Precooling and Storage Facilities

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In-Field Temperature Management

Temperature management of perishable commodities begins with proper handling at harvest. Generally, produce should be harvested in the morning so that it will be at the coolest possible temperature during the delay between harvest and initial cooling. Exceptions to this recommendation are produce, such as some citrus fruit, that are damaged if they are handled when they are turgid in the morning (Eckert and Eaks 1989), or situations in which the produce is harvested in the late afternoon so that it can be transported to a local market during the cool night hours. Produce should be shaded to protect it from solar heat gain. Reduce the time between picking and initial cooling; this is particularly critical because fruits and vegetables transpire and respire at high rates at field temperatures (Maxie et al. 1959, Harvey and Harris 1986, d'Sousa and Ingle 1989, Robbins and Moore 1992).

Initial Cooling Methods

Produce is usually cooled to its long-term storage temperature in special facilities designed to rapidly remove produce heat.

Forced-air cooling is the most widely adaptable method and is commonly used for many fruits, fruit-type vegetables, and cut flowers (Parsons et al. 1970, 1972, Rij et al. 1979, Baird et al. 1988, Thompson et al. 1998).

Hydrocooling uses water as the cooling medium and is less widely used than forced-air cooling because some products do not tolerate water contact and because it requires the use of water-resistant packaging. It is commonly used for root-, stem-, and flower-type vegetables; melons; and some tree fruits (Pentzer et al. 1936, Toussaint 1955, Stewart and Lipton 1960, Bennett 1963, Perry and Perkins 1968, Mitchell 1971).

Vacuum- and water spray vacuum-cooling are usually reserved for crops, such as leafy vegetables, that release water vapor rapidly, allowing them to be quickly cooled (Barger 1963, Harvey 1963). Package icing uses crushed ice to cool and maintain product temperature and is used for a very few commodities, mainly those whose purchasers have a strong traditional demand for this method. It is still common for broccoli.

Room cooling is accomplished by placing warm produce in a refrigerated room. Cooling times are at least 24 h and can be much longer if produce is not packaged correctly or if no provision is made to allow airflow past boxes. It is used for a few commodities, such as citrus and CA-stored apples, which can have acceptable, though not optimal, quality without use of rapid cooling.

Transport cooling in refrigerated ships and containers is used for products, such as bananas, in areas with no cooling infrastructure. Highway trailers have insufficient airflow to cool produce and should never be depended on for initial cooling.

Table 1 is a summary comparison of the six initial cooling methods.

Table 1. Comparison of typical product effects and cost for six common cooling methods

	Forced-air	Hydro	Vacuum	Water spray	Ice	Room
Typical cooling time (h)	1 to 10	0.1 to 1.0	0.3 to 2.0	0.3 to 2.0	0.1 to 0.3*	20 to 100
Product moisture loss (%)	0.1 to 2.0	0 to 0.5	2.0 to 4.0	No data	No data	0.1 to 2.0
Water contact with product	No	Yes	No	Yes	Yes, unless bagged	No
Potential for decay contamination	Low	High†	None	High†	Low	Low
Capital cost	Low	Low	Medium	Medium	High	Low‡
Energy efficiency	Low	High	High	Medium	Low	Low
Water-resistant packaging needed	No	Yes	No	Yes	Yes	No
Portable	Sometimes	Rarely done	Common	Common	Common	No
Feasibility of in-line cooling	Rarely done	Yes	No	No	Rarely done	No

Source: Thompson et al. 1998

*Top icing can take much longer.

†Recirculated water must be constantly sanitized to minimize accumulation of decay-causing pathogens.

‡Low if product is also stored in cooler as is done with apples; otherwise long cooling times make it an expensive system.

Forced-Air Cooling

Refrigerated air is used as the cooling medium with this system. It is forced through produce packed in boxes or pallet bins. A number of airflow systems are used, but the tunnel cooler is the most common (Thompson et al. 1998). Two rows of packages, bins, or palletized product are placed on either side of an air-return channel. A tarp is placed over the product and the channel, and a fan removes air from the channel, drawing air through the product. The product is cooled in batches. Cooling times range from 1 h for cut flowers to more than 6 h for larger fruit, packed in airflow-restricting materials such as bags or paper wraps.

