Pre-cooling 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, like some citrus fruit, that are damaged if they are handled when they are turgid in the morning (Eckert and Eaks, 1989), or situations where 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; Robbins and Moore, 1992; Harvey and Harris, 1986; D'sousa and Ingle, 1989).

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 (Guillou, 1960; Parsons et al., 1970, 1972; Rij. et al., 1979; Baird et al., 1988; Thompson et al., 1998). Hydro-cooling uses water as the cooling medium and is less widely used than forced-air cooling because some products do not tolerate water contact, and 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 utilizes crushed ice to cool and maintain product temperature and is used for a very few commodities, mainly for 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 no provision is made to allow airflow past boxes. It is used for a few commodities, such as citrus and CA-stored apples that can have acceptable, although not optimal, quality without use of rapid cooling. Transport cooling in refrigerated ships and containers is used for products in areas with no cooling infrastructure, such as bananas. 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 (Thompson, et al., 1998).

	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[1]	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[2]	none	high[2]	low	low
Capital cost	low	low	medium	medium	high	low[3]
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

[1] Top icing can take much longer.
[2] Recirculated water must be constantly sanitized to minimize accumulation of decay pathogens.
[3] 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 (Fig. 1). 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 and cooling times range from 1 h for cut flowers to more than 6 h for larger fruit, packed with airflow restricting materials such as bags or paper wraps.

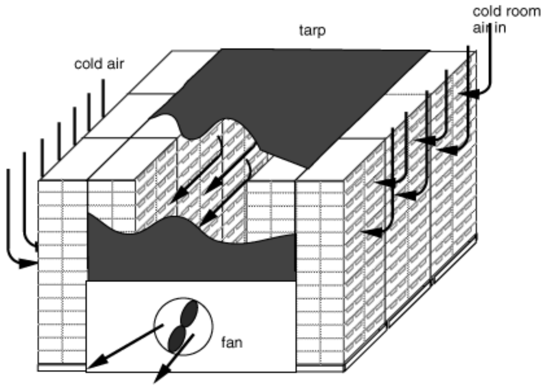

Figure 1. Schematic of a tunnel-type forced-air cooler.
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The *cold wall system* is adapted to cooling smaller quantities of produce. Individual pallets or cartloads of packages are placed against a plenum wall (Fig. 2). Usually the plenum has a slightly 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.

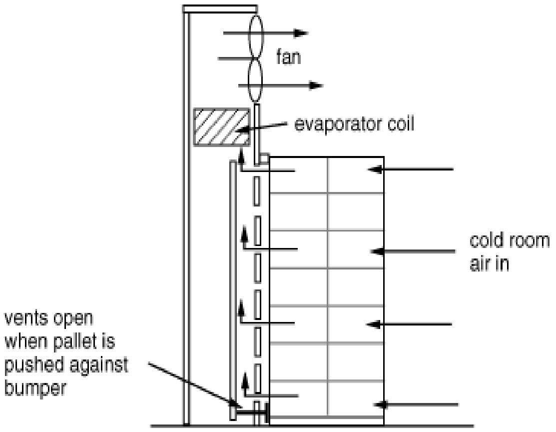

Figure 2. Schematic of a cold-wall forced-air cooler.
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The *serpentine air system* is designed for cooling produce in pallet bins. Stacks of even numbers of bins are placed against a negative pressure plenum wall (Fig. 3). Bottom openings for forklift 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 and this 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 is used for cooling product in long term storage. The system uses cold room volume very efficiently.

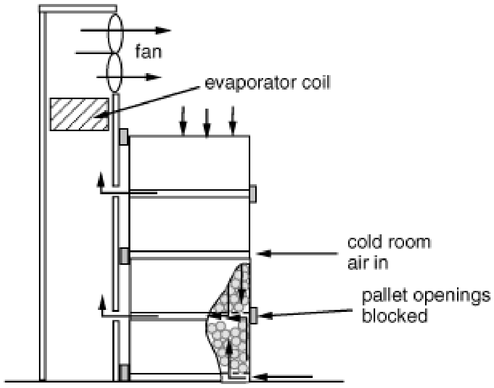

Figure 3. Schematic of a serpentine forced-air cooler.

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 about 1 CFM per lb). At 1 L kg^{-1} sec^{-1}, grapes that have a small minimum diameter will cool in about 2 h and cantaloupes, with a large diameter require > 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 so they restrict airflow as little as possible.

Forced-air cooling causes some moisture loss during cooling. Loss may be immeasurable 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 when the product stats cooling at a lower temperature. 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.

