Division of Agricultural Sciences

UNIVERSITY OF CALIFORNIA

COMMERCIAL COOLING OF FRUITS AND VEGETABLES

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This manual presents information on cooling of fruits and vegetables for persons concerned with designing and operating coolers and for those who will be cooling produce. Part I discusses the postharvest physiology of fresh produce in relation to cooling procedures. Part II describes the leading methods of cooling and the products and conditions to which they are adapted. Part III presents suggestions and data relative to design of coolers, including recently measured effects of venting and stacking patterns on forced-air cooling. Part IV presents cooling data, including product requirements, tables of cooling times, and formulas and conversion factors useful in cooler design.

Emphasis on various topics in this publication is necessarily arbitrary. Included is information on design of forced-air coolers, hydrocoolers, ice bunkers, and air humidification that may be useful to shippers as well as to designers. No attempt is made to cover the design of vacuum coolers or mechanical refrigeration systems—this information, which would require considerably more technical detail to present, is available from other sources listed herein.

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COMMERCIAL COOLING OF FRUITS AND VEGETABLES

Part I—THE COMMODITY

Causes of postharvest deterioration

Fruits and vegetables are living organisms which undergo all physiological and pathological processes associated with life. To sustain essential chemical and physiological activities, they draw energy from the food reserves stored within them prior to harvest. They are in a continual state of deterioration from harvest on, and successful marketing depends upon reducing the rate of deterioration by slowing the processes which cause damage.

Deterioration of fresh produce (the commodity) results from many things, including physiological breakdown, physical injury to the tissue, moisture loss, or invasion by microorganisms. Decay-producing fungi which attack fresh fruits and vegetables are also living organisms, and may be major contributors to deterioration and loss. Some decay organisms can directly penetrate healthy tissue; others enter only after produce has been weakened or injured. Each fruit and vegetable is, therefore, a complex living system of tissue and microorganisms, and satisfactory produce management requires protection of the produce while discouraging growth and spread of microorganisms.

All of the above factors can be interrelated, and all are influenced by temperature. Thus, understanding the relationship of cooling to causes and effects of deterioration is essential if produce is to be properly protected.

Like all other living organisms, fresh fruits and vegetables respire through a complex series

of chemical reactions. Simply stated, the starches and sugars stored in their tissues are converted to carbon dioxide and water. The process (fig. 1) utilizes energy from the stored food reserves, and oxygen from the surrounding air. If oxygen absorption is blocked, normal respiration cannot proceed and fermentation will quickly destroy the produce.

Heat, released as a result of respiratory processes, represents a portion of the energy originally stored in the plant during photosynthesis. The amount of heat produced varies widely with the commodity, and even among varieties (fig. 2). Fruits noted for their long storage life, such as certain types of grapes and apples, typically have low respiratory rates and release relatively little heat. Some vegetables, such as broccoli and asparagus, have high respiratory rates and release large amounts of heat. Highly perishable fruits, such as strawberries, release intermediate amounts of heat.

Effects of temperature on produce

The life processes of a perishable commodity are regulated by the catalytic action of large protein molecules called enzymes. Enzyme activity is temperature sensitive and increases two to four times for each 18°F temperature rise. Temperature is thus the greatest determinant of fresh produce deterioration rate and, consequently, of potential market life (fig. 3).

Produce temperatures are critical from the instant of harvest when postharvest deteriora-

Fig. 1. Simplified schematic diagram of fresh fruit and vegetable respiration showing the role of oxygen in avoiding fermentation and rapid destruction of produce. Energy which is released by the stored food fuels these processes.

Fig. 2. Examples of heat evolution representing low, intermediate and high respiration rates. Levels of heat evolved from respiration may vary from these values as a result of differences in variety, maturity, time after harvest, and other factors.

Fig. 3. General effect of temperature on the market life of fresh fruits and vegetables. Some commodities (for example, those showing chilling sensitivity) exhibit special characteristics which may cause important variations from this curve.

tion begins. With highly perishable commodities, a few hours' delay before starting cooling can cause damage which cannot be overcome by subsequent good handling practices. Cooling of strawberries, for example, should commence within 2 hours of harvest. The longer the delay beyond this time, the greater the deterioration of the fruit (fig. 4).

Temperatures favorable for maximum growth and development of rot organisms often coincide with field temperatures encountered during fruit and vegetable harvest. Without rapid handling and cooling, therefore, rot organisms may quickly consume the produce. The inhibiting effect of low temperatures on these organisms varies with the organism involved. Certain rot organisms will continue to grow, although slowly, below 32°F while others become completely inactive at somewhat higher temperatures. One major cause of loss in many fresh fruits, the *Rhizopus* rot organism, will not grow at temperatures below 40°F. Thus, the presence of *Rhizopus* rot indicates a history of temperatures above 40°F.

Ethylene physiology of fruits and vegetables

Ethylene gas (C_2H_4) is produced by most if not all plant materials, and may have important beneficial or detrimental effects on fruits and vegetables during postharvest handling. The compound induces ripening in fruits and senescence (loss of green color, shedding of leaves, etc.) in other plant tissues. For the gas to exert an effect a certain threshold concentration must accumulate in the internal atmosphere of the tissues, and produce temperature must be above a minimum level. Neither threshold concentration nor minimum temperature requirements for ethylene activity are well defined. The rate of production and action of ethylene is temperature dependent, so rapid cooling and good tem-

Fig. 4. Effect of delays before cooling on the quality of Shasta strawberry during distribution. After initial delay, all fruit was cooled and handled identically. Market value was based on bright firm fruit, free of rot.

perature management are desirable to limit effects of the gas on ripening and senescence. For most commodities, the maximum effect occurs when produce temperatures range from 62 to 70°F.

