CHAPTER 14

METHODS OF PRECOOLING FRUITS, VEGETABLES, AND CUT FLOWERS

COOLING is generally considered the removal of field heat from freshly harvested products to inhibit spoilage and to reduce the rate of quality and flavor loss. The term precooling implies the removal of heat before the product is shipped to a distant market, processed, or stored. Some products are slowly cooled in the room in which they are stored. Precooling is generally done in a separate facility within a few hours or even minutes. Therefore, room cooling is not considered precooling.

PRODUCT REQUIREMENTS

Fruits, vegetables, and cut flowers are all living organisms, and they draw energy from stored reserves to carry out respiration and other physiological processes. Slowing the rate of deterioration after harvest helps to ensure that products are still of good quality when they are marketed.

Deterioration can be caused by product breakdown, tissue injury, moisture loss, or contamination by fungi or bacteria. High product temperatures can increase the rate of deterioration; understanding the relationship between temperature and deterioration is critical to proper produce management.

Product physiology, in relation to harvest maturity and ambient temperature at harvest time, largely determines precooling requirements and methods. Some products are highly perishable and must begin cooling as soon as possible after harvest. Vegetables in this category include asparagus, snap beans, broccoli, cauliflower, sweet corn, cantaloupes, summer squash, vine-ripened tomatoes, leafy vegetables, globe artichokes, brussels sprouts, cabbage, celery, carrots, snow peas, and radishes. Vegetables such as white potatoes, sweet potatoes, winter squash, pumpkins, and mature green tomatoes may need to be cured at some temperature higher than desirable for holding more perishable produce. Cooling of these products is not as important; however, some cooling is necessary if ambient temperature is high during harvest. Vegetables not listed may or may not be cooled because of lack of economic importance. Cooling methods can also be limited by the products' susceptiblity to damage from water contact.

Commercially important fruits that need to be precooled immediately after harvest include apricots, avocados, all of the berries except cranberries, tart cherries, peaches and nectarines, plums and prunes, and tropical and subtropical fruits such as guavas, mangos, papayas, and pineapples. Tropical and subtropical fruits of this group are susceptible to chilling injury and thus need to be cooled according to individual temperature requirements. Sweet cherries, grapes, pears, and citrus fruit have a longer postharvest life than the former fruits, yet prompt cooling is essential to maintain high quality during the holding period. Bananas require special ripening treatment and therefore are not precooled. Chapter 8 lists recommended storage temperatures for many products. Quality is maintained better if products are cooled to these temperatures quickly after harvest, although some products may be damaged if cooled below the recommended temperature.

CALCULATION METHODS

Heat Load

The refrigeration capacity needed for precooling is much greater than that required for holding a product at a constant temperature or for slow cooling of a product. Therefore, the heat load on a precooling system should be determined as accurately as possible. While it is imperative to have an adequate amount of refrigeration for effective precooling, it is uneconomical to have more refrigerating capacity available than is normally needed.

On jobs where refrigeration is needed only during a regular 8 to 12 h workday, ice-builder equipment can be installed to reduce the size of the high-pressure side (compressor and condenser) of the refrigeration equipment. Also, ice-building equipment can reduce electrical cost where off-peak power rates are available.

The total heat load comes from the product, surroundings, air infiltration, containers, and heat-producing devices such as motors, lights, fans, and pumps. Product heat accounts for the major portion of total heat load on a precooling system. Product heat load depends on product temperature and cooling rate, amount of product cooled in a given time, and specific heat of the product. Heat from respiration is part of the product heat load, but it is generally small. Chapter 12 discusses how to calculate the refrigeration load in more detail.

Mass-Average Temperature. Product temperature must be determined accurately in order to calculate heat load accurately. During rapid heat transfer, a temperature gradient develops within the product, with faster cooling causing larger gradients. This gradient is a function of product properties, surface heat transfer parameters, and cooling rate. Initially, for example, hydrocooling rapidly reduces the temperature of the exterior of a product while the center temperature may not change at all. Most of the product mass is in the outer portion. Thus, calculations based on center temperature would show little heat removal while, in fact, substantial heat has been extracted. For this reason, the product mass-average temperature must be used for product heat load calculations (Smith and Bennett 1965). A mass-average temperature denotes the single value from the transient temperature distribution that would become the uniform product temperature when held for a period under adiabatic conditions.

Figure 1 can be used to determine the mass-average temperature t_{ma} of peaches during hydrocooling. Subsequently, the product cooling load can be calculated as

$$Q = mc_p(t_i - t_{ma}) \qquad (1)$$

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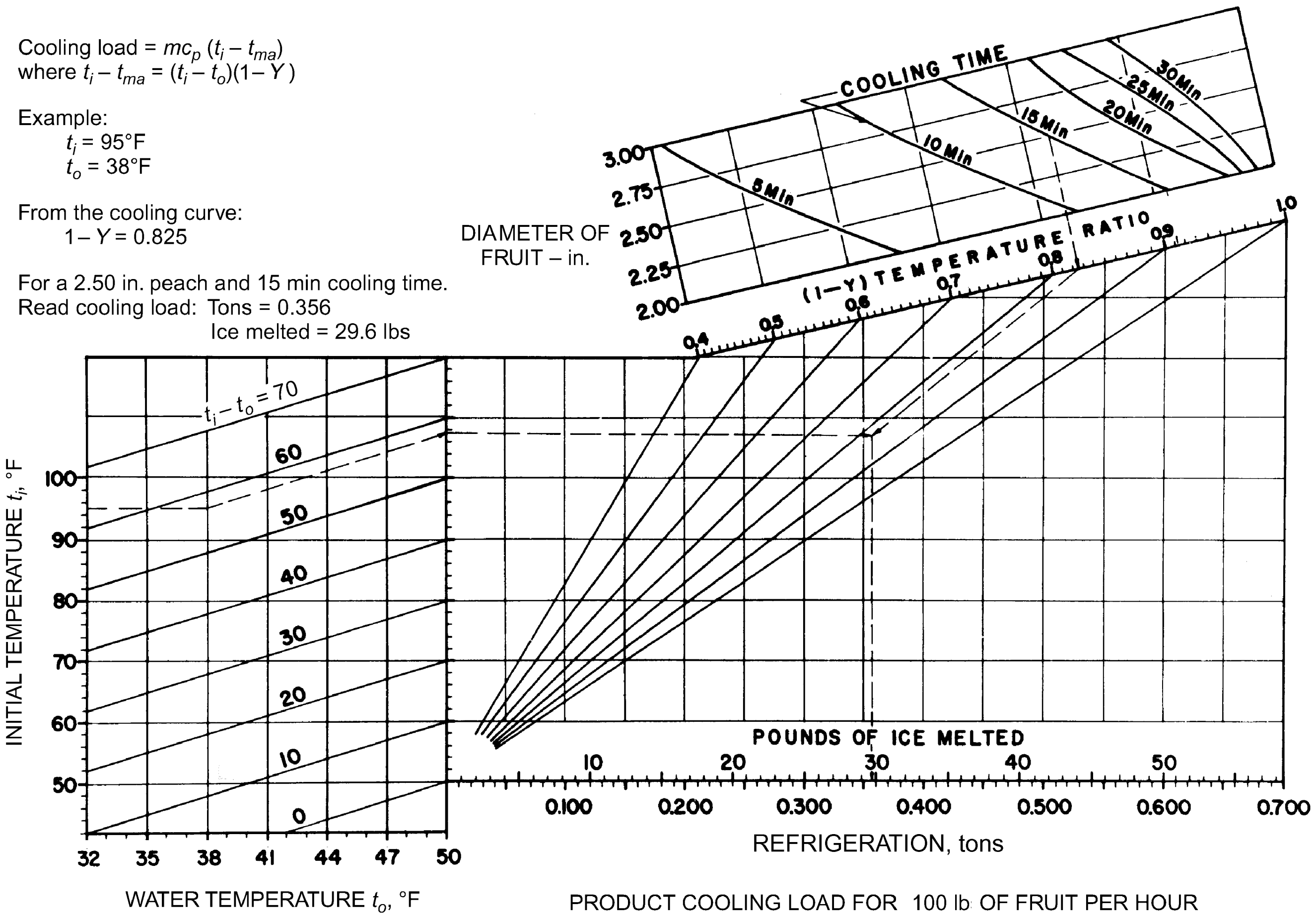