The cold-wall system is adapted to cooling smaller quantities of produce (Thompson et al. 1998). Individual pallets or cartloads of packages are placed against a plenum wall. Usually the plenum has a slightly lower air pressure than the room, and air is pulled through the product. Some coolers, particularly for cut flowers, use a pressurized plenum and air is pushed through the product. Cold-wall systems do not use floor space as efficiently as tunnel coolers and require more management because each pallet is cooled individually.

The serpentine air system is designed for cooling produce in pallet bins (Thompson et al. 1998). Stacks of even numbers of bins are placed against a negative pressure plenum wall. Bottom openings for forklift tines are used for air supply and air return channels. Air flows vertically up or down through the product. The forklift openings are limited in dimension, which restricts airflow and causes slow cooling. This system is used for partially cooling product that will be packaged later and finish-cooled after packing and for cooling product in long-term storage. The system uses cold room volume very efficiently.

Cooling time in forced-air coolers is controlled by volumetric airflow rate and product diameter (Flockens and Meffert 1972, Gan and Woods 1989). Coolers often operate with 1 L kg^{-1} sec^{-1} of produce, with a typical range of 0.5 to 2.0 L kg^{-1} sec^{-1} (1 L kg^{-1} sec^{-1} equals approximately 1 CFM lb^{-1}). At 1 L kg^{-1} sec^{-1}, grapes with a small minimum diameter will cool in about 2 h, while cantaloupes with a much larger diameter require more than 5 h. Boxes should have about 5% sidewall vent area to accommodate airflow without excessive pressure drop across the box (Wang and Tupin 1968, Mitchell et al. 1971). Internal packaging materials should be selected to restrict airflow as little as possible.

Forced-air cooling causes some moisture loss. Loss may not be detectable for produce items with a low transpiration coefficient, like citrus fruits, or it may equal several percent of initial weight for produce with a high transpiration coefficient (Sastry and Baird 1978). Moisture loss is linearly related to difference between initial and final product temperatures. High initial produce temperatures cause higher moisture loss than lower temperatures when cooling starts. Moisture loss can be reduced at the expense of longer cooling times by wrapping product in plastic or packing it in bags.

Details of fan selection, air plenum design, refrigeration sizing, product cooling times, and operational guidelines can be found in Thompson et al. (1998). Forced-air coolers are the least energy efficient type of cooler but are widely used because they are adaptable to a wide range of products and packaging systems (Thompson et al. 2002). Small units can be installed in many existing cold storage facilities.

Hydrocooling

Cooling is accomplished with this technique by moving cold water around produce with a shower system or by immersing produce directly in cold water. Shower coolers distribute water using a perforated metal pan that is flooded with cold water from the refrigeration evaporator (Thompson et al. 1998). Shower-type coolers can be built with a moving conveyor for continuous flow operation, or they can be operated in a batch mode. Immersion coolers are suited for produce that sinks in water (Thompson et al. 1998). They usually cool more slowly than shower coolers because water flows at slower rates past the product.

Water is a better heat-transfer medium than air, and consequently hydrocoolers cool produce much faster than forced-air coolers. In well designed shower coolers, small diameter produce, like cherries, cools in less than 10 min. Large diameter products like melons cool in 45 to 60 min (Stewart and Lipton 1960, Stewart and Couey 1963, Thompson et al., 1998). Immersion coolers usually have longer cooling times than shower coolers because water speed past produce is slower.

Packages for hydrocooled produce must allow vertical water flow and tolerate water contact. Plastic or wood containers work well in hydrocoolers. Corrugated fiberboard must be wax-dipped to withstand water contact.

Hydrocoolers cause no moisture loss in cooling. In fact, they can rehydrate slightly wilted produce. Hydrocooler water spreads plant decay organisms and thus must be obtained from a clean source and treated (usually with hypochlorous acid from sodium hypochlorite or gaseous chlorine) to minimize the levels of decay organisms (Thompson et al. 1998).

Calculations of hydrocooler size, refrigeration capacity, water flow needs, and typical product cooling times can be found in Thompson et al. (1998). Hydrocoolers can be fairly energy efficient and are the least expensive cooling method to purchase (Thompson 1992).

Package Icing

Packing a product with crushed or flaked ice can quickly cool it and provides a source of cooling during subsequent handling. It also maintains high humidity around the product, reducing moisture loss. Its disadvantages are that it has high capital and operating costs, requires a package that will withstand constant water contact, and usually adds a great amount of weight to the package. In addition, meltwater can damage neighboring produce in a shipment of mixed commodities. Cut flowers are sometimes cooled initially with a forced-air system, and a small amount of ice in a sealed package is secured in the container. This greatly reduces the amount of ice needed and eliminates meltwater damage, while providing some temperature control during subsequent transit and handling.

