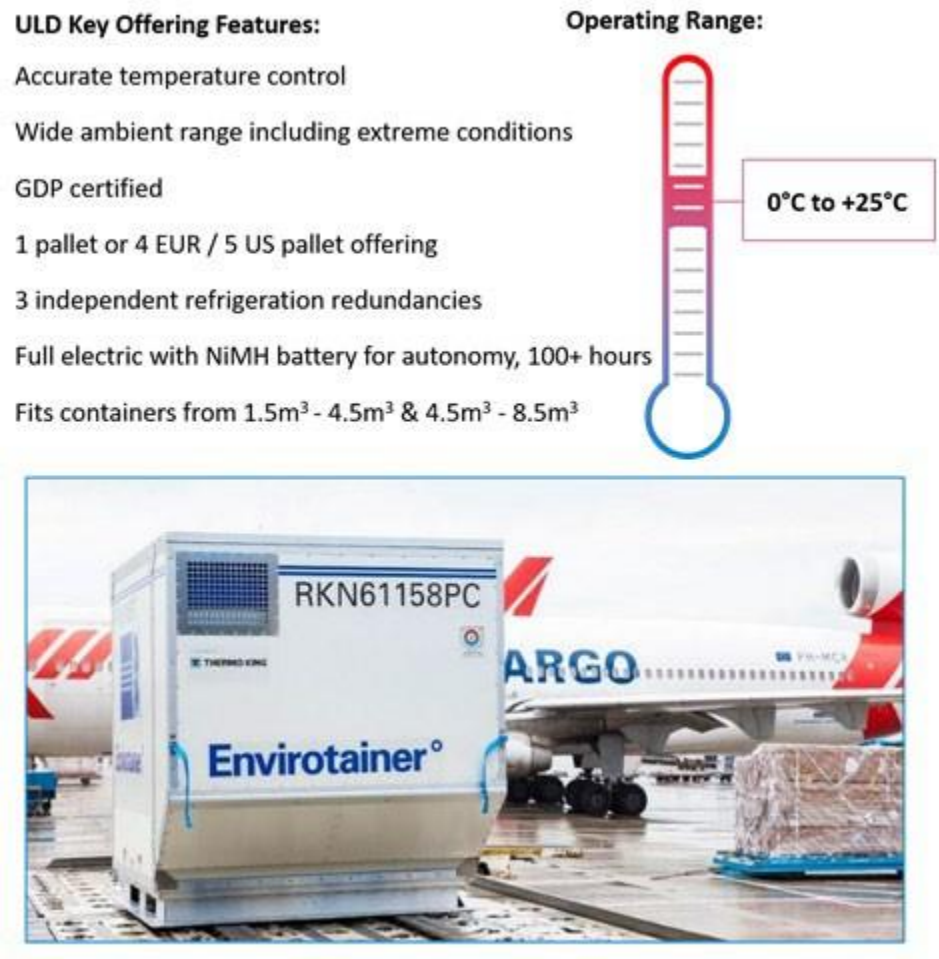

Figure 3: Example of air transport insulated container with refrigeration unit [10,11]

5.2 Ship Transport Products, Also Used for Onsite Storage

Container units are systems utilized on ships for refrigerated transport. Figure 4 shows examples of marine intermodal refrigerated containers. Container size typically ranges from 3 to 12 m 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.