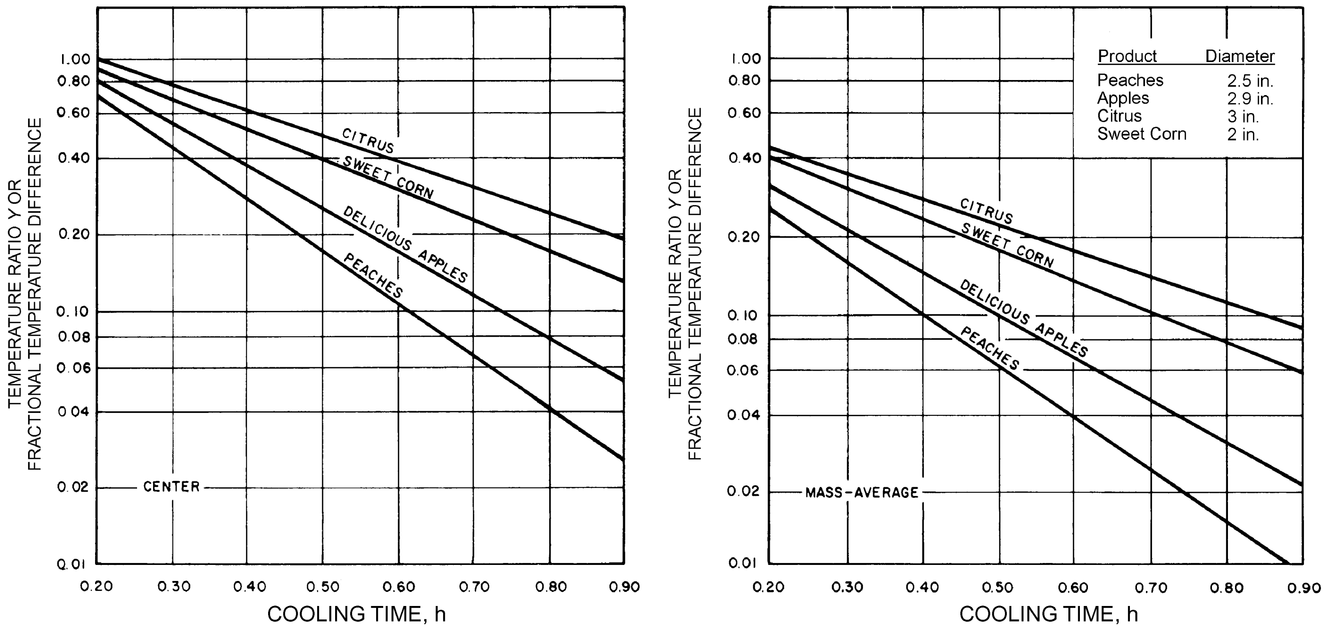
Cooling load = $mc_p\,(t_i - t_{ma})$
where $t_i - t_{ma} = (t_i - t_o)(1 - Y)$

Example:
t_i = 95°F
t_o = 38°F

From the cooling curve:
$1 - Y = 0.825$

For a 2.50 in. peach and 15 min cooling time.
Read cooling load: Tons = 0.356
Ice melted = 29.6 lbs

Fig. 1 Nomograph to Determine Product Heat Load of Hydrocooled Peaches



Product	Diameter
Peaches	2.5 in.
Apples	2.9 in.
Citrus	3 in.
Sweet Corn	2 in.

Fig. 2 Time-Temperature Response for Hydrocooled Produce

Figure 1 can be applied to products other than peaches, when temperature ratio with respect to cooling time and product size is known. Figure 2 illustrates the comparative relationship of fractional temperature difference, or temperature ratio Y, to cooling time for 2.5 in. diameter peaches, 2.88 in. diameter apples and citrus fruit, and 2 in. diameter sweet corn when hydrocooled under ideal conditions of negligible surface resistance to heat transfer.

Cooling Rate

Cooling rate data are commonly presented in terms of **cooling coefficient** C and **half-cooling time** Z. The **temperature ratio** Y is the unaccomplished temperature change at any time in relation to the total temperature change possible for the cooling condition. It is calculated by the equation

$$Y = \frac{t - t_o}{t_i - t_o} \tag{2}$$

The inverted temperature ratio times 100 denotes the percent accomplished temperature change. The value of the cooling coefficient is the same in either case.

The cooling coefficient denotes the change in product temperature per unit change of cooling time for each degree temperature difference between the product and its surroundings. In most cases, a logarithmic transformation of the temperature ratio provides a fairly accurate straight-line fit to the data points. If Newtonian heat transfer occurs (a negligible temperature gradient within the product during cooling) and the straight line asymptote intercepts the temperature ratio at unity for zero time, the cooling coefficient may be calculated by the simplified formula

$$C = \ln Y/\theta \tag{3}$$

When produce is rapidly cooled, the conditions for Newton's law are seldom satisfied because a considerable temperature gradient often develops within the product, depending on its properties and rate of surface heat transfer. Also, the zero asymptote intercepts the temperature ratio at some value either greater or less than unity. In this case, the constant cooling coefficient is calculated by the equation

$$C = \frac{\ln Y_1 - \ln Y_2}{\theta_1 - \theta_2} \tag{4}$$

where the subscripts 1 and 2 denote points along the straight line asymptote to the cooling curve.

The half-cooling time is the time required to reduce the temperature difference between the product and its surroundings by one-half. Mathematically, it is expressed as

$$Z = \ln(0.5)/C \tag{5}$$

where C is a negative value.

The previous solutions treat the product as an individual unit in a specified environment and isolated from the influence of surrounding material, which is rarely the case. Often, products are cooled in bulk or in packages of several layers, where the surrounding material influences the cooling response, particularly in air-cooling systems. Thus the individual approach usually gives poor estimates for cooling of bulk loads.