Vacuum Cooling

This method achieves cooling by causing water to rapidly evaporate from a product. Water loss of about 1% causes 6 °C (11 °F) product cooling (Barger 1963). Product is placed in a steel vessel and vacuum pumps reduce pressure in the vessel from 760 mm Hg to 4.6 mm Hg (Thompson et al. (1998). Water boils at a pressure of 20 to 30 mm Hg depending on temperature. This causes rapid moisture evaporation and produce cooling. At the end of the cooling cycle, pressure equals 4.6 mm Hg and water boils at 0 °C (32 °F). If the product is held at this pressure long enough, it will cool to 0 °C (32 °F). For produce that releases moisture rapidly, like leafy green vegetables, cooling can be accomplished in 20 to 30 min, even when the product is wrapped in plastic film (Cheyney et al. 1979). The produce loses 2 to 4% of its weight during cooling, depending on its initial temperature. Spraying the produce with water before cooling minimizes product moisture loss. Some coolers are fitted with water spray systems that are activated during the cooling cycle.

Procedures for estimating vacuum pump capacity, refrigeration capacity, and condensing coil design can be found in Wang and Gitlin (undated). Use Thompson et al. (1998) and assume a -9 to -7 °C (15 to 20 °F) refrigerant evaporating temperature to estimate compressor horsepower. Vacuum coolers are very energy efficient (Thompson et al. 1987) and are cost competitive if well utilized (Thompson 1992).

Marine Transport Cooling

Perishable products should be cooled before being loaded into a refrigerated transport vehicle. However, some production areas do not have cooling facilities, and transport cooling is the only feasible option. Citrus and bananas in the tropics are often cooled during marine transport.

Refrigerated containers and ships supply refrigerated air through a floor plenum. Fastest possible cooling is obtained by using packages that allow vertical airflow and by loading the cargo so that refrigerated air is forced through the product. Boxes should have top and bottom vents, and interior packaging materials should not block air flow. The load or dunnage material must cover the entire floor to prevent refrigerated air from traveling up though spaces between pallet loads and bypassing the load. Proper packaging and loading will allow product to cool in 1 to 2 days (Heap 1998). Improper practices will prevent the load from cooling and the product will arrive at destination too warm and in poor quality.

Cooling Time Calculations

Rate of cooling is directly related to the temperature difference between the cooling medium and the product. Initially, when the product is warm, temperature drops quite rapidly; later, the rate slows as product temperature drops. The product is considered “half cool” when its temperature drops to half the difference between its initial temperature and the cooling medium temperature. After another half-cooling period, the product is considered “three-quarters” cool. Product is usually finished cooling at “seven-eighths” or “fifteen-sixteenths” cool. Cooling time predictions can be done with equations presented in Thompson et al. (1998) or with a graphical method like that in Sargent et al. (1988).

Cold Storage

Building Design and Layout

The floor area needed for refrigerated storage can be calculated by determining the maximum amount of product the facility will be expected to handle in units of volume (m^3 or ft^3) divided by the storage height. Storage height is usually about 2 m, the height of a pallet load. Product height can be increased by adding pallet racks or, if boxes are strong enough, by stacking pallets up to three high. Pallet bins are sometimes stacked to a height of over 3 m. Add to this area space for corridors and space for lift truck movement.

Airflow Design

Adequate airflow is needed to distribute refrigerated air throughout the facility to maintain uniform air temperatures. Most cold storage is designed to have an air flow capacity of 0.3 m^3 min^{-1} $tonne^{-1}$ of product (100 ft^3 min^{-1} ton^{-1}). In long-term storage, the product will reach setpoint temperature within a few days to about 1 week after the facility is filled. Airflow can then be reduced to about 20 to 40% of the design capacity and still maintain adequate temperature uniformity. This can be done by intermittent operation of fans or by keeping the fans constantly on but reducing their speed with an electronic speed control system. Slow air speeds reduce moisture loss from the product (Kroca and Hellickson 1993).