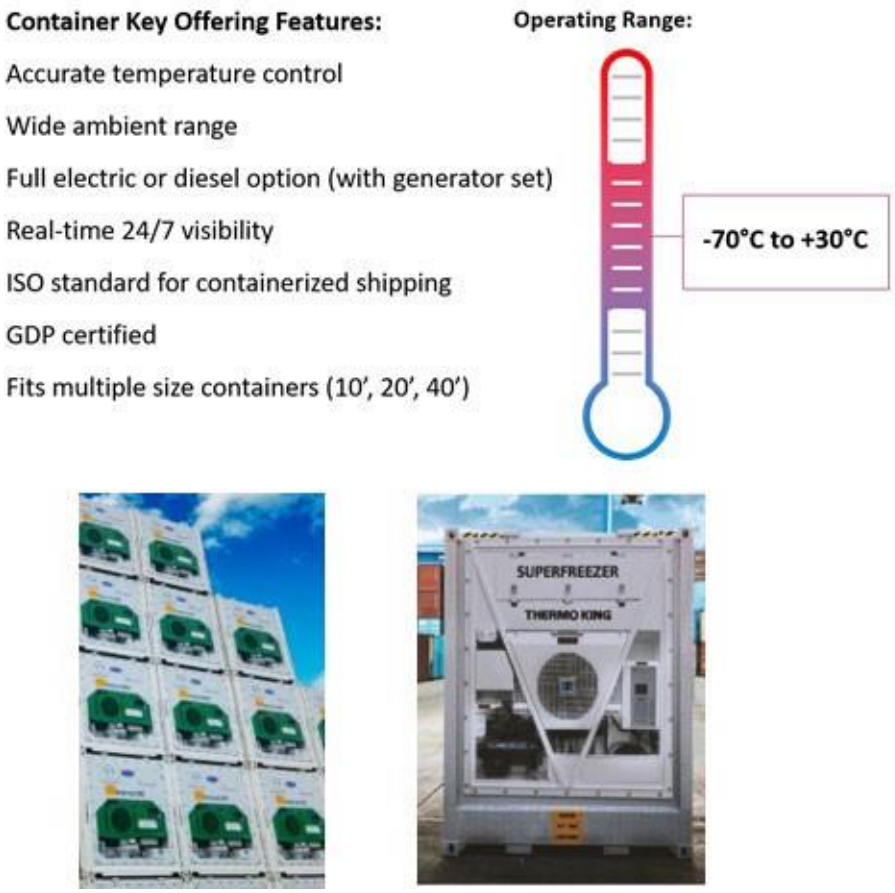

Figure 4: Examples of marine intermodal refrigerated containers [10,11,12]

A wide range of product technologies are available which could be utilized in the vaccine cold chain. Conventional systems are capable of maintaining box temperatures from -30°C to 30°C in up to 50°C ambient, making them suitable for the transport of many vaccines, aside from those requiring ultra-low conditions. Additional products are available which provide storage temperatures down to -40°C as well. For ultra-low refrigeration, products are available using a dual compressor cascade refrigeration system capable of maintaining a -70°C in 3 to 6-meter special insulated containers. Such products are capable of direct storage of vaccines requiring ultra-low 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 utilized for long-term transport, they are designed for optimum air distribution and temperature control of $\pm$ 0.25°C. 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 employ 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 utilize data

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

5.3 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 to 9.5 m range. Trailer systems are applied to larger box sizes in the 12 to 16 m range. Rail applications can be trailer units mounted directly to rail cars ranging in size up to 22 m, or intermodal applications such as trailer or container units (with genset) on the flat car.

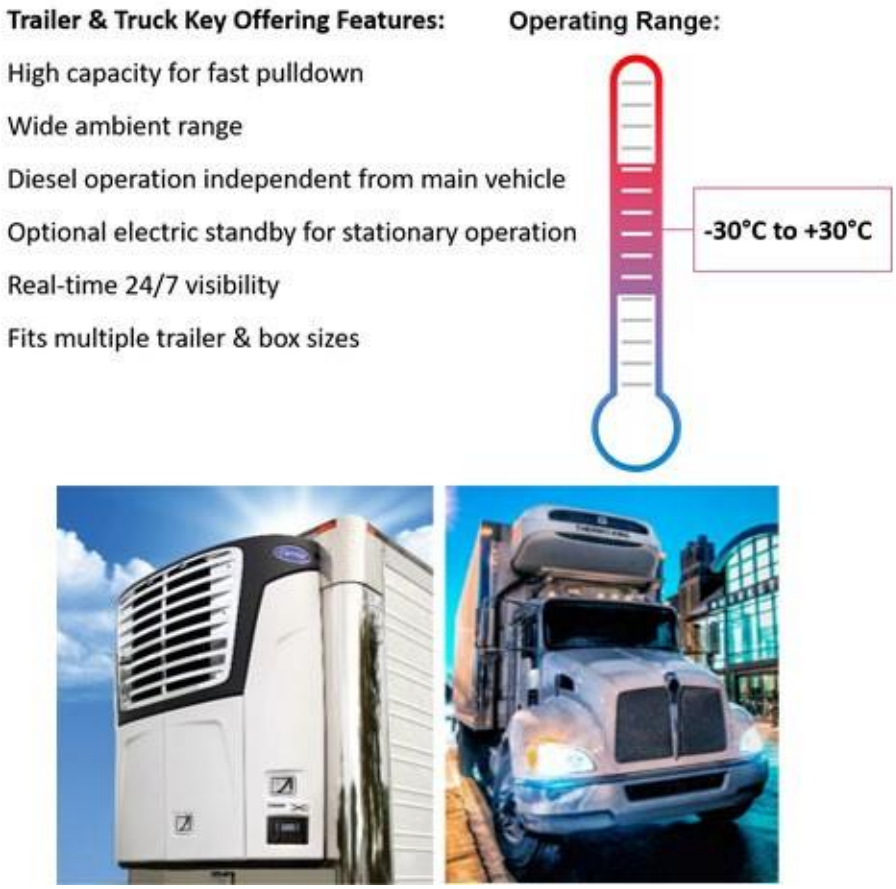

Figure 5: Examples of over-the-road trailer and truck transport refrigeration units [10,11,12]

Refrigerated products for road or rail transportation employ 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 utilize 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 utilizing 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 the use of an electric standby motor and clutch for the compressor.