Baird and Gaffney (1976) developed a numerical technique for calculating cooling rates in bulk loads of fruits or vegetables. This procedure, applicable to spherical products, uses finite difference solutions of the differential equations that describe heat transfer both within individual fruits and at different levels in bulk loads. The models can be used to calculate temperatures at various points within individual products and at different depths in bulk loads at regular time intervals during cooling. Required inputs to the models include product size and shape, thermal properties of the product, the convective coefficient, and flow rate of the cooling medium.

COOLING METHODS

The principal methods of precooling are hydrocooling, forced-air cooling, forced-air evaporative cooling, package icing, and vacuum cooling. Most cooling is done at the packinghouse or in central cooling facilities. Some products can be cooled by any of these methods without suffering any adverse effects. For these products, the cooling method chosen is often determined more by such factors as economy, convenience, relation of the cooling equipment to the total packing operation, and personal preference.

HYDROCOOLING

Because of its simplicity, economy, and effectiveness, hydrocooling is a popular precooling method. When a film of cold water flows briskly and uniformly over the surface of a warm substance, the surface temperature of the substance becomes essentially equal to that of the water. Rate of internal cooling is limited by the size and shape (volume in relation to surface area) and thermal properties of the substance being cooled. For example, Stewart and Lipton (1960) showed a substantial difference in half-cooling time for sizes 36 and 45 cantaloupes. A weighted average of temperatures taken at different depths showed that 20 min was required to half-cool size 36 melons and only 10 min for size 45.

Freestone peaches, clingstone peaches for canning, tart cherries, and cantaloupes are hydrocooled. Few apples and citrus fruits are hydrocooled. Hydrocooling is not popular for citrus fruit because it has a long marketing season and good postharvest holding ability. Citrus fruits are also susceptible to increased peel injury and to decay and loss of quality and vitality after hydrocooling.

Many vegetables are successfully hydrocooled. The more important of these are sweet corn, celery, radishes, and carrots.

Types of Hydrocoolers

Hydrocooling is accomplished by flooding, drenching, or immersing the product in an agitated bath of chilled water.

Product-immersion hydrocoolers are used to cool freestone peaches. A **flood hydrocooler** cools the packaged product by flooding as it is conveyed through a cooling tunnel. Adaptations consist of conveying the product through the cooling tunnel in loose bulk or in bulk bins. A **bulk cooler** uses combined immersion and flood cooling. Loose fruit, dumped into cold water, remains immersed for half of its travel through the cooling tunnel. An inclined conveyor gradually lifts the fruit out of the water and moves it through an overhead shower. The bulk cooler permits greater packaging flexibility than the flood cooler.

Water shower hydrocoolers with conveyors are used to cool vegetables before packaging. The water is cooled by flooded refrigerated plates or pipe coils located over or adjacent to flood pans above the mesh belt conveyor. The flood pans deliver 33 to 34°F water evenly over the produce as it is conveyed below. The water passes through the mesh conveyor, is filtered, and returned by pump and piping to the chiller. In some cases, particularly where produce has a high initial temperature, it may be worthwhile to augment the basic hydrocooler with ambient water or air cooling sections prior to the refrigerated hydrocooler to reduce refrigeration and energy costs.

Most vegetables are moved by fork truck in unit loads of as many as 40 packages. In one system, chilled water sprays on stacks of packed vegetables placed in a refrigerated room. Water is collected in floor drains leading to a sump and recirculated over the product. One nozzle spraying approximately 90 gpm of water is located over each stack, which may contain from 30 to 40 crates (Grizzell and Bennett 1966).

Other unit load systems convey the stacks through cooling tunnels. Either spray nozzles or a flood pan may be used to deliver up to 400 gpm of chilled water to each stack. Most commercial hydrocoolers provide overhead showering at a rate of 20 to 25 gpm per square foot of top face area. This type of hydrocooler requires less space than the batch type, but is not as flexible. With the batch system, chilled water can be sprayed on the product indefinitely, depending on the season and the incoming product temperature. Also, the crates can be left in place after cooling until they are shipped.

Hydrocooler Design and Operation

The rate of heat transfer q is directly proportional to the surface heat transfer coefficient h, the total surface area A, and the difference in temperature between the surface and its surroundings Δt. To determine refrigeration requirements, the product mass-average temperature, which was described previously, should be used.

If the fluid velocity is sufficient, as in gravity flow or forced convection over fruit and vegetable products, the resistance to heat transfer at the surface is negligible. In this case, the heat is removed as fast as it comes to the surface, and the temperature difference across the surface boundary layer is small (1°F or less). In ideal hydrocooling, the optimum average film coefficient of heat transfer is roughly 120 Btu/h·ft^2·°F; the average temperature difference across the boundary layer is about 0.8°F. On this basis, the rate of heat transfer per unit surface area is $h = 120 \times 0.8 = 960$ Btu/h per square foot of product area. The value of h varies substantially, depending on many conditions. However, because of limitations in water temperature and product thermal properties and similarity among products, this is about as fast as any fruit or vegetable can be cooled in water. The ideal (maximum h) time-temperature response curves for hydrocooling select fruit and vegetable products are shown in Figure 2, based on both center and mass-average temperatures.

Flooded ammonia systems are often used to cool the water for hydrocoolers in large packing houses. Some use a secondary coolant. In packing houses with central plants, cooling coils are contained in a tank through which water is rapidly circulated. Refrigerant temperature inside the cooling coils is approximately 28°F, except in systems with ice-building coils, which may operate at a lower temperature.

Solar load, radiation from hot surfaces, convection from ambient air, or conduction from surroundings can affect the load. Protecting the hydrocooler from these sources of heat gain will enhance efficiency. Refrigeration capacity in excess of needs and cooling to a temperature below that required also reduces efficiency.

When hydrocooler water is recirculated, as is usually the case in mechanically refrigerated units, decay-producing organisms accumulate. Mild disinfectants such as chlorine will reduce buildup of bacteria and fungus spores, but they will not kill infections already in the products or sterilize either the water or the product surfaces. Brown rot and rhizopus decay spores on the surface and under the skin of peaches can be destroyed by soaking the fruit in water at 125°F for 2 to 3 min. (Smith and Redit 1968), or by treating the fruit with a chemical fungicide, which is usually put into the hydrocooling water. The principal problem with chemicals is maintenance of uniform concentrations, particularly in ice-refrigerated equipment because of the constant dilution from melting ice. In addition, hydrocooler shower pans and/or trash screens need regular (daily) cleaning to provide maximum efficiency.

FORCED-AIR COOLING

Theoretically, air cooling at a rate comparable to hydrocooling can be obtained by providing certain conditions of product exposure and air temperature. In air cooling, the optimum value of the surface heat transfer coefficient is considerably smaller than in cooling with water. However, Pflug et al. (1965) showed that apples moving through a cooling tunnel on a conveyer belt cool faster with air at 20°F approaching the fruit at a velocity of 600 fpm than they would in a water spray at 35°F. For this condition of air cooling, they calculated an average film coefficient of heat transfer of 7.3 Btu/h·ft^2·°F. They note that the advantage of air is its lower temperature and that if the water were reduced to 34°F, the time for water cooling would be less. It must be noted, however, that air temperatures could be more difficult to manage without specifically fine control below 34°F.