Airflow must be distributed uniformly throughout the coldroom to minimize temperature variability. For product in pallet loads, one of three systems is commonly used (Thompson et al. 1998). All three require placement of pallets in lanes separated by 10 to 15 cm (4 to 6 in). In rooms where the air must travel more than 15 m (50 ft), air is distributed through ceiling ducts or a plenum and returns to evaporators through a long opening in a plenum wall. Another system distributes air into the pallet lanes, and the air returns across the ceiling. Pallet bin storage can use the same systems, or air can be distributed through forklift openings or with a serpentine airflow system, as is used in some forced-air coolers.

Refrigeration Load

Determining the refrigeration capacity needed for a facility is based on estimating heat input to the cold storage from the following: uncooled product; product respiration; heat conduction through walls, floors, and roof; air infiltration through doors; lights; motors; equipment; and personnel. However these estimates cannot be done exactly. Over the life of a facility, it may be used for different products, the amount of product may change, and equipment performance deteriorates over time. Coldroom designers make estimates based on methods presented in Stoecker (1998) or ASHRAE (1999) and then add perhaps 20 to 30% extra capacity as a cushion. As a rule of thumb, refrigerated produce storage requires 10 to 14 kW of refrigeration capacity per 1,000 m^3 of storage volume and refrigerated shipping docks require 14 to 25 kW per 1,000 m^3 (Stoecker 1998).

Refrigeration Equipment

Most cold storage uses vapor recompression, also called mechanical refrigeration. A few facilities use absorption refrigeration, though this is only cost effective if there is an inexpensive source of low-temperature heat available. Detailed discussions of equipment selection and design are given in Stoecker (1998) and ASHRAE (1999).

The key design constraints for produce storage is uniformly maintaining desired temperature and relative humidity (RH). Uniform temperature is maintained by adequate refrigeration capacity, uniform air distribution, minimal temperature difference between the evaporator coil and the air temperature, and a precise temperature control system. High RH is needed to reduce product moisture loss. Most fresh produce requires 85 to 95% RH, while dried commodities, such as onion and ginger, need a low RH. High RH is obtained by minimizing temperature variation in the room and by operating the evaporator coil at a temperature close to the setpoint temperature of the room. This is done by installing a coil with a high surface area and by using a control system that maintains the refrigerant at its highest possible temperature.

Humidifiers may be needed to add moisture to paper or wood packaging materials; otherwise, packaging will absorb water from the product. Alternatively, the product can be packed in plastic packages that do not absorb water or in plastic bags that slow moisture loss. Plastic materials with minimum amounts of venting retard moisture loss from the produce (Crisosto et al. 1994) and may allow the cold storage to be held at a lower humidity. Products with low transpiration coefficients lose water slowly (Sastry and Baird 1978) and may not need special provision for high RH storage, especially if they are not stored for a long time.

Alternative Refrigeration Options

In areas with limited capital for investment in refrigeration, there are other options besides using mechanical refrigeration for temperature control, though none of them provide the optimum conditions that refrigeration does (Thompson 1999). Evaporative cooling drops air temperature to within a few degrees of the wet bulb temperature of the outside air and is sometimes used in dry climates. In these same climates, the nighttime air temperature tends to be lower and product can be ventilated with cool night air. Soil temperature at 2 m (6 ft) below the surface is equal to the average annual air temperature. Storage facilities can be built underground to take advantage of these lower temperatures. Well water is also usually equal to average annual air temperature and can sometimes be used to cool products. Using ice formed in winter and storing products at high altitudes are also occasionally used to provide cool storage temperatures. Unfortunately, few of the above options work well in humid, tropical climates.

Ethylene Control

Certain types of produce are sensitive to damage from ethylene; thus it is necessary to minimize ethylene level in their storage environment. Unless outside temperatures are very low or very high, ventilation is an inexpensive method of reducing ethylene levels. Ethylene can also be absorbed on commercially available potassium permanganate pellets or potassium permanganate pellets that have been scrubbed with heated catalyst devices. A few products, especially floral and ornamental crops, can be chemically treated to make them insensitive to ethylene damage.

Controlled Atmosphere Facilities

Storage rooms can be built for controlled atmosphere (CA) storage for about 5% additional cost if they are properly designed initially. The extra cost is for sealing joints between walls, ceilings, and floors and for installing gas-tight doors. Tilt-up concrete, metal panels, urethane foam, and plywood have all been successfully used as gas barriers. These storage rooms also need equipment for monitoring and controlling gas levels (Waelti and Bartsch 1990).

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