Typical temperature control ranges are from -30°C to 30°C in up to 50°C ambient, making them suitable for all but ultra-low 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 utilize 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.

5.4 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 utilize a compressor driven from the main vehicle, with refrigerant hoses connected to the refrigeration unit. Others utilize a generator driven from the vehicle, with electric power provided to the refrigeration unit. Thermal storage is also utilized in some applications. Temperature control ranges are from -29°C to 30°C in up to 50°C ambient, also making them suitable for some vaccine storage conditions.

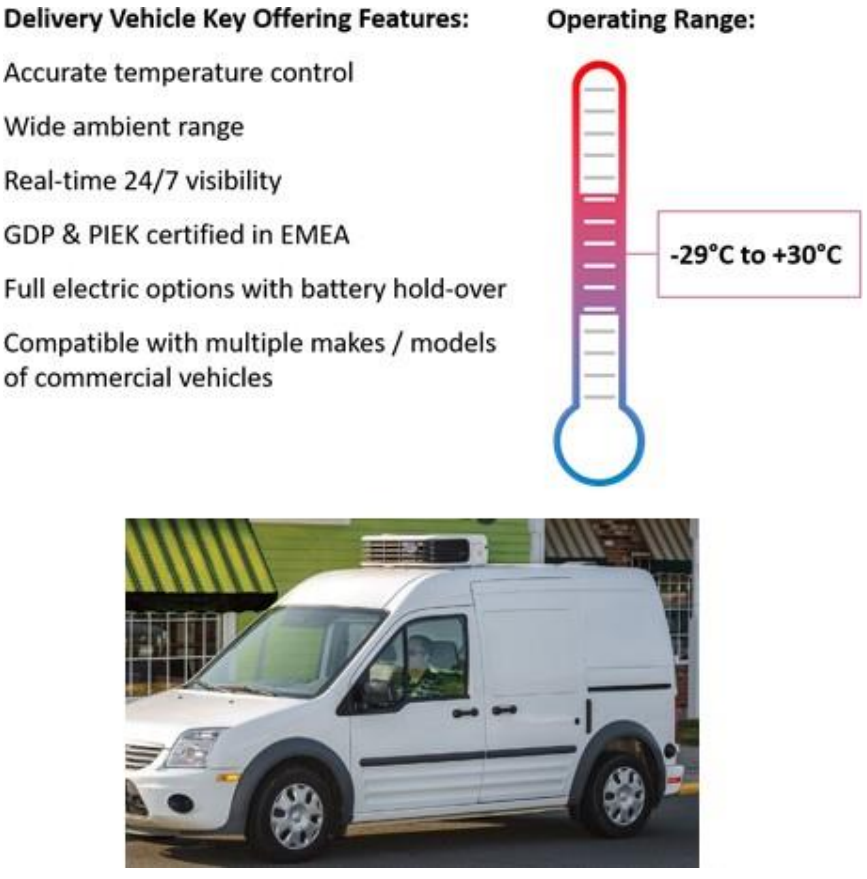

Figure 6: Example of small refrigerated delivery vehicle [12]

5.5 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 of optional, integrated battery power. Once brought to their destination, these containers can be utilized to store the product at desired temperatures off conventional wall power.

Pharma-specific application volumes range from 140 L to 720 L. Temperature control generally ranges from -21 to 30°C, with some of the larger containers capable of -30°C set-points in up to 50°C ambient. Small, cooler-sized (32 L to 82 L) products are also available for smaller-scale distribution. Cooling capability ranges by size, from -24°C down to -31°C.

Figure 7: Examples of refrigerated portable containers [10,11]

5.6 Use of Refrigerated Transport to Assist Vaccine Thermal Storage Packages

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

5.7 Portable Transportation (Passive cooling)

Passive cooling portable devices must maintain the same temperatures as CDC suggested.

5.7.1 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 cycle is shown in Figure 8.