In tests to evaluate film coefficients of heat transfer for anomalous shapes, Smith et al. (1970) obtained an experimental value of 6.66 Btu/h·ft^2·°F for a single Red Delicious apple in a cooling tunnel with air approaching at 1570 fpm. At this rate of airflow, the logarithmic mean surface temperature of a single apple cooled for 0.5 h in air at 20°F is approximately 35°F. The average temperature difference across the surface boundary layer is, therefore, 15°F and the rate of heat transfer per square foot of surface area is

$$q/A = 6.66 \times 15 = 100 \text{ Btu/h} \cdot \text{ft}^2$$

For these conditions, the cooling rate compares favorably with that obtained in ideal hydrocooling. However, these coefficients are based on single specimens isolated from surrounding fruit. Had the fruit been in a packed bed at equivalent flow rates, the values would have been less because less surface area would have been exposed to the cooling fluid. Also, the rate of evaporation from the product surface significantly affects the cooling rate.

Because of physical characteristics, mostly geometry, various fruit and vegetable products respond differently to similar treatments of airflow and air temperature. For example, peaches cool faster than potatoes when they are cooled in a packed bed under similar conditions of airflow and air temperature.

Surface coefficients of heat transfer are sensitive to the physical conditions involved among objects and their surroundings. Experimental surface coefficients ranging from 9 to 12 Btu/h·ft^2·°F were obtained by Soule et al. (1966) for bulk lots of Hamlin oranges and Orlando tangelos with air approaching the fruit at velocities ranging from 225 to 350 fpm. Bulk bins containing 1000 lb of 2.85 in. diameter Hamlin oranges were cooled from 80°F to a final mass-average temperature of 46.5°F in 1 h with air approaching the fruit at 330 fpm (Bennett et al. 1966). Surface heat transfer coefficients for these tests averaged slightly above 11 Btu/h·ft^2·°F. On the basis of a log mean air temperature of 44°F, the calculated half-cooling time was 0.27 h.

By correlating data from experiments on cooling 2.8 in. diameter oranges in bulk lots with results of a mathematical model, Baird and Gaffney (1976) found surface heat transfer coefficients of 1.5 and 9 Btu/h·ft^2·°F for approach velocities of 11 and 412 fpm, respectively. A Nusselt-Reynolds heat transfer correlation representing data from six experiments on air cooling of 2.8 in. diameter oranges and seven experiments on 4.2 in. diameter grapefruit, with approach air velocities ranging from 5 to 412 fpm, gave the relationship $\text{Nu} = 1.17\text{Re}^{0.529}$, with a correlation coefficient of 0.996.

Ishibashi et al. (1969) constructed a stage forced-air cooler that exposed bulk fruit to air at a progressively declining temperature (50, 32, and 14°F) as the fruit was conveyed through the cooling tunnel. Air approached the fruit at 700 fpm. With this system, 2.5 in. diameter citrus fruit cooled from 77 to 41°F in 1 h. Their half-cooling time of 0.32 h compares favorably with a half-cooling time of 0.30 h for similarly cooled Delicious apples at an approach air velocity of 400 fpm (Bennett et al. 1969). Perry et al. (1968) obtained a half-cooling time of 0.5 h for potatoes in a bulk bin with air approaching at 250 fpm, as compared to 0.4 h for similarly treated peaches and 0.38 h for apples. Optimum approach velocity for this type of cooling is in the range of 300 to 400 fpm, depending on conditions and circumstances.

Hydraircooling uses a mixture of refrigerated air and water in a fine mist spray that is circulated around and through the stack by forced convection (Henry et al. 1976). It has the advantage of reduced water requirements, the potential for improved sanitation, and the capability of adapting to fiberboard containers of the type that cannot be used in conventional hydrocooling systems. Cooling rates equal to, and in some cases better than, those obtained in conventional unit load hydrocoolers are possible.

Commercial Methods

Produce can be satisfactorily cooled (1) with air circulated in refrigerated rooms adapted for that purpose, (2) in rail cars using special portable cooling equipment that cools the load before it is transported, (3) with air forced through the voids of bulk products moving through a cooling tunnel on continuous conveyors, (4) on continuous conveyors in wind tunnels, or (5) by the forced-air method of passing air through the containers by pressure differential. Each of these methods is used commercially, and each is suitable for certain commodities when properly applied. Figure 3 shows a schematic of a serpentine forced-air cooler.

In circumstances where air cannot be forced directly through the voids of products in bulk, a container type and a load pattern that permits air to circulate through the container and reach a substantial part of the product surface is beneficial. Examples of this are (1) small products such as grapes and strawberries that offer appreciable resistance to airflow through the voids in bulk lots, (2) delicate products that cannot be handled in bulk, and (3) products that are packed in the shipping containers before they are precooled.

Forced-air or pressure cooling involves definite stacking patterns and the baffling of stacks so that cooling air is forced through, rather than around, individual containers. Successful use of the method requires a container with vent holes placed in the direction in which the air will move and a minimum of packaging materials that would interfere with free movement of air through the containers. Under these conditions, a relatively small pressure differential between the two sides of the containers results in good air movement and excellent heat transfer. Differential pressures in use are about 0.25 to 3 in. of water, with airflows ranging from 1 to 3 cfm/lb of product.

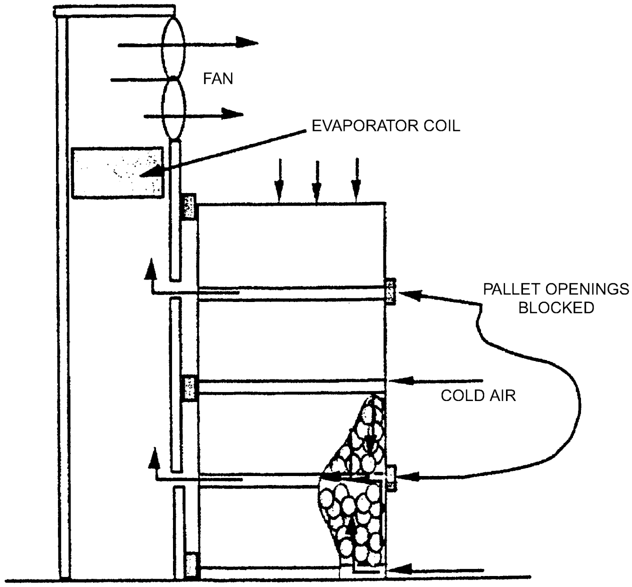


Fig. 3 Serpentine Forced-Air Cooler

Because the cooling air comes in direct contact with the product being cooled, cooling is much faster than with conventional room cooling. This gives the advantage of rapid product movement through the cooling plant, and the size of the plant is one-third to one-fourth that of an equivalent cold room type of plant.

Mitchell et al. (1972) observed that forced-air cooling usually cools in one-fourth to one-tenth the time needed for conventional room cooling, but it still takes two to three times longer than hydrocooling or vacuum cooling.