Hydro-cooling: 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 (Fig. 4) distribute water using a perforated metal pan that is flooded with cold water from the refrigeration evaporator. 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 (Fig. 5) are suited for product that sinks in water. They usually cool slower than shower coolers because water flows at slower rates past the product.

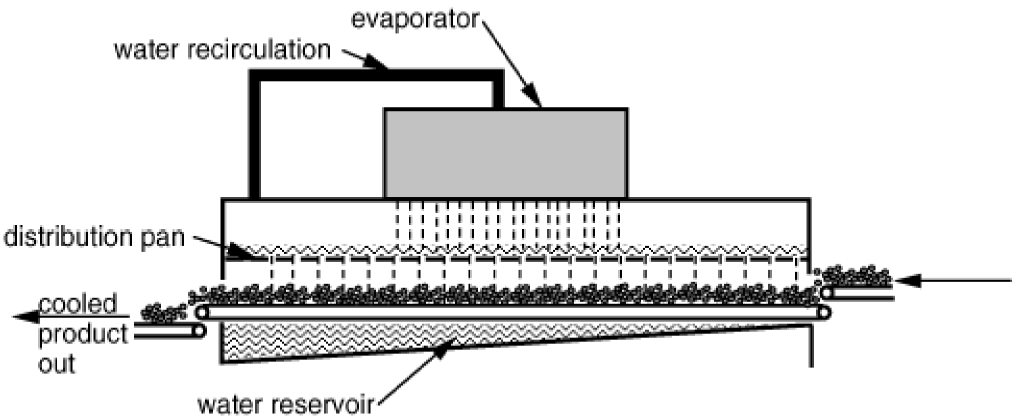

Figure 4. Cut-away side view of a continuous-flow shower-type hydrocooler.
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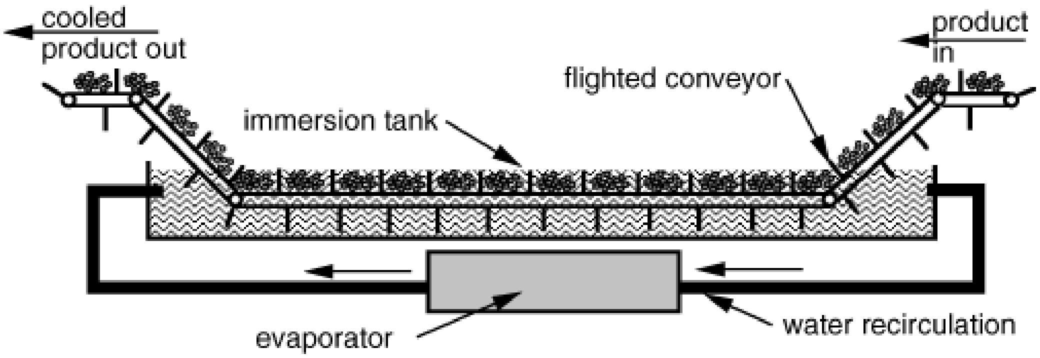

Figure 5. Cut-away side view of a continuous-flow immersion hydrocooler.
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Water is a better heat-transfer medium than air and, consequently, hydrocoolers cool produce much faster than forced-air coolers. In well-designed shower coolers, small diameter produce, like cherries, cool 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 hydro-cooled produce must allow vertical water flow and must tolerate water contact. Plastic or wood containers work well in hydrocoolers. Corrugated fiberboard must be wax-dipped to withstand water contact.

Hydro-coolers cause no moisture loss in cooling. In fact, they can rehydrate slightly wilted product. Hydrocooler water spreads plant decay organisms and it 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 hydro-cooler 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 provide 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, usually adds a great amount of weight to the package, and melt water 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 package. This greatly reduces the amount of ice needed and eliminates melt water damage, while providing some temperature control in 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 an atmospheric pressure of 760 mm of Hg to 4.6 mm Hg (Fig. 6). Water boils at a pressure of 20 to 30 mm Hg depending on its 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.