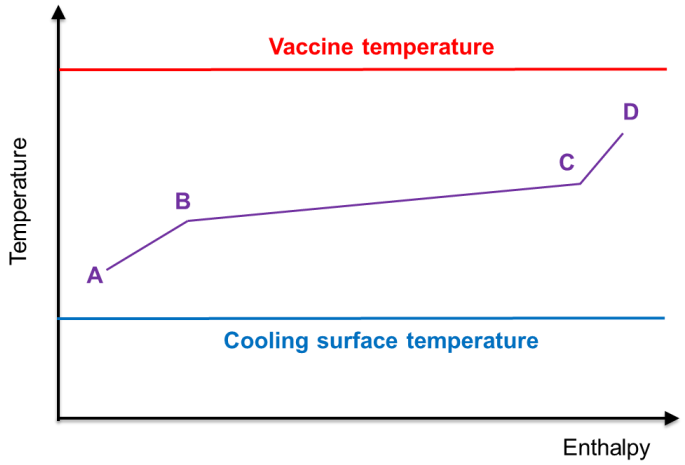

Figure 8: Melting-solidification cycle

The PCM must be cooled prior to use in portable devices: D to C is the process of sensible cooling liquid PCM, C toB is the solidification of the liquid PCM during latent heat release, and B to A is the sensible sub-cooling of the solid PCM. B is the saturated solid state and C is the saturated liquid state at the solid region. The cooling source temperature must be below lowest PCM temperature. The freezers recommended by CDC can be used to precool the PCM. During cooling the vaccine: AB - is the sensible

heating of the solid PCM, BC - is the melting of the solid PCM during latent heat absorption, and CA - is the sensible heating of the liquid PCM. Melting must be performed at temperatures below the vaccine temperature.

Fleisher [13] 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, a PCM with the highest possible melt 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 is the better.

The other criteria are:

- single-phase specific heat (high specific heat is preferred)
- thermal conductivity (the 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
- non-flammable
- non-toxic
- cost-effective

The PCM market is dominated by paraffin products. The Department of Agriculture and the National Science Foundation has sponsored research to investigate the potential for vegetable-derived compounds to become a significant factor in the PCM market [14-16]. The melting temperature of about 300 different fat- and vegetable-oil-based PCM ranges from minus -90°C to 150°C with latent heats between 150 and 220 kJ/kg.

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. Dry ice is colorless, odorless, and non-flammable. It is not toxic, but is considered a hazardous material in the U.S. The U.S. Department of Transpiration issued Safety Alert for Operators [17]. 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 on Figure 9. The figure demonstrates three thermodynamics phases: solid, liquid, and gas. The critical point of carbon dioxide is 7,377 kPa and 31°C. 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 liquid + gas. The dry ice triple point is 519.8 kPa and -56.4°C. 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 at the atmospheric pressure and this is the sublimation point. The enthalpy of sublimation is 571 kJ/kg. The density of dry ice is 1,550 – 1,700 kg/m^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 utilized in real applications [18]. According to Langebach et al. [19] 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.

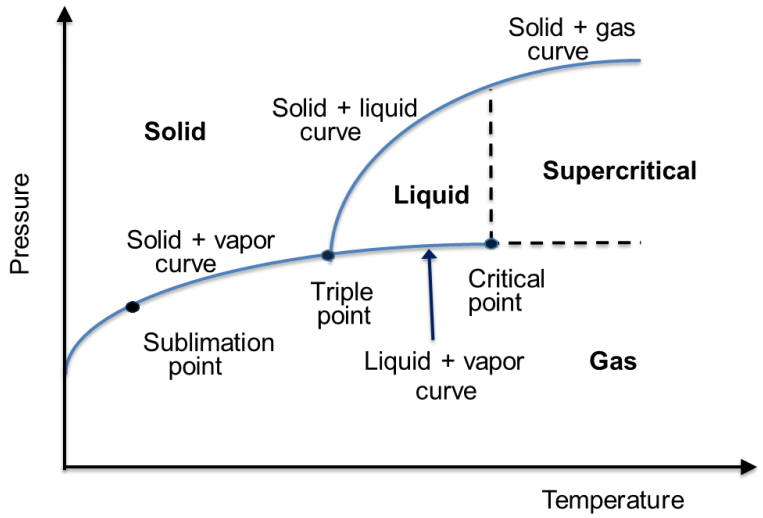

Figure 9: Phase diagram of carbon dioxide

5.6.2 Vacuum insulation panel (VIP)

A vacuum insulated panel (VIP) is a form of thermal insulation consisting of a gas-tight enclosure surrounding a rigid core, from which the air has been evacuated. According to Skulka et al. [20], an ultra-low thermal conductivity of VIP is almost 5 -10 times smaller than the conventional insulations such as foams and fibers. Passive cooling systems may use VIPs as insulation for containers.

Acknowledgement

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