A proprietary direct-contact heat exchanger cools air and maintains high humidities using chilled water as a secondary coolant and a continuously wound polypropylene monofilament packing. It contains about 2000 linear feet of filament per cubic foot of packing section. Air is forced up through the unit while chilled water flows downward. The dew-point temperature of the air leaving the unit equals the entering water temperature. Chilled water can be supplied from coils submerged in a tank. Buildup of ice on the coils provides an extra cooling effect during peak loads. This design also allows an operator to add commercial ice during long periods of mechanical equipment outage.

In one portable, forced-air method, refrigeration components are mounted on flat bed trailers and the warm, packaged produce is cooled in refrigerated transport trailers. Usually the refrigeration equipment is mounted on two trailers—one holds the forced-air evaporators and the other holds compressors, air-cooling condensers, a high-pressure receiver, and electrical gear. The loaded produce trailers are moved to the evaporator trailer and the product is cooled. After cooling, the trailer is transported to its destination.

Effects of Containers and Stacking Patterns

The accessibility of the product to the cooling medium, essential to rapid cooling, may involve both access to the product in the container and to the individual container in a stack. This effect is evident in the cooling rate data of various commodities in various types of containers reported by Mitchell et al. (1972). Parsons et al. (1972) developed a corrugated paperboard container venting pattern for palletized unit loads that produced cooling rates equal to those from conventional register stacked patterns. Fisher (1960) demonstrated that spacing apple containers on pallets reduced cooling time by 50% as compared with pallet loads stacked solidly. A minimum of 5% sidewall venting is recommended.

Palletization is essential for shipment of many products, and pallet stability is improved if cartons are packed closely together. Thus, cartons and packages should be designed to allow ample airflow though the stacked products. Amos (1993) and Parsons et al. (1972) showed the importance of vent sizes and location to obtain good cooling in palletized loads without reducing the strength of the container. Some operations wrap the palletized products in polyethylene to increase stability. In this case, the product may need to be cooled before it is palletized.

Moisture Loss in Forced-Air Cooling

The information in this section is drawn from Thompson et al. (1998).

Moisture loss in forced-air cooling ranges from very little to amounts significant enough to damage produce. Factors that affect moisture loss include product initial temperature and respiration coefficient, rate of cooling, humidity, exposure to airflow after cooling, and whether waxes or moisture-resistant packaging is used.

High initial temperature results in a greater moisture loss; this factor can be minimized by harvesting at cooler times of day (i.e., early morning or night), and cooling (or at least shading) products immediately after harvest. Keep reheat during packing to a minimum.

The primary advantage of high humidity during cooling is that product packaging can absorb moisture, which reduces the packaging's absorption of moisture from the product itself.

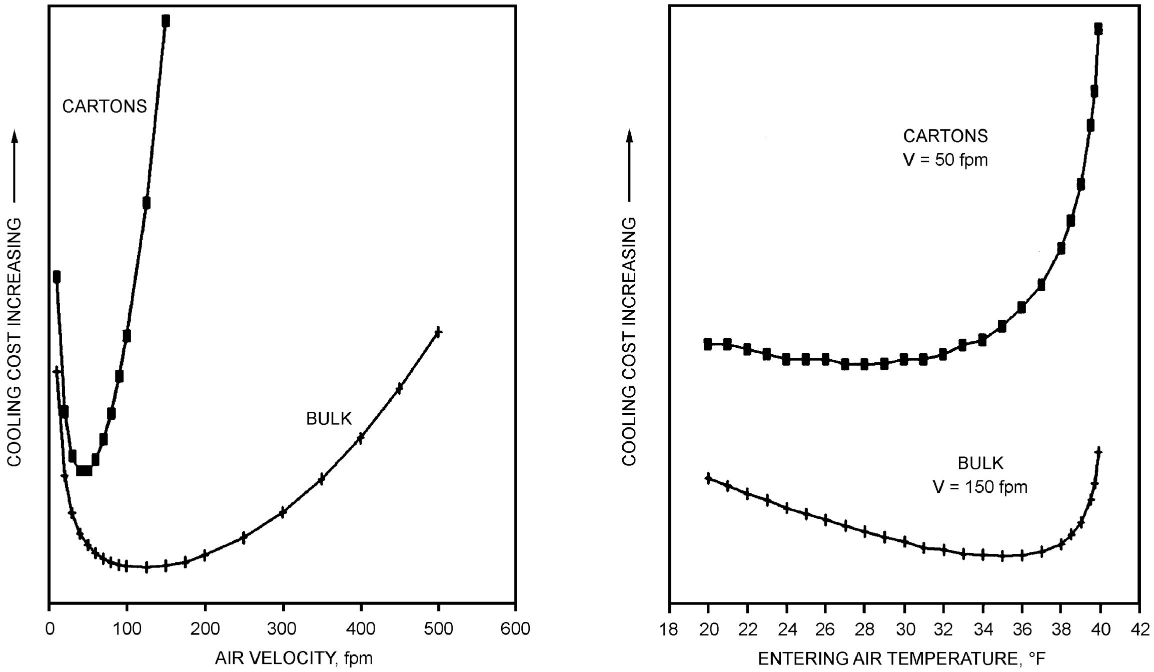


Fig. 4 Engineering-Economic Model Output for a Forced-Air Cooler

High respiration coefficients also increase moisture loss. For example, carrots, with a high respiration rate, can lose 0.6 to 1.8% of their original, uncooled weight during cooling. Packing carrots in polyethylene packaging has reduced moisture loss to 0.08%, although cooling times are about five times longer. Film box liners, sometimes used for packing products with low respiration coefficients (e.g., apples, pears, kiwifruit, and grapes), are also useful in reducing moisture loss, but they also increase the time required to cool products. Some film box liners are perforated to reduce condensation; liners used to package grapes must also include an SO_2-generating pad to reduce decay.

To prevent exposing product to unnecessary airflow, forced-air coolers should reduce or stop airflow as soon as the target product temperature is reached. Otherwise, moisture loss will continue unless the surrounding air is close to saturation. One method is to link cooler fan control to return air plenum temperature, slowing fan speeds as the temperature of the return air approaches that of the supply air.

Computer Solution

Baird et al. (1988) developed an engineering economic model for designing forced-air cooling systems. Figure 4 shows the type of information that can be obtained from the model. By selecting a set of input conditions (which varies with each application) and varying the approach air velocity, the entering air temperature, or some other variable, the optimum (minimum cost) value can be determined. The curves in Figure 4 show that the selection of air velocity for containers is critical, whereas the selection of entering air temperature is not as critical until the desired final product temperature of 40°F is approached. The results shown are for four cartons deep with a 4% vent area in the direction of airflow, and they would be quite different if the carton vent area was changed. Other design parameters that can be optimized using this program are the depth of product in direction of airflow and the size of evaporators and condensers.