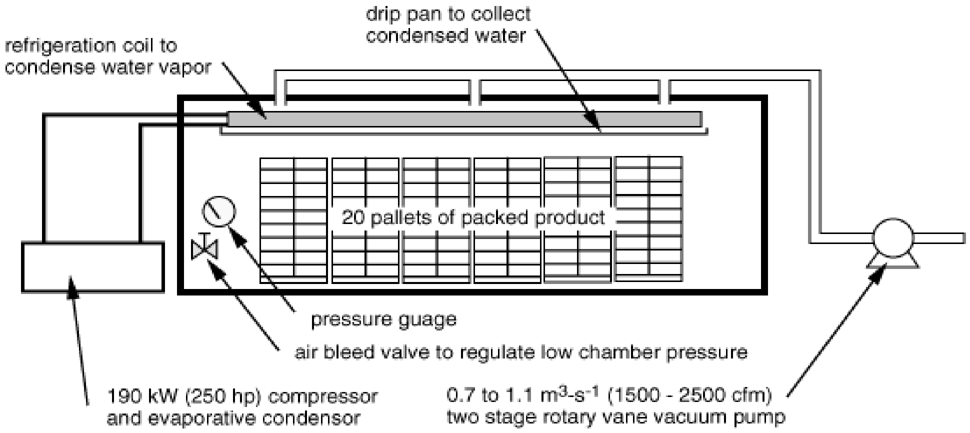

Figure 6. Key components of a 20-pallet capacity vacuum cooler.

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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).

Room Cooling: Warm products placed in a refrigerated storage cool quite quickly if they have direct exposure to the cold air. For example, cut flowers placed in water buckets will cool to room temperature in < 30 min. But boxed and palletized produce is shielded from the cold air and cooling can take many days. Packed produce can be cooled in about 24 h if packed in containers with about 5% venting; vents align between boxes when the boxes are palletized; pallets are spaced 10 to 15 cm apart; and the cold room has an evenly-distributed air flow of at least 100 ft^3 min^{-1} ton^{-1} of product storage capacity (Guillou, 1960).

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 one to two 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. Average product temperature during cooling follows a pattern similar to Fig. 7. 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 '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 in Sargent et al. (1988).

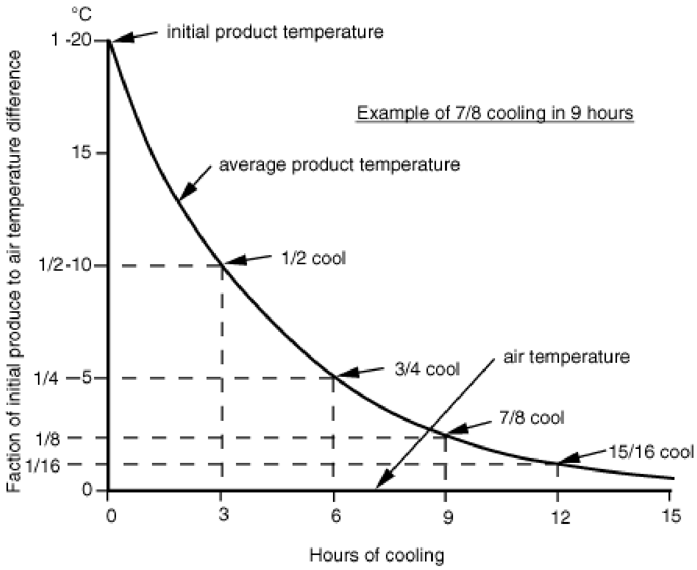

Figure 7. Typical time-temperature pattern in produce cooling. Numbers along the temperature curve indicate the fraction obtained by dividing the difference between product temperature and air temperature in the cooler by the difference between the initial produce temperature and the air temperature.

Cold Storage:

Building Design and Layout: The floor area of a 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 in order to maintain uniform air temperatures. Most cold storages are 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)

The airflow must be distributed uniformly throughout the cold room in order to minimize temperature variability. For product in pallet loads, one of three systems is commonly used (Figs. 8, 9, and 10). All require that the pallets are placed 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 it 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.

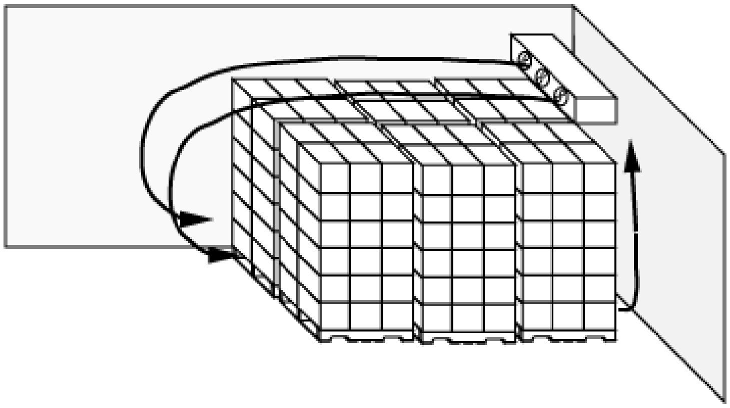

Figure 8. Airflow pattern in a room with unit evaporators.