PACKAGE ICING

Finely crushed ice placed in shipping containers can effectively cool products that are not harmed by contact with ice. Spinach, collards, kale, brussels sprouts, broccoli, radishes, carrots, and green onions are commonly packaged with ice (Hardenburg et al. 1986). Cooling a product from 95 to 35°F requires melting ice equal to 38% of the product's mass. Additional ice must melt to remove heat leaking into the packages and to remove heat from the container. In addition to removing field heat, package ice can keep the product cool during transit.

Pumping **slush ice** or liquid ice into the shipping container through a hose and special nozzle that connect to the package is another method used for cooling some products. Some systems can ice an entire pallet at one time.

Top icing, or placing ice on top of packed containers, is used occasionally to supplement another cooling method. Because corrugated containers have largely replaced wooden crates, the use of top ice has decreased in favor of forced-air and hydrocooling. Wax-impregnated corrugated containers, however, have allowed the use of icing and hydrocooling of products after packaging.

Flaked or crushed ice can be manufactured on site and stored in an ice bunker for later use; for short-season cooling requirements with low ice demands (e.g., a few tons a day), it may be more economical to buy block ice and crush it on site. Another option is to rent liquid ice equipment for on-site production.

The cooling capacity of ice is 144 Btu/lb; 1 lb of ice will reduce the temperature of 3 lb of produce by approximately 50°F. However, commercial ice-injection systems require significantly more ice beyond that needed for produce cooling. For example, 20 lb of broccoli requires about 32 lb of manufactured ice (losses occur in product cooling, transport, and equipment heat gain; also, a remainder of ice is required in the box on delivery to the customer). The high ice requirement makes liquid icing an energy-inefficient and expensive cooling method (Thompson et al. 1998). Other disadvantages of ice cooling include (1) the space taken up bythe ice, which decreases the amount of space available for transporting the product; and (2) the need for water-resistant packaging to prevent both water damage to other products and safety hazards during storage. These disadvantages can be minimized if ice is used for temperature maintenance in transit rather than for cooling, or by using gel-pack ice (often used for flowers), which is sealed in a leakproof bag.

VACUUM COOLING

Principle

Vacuum cooling of fresh produce by the rapid evaporation of water from the product works best with vegetables having a high ratio of surface area to volume. In vacuum refrigeration, water, as the primary refrigerant, vaporizes in a flash chamber under low pressure. The pressure in the chamber is lowered to the saturation point corresponding to the lowest required temperature of the water.

Vacuum cooling is a batch process. The product to be cooled is loaded into the flash chamber, the system is put into operation, and the product is cooled by reducing the pressure to the corresponding saturation temperature desired. The system is then shut down, the product removed, and the process repeated. Since the product is normally at ambient temperature before it is cooled, vacuum cooling can be thought of as a series of intermittent operations of a vacuum refrigeration system in which the water in the flash chamber is allowed to come to ambient temperature before each start. The functional relationships for determining refrigerating capacity are the same in each case.

Cooling is achieved by boiling water, mostly off the surface of the product to be cooled. The heat of vaporization required to boil the water is furnished by the product, which is cooled accordingly. As the pressure is further reduced, cooling continues to the desired temperature level. The saturation pressure for water at 212°F is 760 mm Hg. At 32°F, the saturation pressure is 4.58 mm Hg. Commercial vacuum coolers normally operate in this range.

Although the cooling rate of lettuce could be increased without danger of freezing by reducing the pressure to 3.8 mm Hg, corresponding to a saturation temperature of 27°F, most operators do not reduce the pressure below that which freezes water because of the extra work involved and the freezing potential.

Pressure, Volume, and Temperature

In a vacuum cooling operation, the thermodynamic process is assumed to take place in two phases. In the first phase, the product is assumed to be loaded into the flash chamber at ambient temperature, and the temperature in the flash chamber remains constant until saturation pressure is reached. At the onset of boiling, the small remaining amount of air in the chamber is replaced by the water vapor, the first phase ends, and the second phase begins simultaneously. The second phase continues at saturation until the product has cooled to the desired temperature.

If the ideal gas law is applied for an approximate solution in a commercial vacuum cooler, the pressure-volume relationships are

$$\text{Phase 1} \quad pv = 29{,}318 \text{ ft}\cdot\text{lb/lb}$$

$$\text{Phase 2} \quad pv^{1.056} = 66{,}370 \text{ ft}\cdot\text{lb/lb}$$

where p is the absolute pressure and v is the specific volume.

The pressure-temperature relationship is determined by the value of ambient and product temperature. Based on 90°F for this value, the temperature in the flash chamber theoretically remains constant at 90°F as the pressure is reduced from atmospheric to saturation, after which it declines progressively along the saturation line. These relationships are illustrated in Figure 5. The product temperature would respond similarly but would vary depending on where temperature is measured in the product, the physical characteristics of the product, and the amount of product surface water available.

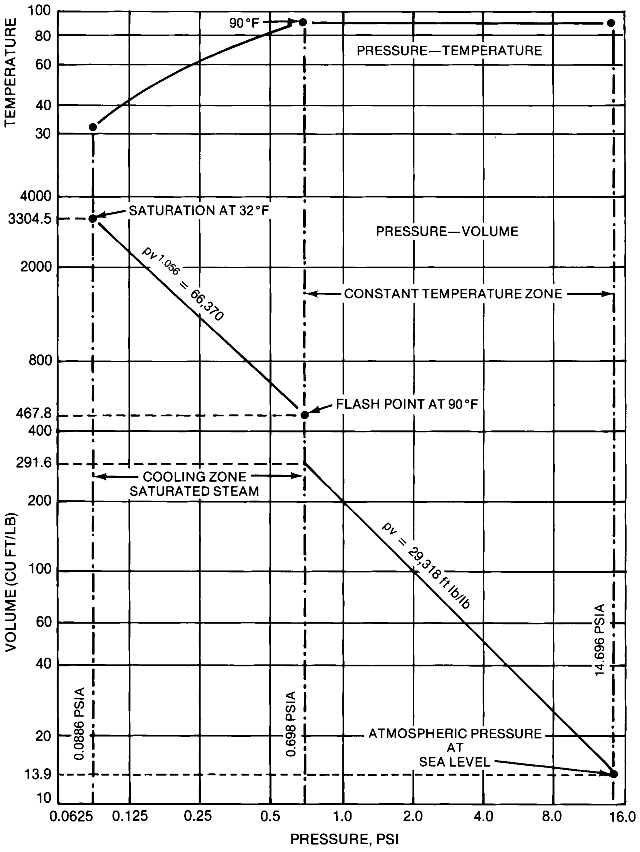


Fig. 5 Pressure, Volume, and Temperature in a Vacuum Cooler Cooling Product from 90 to 32°F

Although it is possible for some vaporization to occur within the intercellular spaces beneath the product surface, most of the water is vaporized off the surface. The heat required to vaporize this water is also taken off the product surface, where it flows by conduction under the thermal gradient produced. Thus, the rate of cooling depends on the relation of surface area to volume of the product and the rate at which the vacuum is drawn in the flash chamber.

Because water is the sole refrigerant, the amount of heat removed from the product depends on the mass of water vaporized m_v and its latent heat of vaporization L. Assuming an ideal condition, with no heat gain from surroundings, total heat Q removed from the product is

$$Q = m_v L \tag{6}$$

The amount of moisture removed from the product during vacuum cooling, then, is directly related to the specific heat of the product and the amount of temperature reduction accomplished. A product with a specific heat capacity of 0.95 Btu/lb·°F would theoretically lose 1% moisture for each 11°F reduction in temperature. In a study of vacuum cooling of 16 different vegetables, Barger (1963) showed that cooling of all products was proportional to the amount of moisture evaporated from the product. Temperature reductions averaged 9 to 10°F for each 1% of weight loss, regardless of the product cooled. This weight loss may reduce the amount of money the grower receives as well as the turgor and crispness of the product. Some vegetables are sprayed with water during cooling to reduce this loss.

Commercial Systems

The four types of vacuum refrigeration systems that use water as the refrigerant are (1) steam ejector, (2) centrifugal, (3) rotary, and

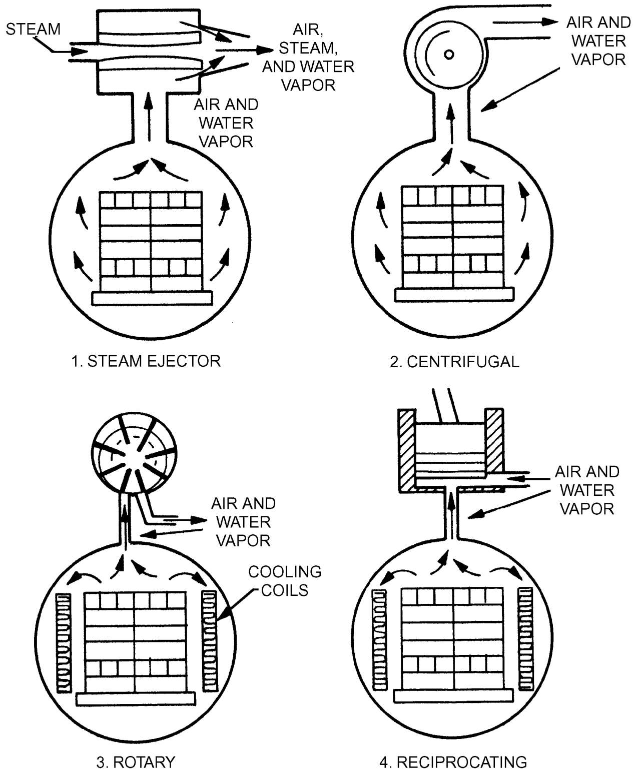


Fig. 6 Schematic Cross Sections of Vacuum-Producing Mechanisms

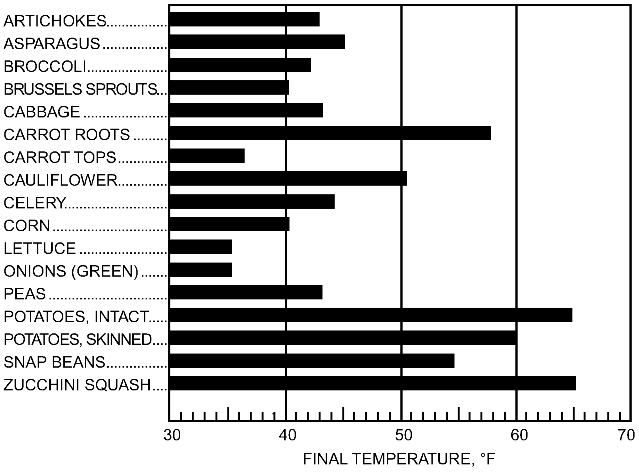
(4) reciprocating. A schematic of the vacuum-producing mechanism of each is illustrated in Figure 6.

Of these, the steam ejector type is best suited for displacing the extremely high volumes of water vapor encountered at the low pressures needed in vacuum cooling. It also has the advantage of having few moving parts, thus requiring no compressor to condense the water vapor. High-pressure steam is expanded through a series of jets or ejectors arranged in series and condensed in barometric condensers mounted below the ejectors. Cooling water for condensing is accomplished by means of an induced-draft cooling tower. In spite of these advantages, few steam ejector vacuum coolers are used today, due to the inconvenience of using steam and the lack of portability. Instead, vacuum coolers mounted on semitrailers are used to follow the seasonal crops.

The centrifugal compressor is also a high-volume pump and can be adapted to water vapor refrigeration. However, its use in vacuum cooling is limited because of inherent mechanical difficulties at the high rotative speeds required to produce the low pressures needed.

Both rotary and reciprocal vacuum pumps are capable of producing the low pressures needed for vacuum cooling, and they also have the advantage of portability. Being positive-displacement pumps, however, they have low volumetric capacity; therefore, vacuum coolers using rotary or reciprocating pumps have separate refrigeration systems to condense much of the water vapor that evaporates off the product, thus substantially reducing the volume of water vapor passing through the pump. Ideally, when it can be assumed that all of the water vapor is condensed, the required refrigeration capacity is equal to the amount of heat removed from the product during cooling.

The condenser must contain adequate surface to condense the large amount of vapor removed from the produce in a few minutes. Refrigeration is furnished from cold brine or a direct-expansion system. A very large peak load occurs from rapid condensing of so much vapor. Best results are obtained if the refrigeration plant is equipped with a large brine or icemaking tank having enough stored refrigeration to smooth out the load. A standard three-tube plant, with capacity to handle three cars per hour, has a peak refrigeration load of at least 250 tons.



Vacuum-Cooling Conditions

Initial Product Temperature	= 68 to 72°F
Minimum Pressure	= 4 to 4.6 mm Hg
Condenser Temperature	= 29 to 32°F
Time in Vacuum Tank	= 0.42 to 0.5 h

Fig. 7 Comparative Cooling of Vegetables Under Similar Vacuum Conditions

To increase cooling effectiveness and reduce product moisture loss, the product is sometimes wetted before cooling begins. However, iceberg lettuce is rarely prewetted. A modification of vacuum cooling circulates chilled water over the product throughout the vacuum cooling process. Among the chief advantages are increased cooling rates and residual refrigeration that is stored in the chilled water following each vacuum process. It also prevents water loss from products that show objectionable wilting after conventional vacuum cooling.

Applications

Because vacuum cooling is generally more expensive, particularly in capital cost, than other cooling methods, its use is primarily restricted to products for which vacuum cooling is much faster or more convenient. Lettuce is ideally adapted to vacuum cooling. The numerous individual leaves provide a large surface area and the tissues release moisture readily. It is possible to freeze lettuce in a vacuum chamber if pressure and condenser temperatures are not carefully controlled. However, even lettuce does not cool entirely uniformly. The fleshy core, or butt, releases moisture more slowly than the leaves. Temperatures as high as 43°F have been recorded in core tissue when leaf temperatures were down to 33°F (Barger 1961).