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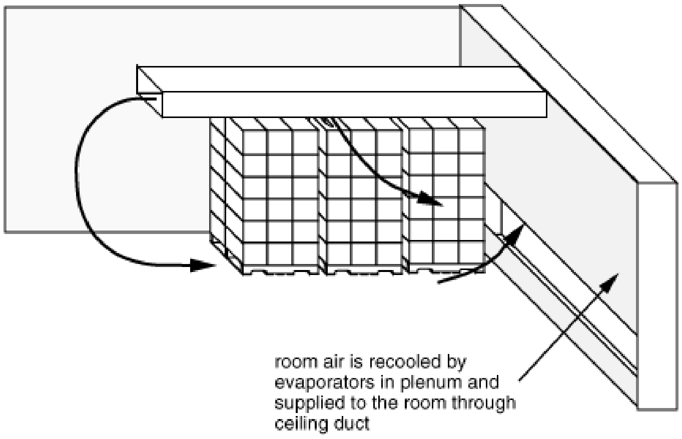

Figure 9. Airflow pattern in a room with a slotted ceiling duct.

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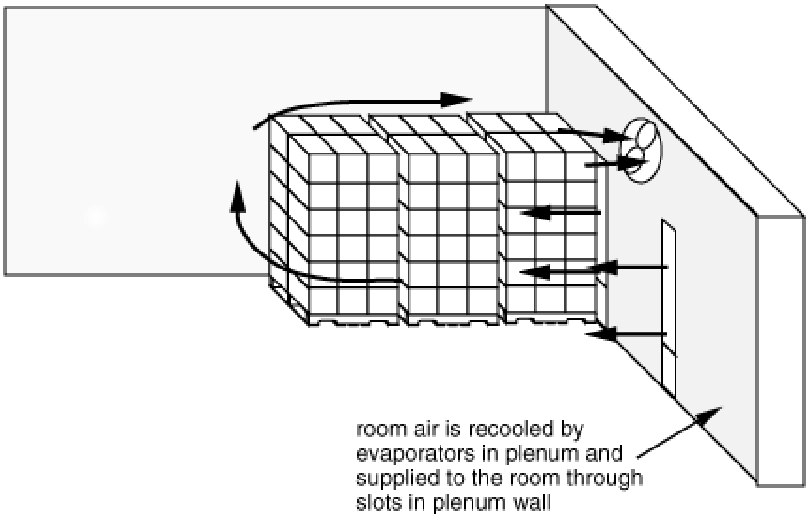

Figure 10. Airflow pattern in a room with a slotted plenum wall.
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Refrigeration Load: Determining the refrigeration capacity needed for a facility is based on estimating heat input to the cold storage from: uncooled product, product respiration, heat 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, amount of product may change, and equipment performance deteriorates over time. Cold room designers make estimates based on methods presented in Stoecker (1998) or ASHRAE,(1999) and then add perhaps 20 to 30% extra capacity as a safety factor. As a rule of thumb, refrigerated produce storage will require 10 to 14 kW of refrigeration capacity per 1,000 m^3 of storage volume (0.08 to 0.11 tons per 1,000 ft^3) and refrigerated shipping docks require 14 to 25 kW per 1,000 m^3 (0.11 to 0.2 tons per 1,000 ft^3) (Stoecker, 1998).

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

The key design constraints for produce storages are to uniformly maintain desired temperature and RH. Uniform temperature is maintained by having adequate refrigeration capacity, uniform air distribution, minimizing the 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. Although 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 set point 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 some alternatives to using mechanical refrigeration for temperature control, although 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 low and storages can be ventilated with cool night air. Soil temperature 2 m (6 ft) below the surface is equal to the average annual air temperature. Storages 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. Ice formed in the Winter and storing products at high altitudes are also occasionally used to provide cool storage temperatures. Unfortunately, few of the above alternatives work well in humid, tropical climates.

Ethylene Control: Some produce is sensitive to damage from ethylene and their storage environment must have low levels of this gas. Unless outside temperatures are very low or very high, ventilation is an inexpensive method of reducing levels. Ethylene can also be absorbed on commercially available potassium permanganate pellets, or 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 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 installing gas-tight doors. Tilt-up concrete, metal panels, urethane foam and plywood have all been successfully used as gas barriers. These storages also need equipment for monitoring gas levels and controlling concentrations (Waelti and Bartsch, 1990).

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