Other leafy vegetables such as spinach, endive, escarole, and parsley are also suitable for vacuum cooling. Vegetables that are less suitable but adaptable by wetting are asparagus, snap beans, broccoli, brussels sprouts, cabbage, cauliflower, celery, green peas, sweet corn, leeks, and mushrooms. Of these vegetables, only cauliflower, celery, cabbage, and mushrooms are commercially vacuum cooled in California. Fruits are generally not suitable, except some berries. Cucumbers, cantaloupes, tomatoes, dry onions, and potatoes cool very little because of their low surface-to-mass ratio and relatively impervious surface. The final temperatures of various vegetables when vacuum cooled under similar conditions are illustrated in Figure 7.

Table 1 Cooling Methods Suggested for Horticultural Commodities

	Size of Operation	
Commodity	**Large**	**Small**
Tree fruits		
Citrus	R	R
Deciduous [a]	FA, R, HC	FA
Subtropical	FA, R	FA
Tropical	FA, R	FA
Berries	FA	FA
Grapes [b]	FA	FA
Leafy vegetables		
Cabbage	VC, FA	FA
Iceberg lettuce	VC	FA
Kale, collards	VC, R, WV	FA
Leaf lettuces, spinach, endive, escarole, Chinese cabbage, bok choy, romaine	VC, FA, WV, HC	FA
Root vegetables		
With tops [c]	HC, PI, FA	HC, FA
Topped	HC, PI	HC, PI, FA
Irish potatoes, sweet potatoes [d]	R w/evap coolers, HC	R
Stem and flower vegetables		
Artichokes	HC, PI	FA, PI
Asparagus	HC	HC
Broccoli, Brussels sprouts	HC, FA, PI	FA, PI
Cauliflower	FA, VC	FA
Celery, rhubarb	HC, WV, VC	HC, FA
Green onions, leeks	PI, HC	PI
Mushrooms	FA, VC	FA
Pod vegetables		
Beans	HC, FA	FA
Peas	FA, PI, VC	FA, PI
Bulb vegetables		
Dry onions [e]	R	R, FA
Garlic	R	
Fruit-type vegetables [f]		
Cucumbers, eggplant	R, FA, FA-EC	FA, FA-EC
Melons		
Cantaloupes, muskmelons, honeydew, casaba	HC, FA, PI	FA, FA-EC
Crenshaw	FA, R	FA, FA-EC
Watermelons	FA, HC	FA, R
Peppers	R, FA, FA-EC, VC	FA, FA-EC
Summer squashes, okra	R, FA, FA-EC	FA, FA-EC
Sweet corn	HV, VC, PI	HC, FA, PI
Tomatillos	R, FA, FA-EC	FA, FA-EC
Tomatoes	R, FA, FA-EC	
Winter squashes	R	R
Fresh herbs		
Not packaged [g]	HC, FA	FA, R
Packaged	FA	FA, R
Cactus		
Leaves (nopalitos)	R	FA
Fruit (tunas or prickly pears)	R	FA
Ornamentals		
Cut flowers [h]	FA, R	FA
Potted plants	R	R

R = Room cooling
HC = Hydrocooling
FA = Forced-air cooling
VC = Vacuum cooling
WV = Water spray vacuum cooling
PI = Package icing
FA-EC = Forced-air evaporative cooling

[a] Apricots cannot be hydrocooled.
[b] Grapes require rapid cooling facilities adaptable to sulfur dioxide fumigation.
[c] Carrots can be vacuum cooled.
[d] With evaporative coolers, facilities for potatoes should be adapted to curing.
[e] Facilities should be adapted to curing onions.
[f] Fruit-type vegetables are chilling sensitive but at varying temperature.
[g] Fresh herbs can be easily damaged by water beating in hydrocooler.
[h] When cut flowers are packaged, only use forced-air cooling.

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The rate of cooling and the final temperature attained by vacuum cooling are largely affected by the ratio of the surface area of the commodity to its mass and the ease with which the product gives up water from its tissues. Consequently, the adaptability of fruits and vegetables varies tremendously for this method of precooling. For products that have a low surface-to-mass ratio, high temperature gradients occur. To prevent the surface from freezing before the desired mass-average temperature is reached, a procedure referred to as “bouncing” is practiced. This is accomplished by switching the vacuum pump off and on to keep the saturation temperature above freezing.

Mechanical vacuum coolers have been designed in several sizes. Most installations use cylindrical or rectangular retorts. For portability, some vacuum coolers and associated refrigeration equipment have been placed on flat bed trailers.

SELECTING A COOLING METHOD

Packing house size and operating procedures, response of product to the cooling method, and market demands largely dictate the cooling method used. Other factors considered are whether the product is packaged in the field or in a packinghouse, the product mix being cooled, length of cooling season, and comparative costs of dry versus water-resistant cartons. In some cases, there is little question about the type of cooling to be used. For example, vacuum cooling is most effective on lettuce and other similar vegetables. Peach packers in the southeastern United States and some vegetable and citrus packers are satisfied with hydrocooling. Air (room) cooling is used for apples, pears, and citrus fruit. In other cases, choice of cooling method is not so clearly defined. Celery and sweet corn are usually hydrocooled, but they may be vacuum cooled as effectively. Cantaloupes may be satisfactorily cooled by several methods. *Note*: Sweet cheeries are often hydrocooled in packing houses but are air cooled if orchard packed.

When more than one method can be used, cost becomes a major consideration. Although rapid, forced-air cooling is more costly than hydrocooling, if the product does not require rapid cooling, a forced-air system can operate almost as economically as hydrocooling. In a study to evaluate costs of hypothetical precooling systems for citrus fruit, Gaffney and Bowman (1970) found that the cost for forced-air cooling in bulk lots was 20% more than that for hydrocooling in bulk and that forced-air cooling in cartons costs 45% more than hydrocooling in bulk.

Table 1 summaries precooling and cooling methods suggested for various commodities.

COOLING CUT FLOWERS

Because of their high rates of respiration and low tolerance for heat, deterioration in cut flowers is rapid at field temperatures. Refrigerated highway vans do not have the capacity to remove the field heat in sufficient time to prevent some deterioration from occurring (Farnham et al. 1979). Forced-air cooling is commonly used by the flower industry. As with most fruits and vegetables, the cooling rate of cut flowers varies substantially among the various types. Rij et al. (1979) found that the half-cooling time for packed boxes of gypsophila was about 3 min compared to about 20 min for chrysanthemums at airflows ranging from 80 to 260 cfm per box. Within this range, cooling time was proportional to the reciprocal of airflow but varied less with airflow than with flower type.

SYMBOLS

A = product surface area, ft^2
c_p = specific heat of product, Btu/lb·°F
C = cooling coefficient, reciprocal of hours
L = heat of vaporization, Btu/lb
m = mass of product, lb
m_v = mass of water vaporized, lb
p = pressure, lb/ft^2

q = cooling load or rate of heat transfer, Btu/h
Q = total heat, Btu
t = temperature of any point in product, °F
t_i = initial uniform product temperature, °F
t_o = surrounding temperature, °F
t_{ma} = mass-average temperature, °F
v = specific volume of water vapor, ft^3/lb
Y = temperature ratio $(t - t_o)/(t_i - t_o)$
Z = half-cooling time, h
θ = cooling time, h

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