Ethylene gas is widely used to initiate commercial ripening of bananas and melons, and for the degreening of citrus. In the future it may be adapted for use with other commodities.

Wilting and shriveling caused by water loss

Wilting and shriveling caused by water loss seriously damages the appearance of produce and thus affects consumer appeal. Many fruits and vegetables will appear shriveled or wilted after water loss of only a small percentage of their original weight (nectarines, for example, will show shrivel after 4 to 5 per cent weight loss). Stem browning can occur in grapes and cherries which have had only minor weight loss. Severe desiccation can result in considerable produce loss; wilted leafy produce may require excessive trimming to make it marketable; grapes may shatter loose from clusters if their stems are severely dried; and seriously shriveled fruits must be discarded before sale or consumption.

The loss in produce weight as a result of water loss becomes another direct loss in marketing. A 5 per cent weight loss (which is not uncommon) means 1 pound less in each 20-pound package, or 100 pounds less for each ton of produce handled.

Water is lost from produce in the form of moisture vapor. Most fruits and vegetables are composed of cells loosely bound together, with considerable intercellular space which is interconnected and leads to natural openings called lenticles or stomates (fig. 5). Water from the cells vaporizes into the intercellular spaces, and maintains an essentially saturated atmosphere within

Fig. 5. Schematic of common route of water loss in fresh produce. Cuticle is a natural waxy covering found on some fruits and vegetables.

the product. Water vapor may then move to the outside atmosphere through the lenticles, through stems or stem scars, through any injured area, or directly through the cuticle (fig. 6). Water vapor will leave produce in direct proportion to the difference between its internal concentration and that of the surrounding atmosphere.

Proper relative humidity (RH) is important in preventing water loss from fresh produce, but temperature of the produce and its surrounding atmosphere, as well as air velocity also affect the amount of loss. Water loss from warm produce to warm air is particularly serious under windy conditions or during transport on an open vehicle. The effect of air velocity is to sweep released moisture from air surrounding the produce. Air velocity is not a major factor in total water loss during cooling, as it affects the rates

of both drying and cooling about equally. However, any air movement that continues after cooling is completed will continue to remove moisture.

Air movement can cause serious loss during storage. Unless air is very humid, it is extremely important to limit its movement in the storage area to the least that suffices to carry away heat produced by respiration of produce and heat leaking into the area. Air movement of 12 feet per minute is often sufficient to maintain desired temperature during storage, if the produce has been thoroughly cooled. Water loss at this air velocity is about one-half of that at a velocity of 100 feet per minute (1.1 miles per hour).

Figure 7 depicts the influence of management variables on water loss of grapes. Although more severe handling practices (upper line in figure) resulted in greater weight loss, the treatments shown are less extreme than those often encountered in commercial practice.

The following points about RH, air temperature and air velocity should be noted:

- Each hour of exposure to warm, dry air results in over twice as much water loss as holding in humidified storage for 1 week.
- Use of colder air during cooling reduces water loss only slightly, but leaves produce at a much better temperature for storage or shipment.
- Humidifying air in a cooler reduces water loss by 0.2 per cent of produce weight during cooling (32°F, 95 per cent RH, compared with 32°F, 75 per cent RH).

Fig. 6. Air injected into neck of the pear causes immediate and simultaneous appearance of air bubbles over surface of the fruit, thus demonstrating the open structure of the tissue. (Photo courtesy E. C. Maxie.)

Fig. 7. Water loss resulting from two different cooling and handling regimes for table grapes. Lower line illustrates nearly ideal conditions; upper line illustrates the additive effect of a series of typical commercial practices.

- Humidifying air during storage reduces water loss by 0.2 per cent of produce weight in 3 or 4 days.
- Reducing air velocity during storage reduces water loss by 0.2 per cent of weight of produce in 3 or 4 days—but this should only be done after the produce has been thoroughly cooled.

Loading cold produce into a cooled transport vehicle can further reduce water loss. Many transport vehicles maintain produce temperatures at or near 40°F and consequently it is common practice to cool produce to this temperature before loading. Loading produce at 32°F with the interior of the transport vehicle at 40°F can reduce moisture loss. If RH in the transport vehicle is 75 per cent, loading produce at 32°F should reduce water loss by approximately one-half. For produce that is not subject to chilling injury, a further reduction in water loss can be achieved by setting the thermostat in the transport vehicle as low as possible without danger of freezing.

Relationship of temperature to produce injuries

Bruises and other wounds can cause serious produce deterioration during marketing and will also usually speed deterioration from other causes. Bruising accelerates respiratory activity (and, often, the ethylene production) of tissue; this causes faster heat release and ripening and so shortens potential shelf life. Because bruising damages the natural moisture barrier on fruits and vegetables, the rate of water loss is accelerated. Bruised areas also serve as entry points for decay organisms.

Temperature has a noticeable, but contradictory influence on the susceptibility of produce to injuries—some types of fruit are more susceptible to compression and impact bruising when they are cold than when they are warm. Although packing before cooling reduces such bruising, it is better to eliminate the causes of these injuries in the packing plant.

EFFECT OF TEMPERATURE ON SEVERITY OF BRUISING ON VARIOUS FRUITS*

Fruit	Per cent impact bruising		Vibration bruising†	
	cold	warm	cold	warm
Tilton apricot	75	19	0.7	2.3
Bartlett pear	98	93	2.4	3.1
Kelsey plum	73	15	2.2	2.7
Rio Oso Gem peach	97	70	1.0	3.1

* Fruits were individually dropped (either 24 or 36 inches) onto a hard surface. Vibration was at 510 cycles per minute with a one-fourth-inch stroke for either 20 or 30 minutes, with fruit loose in containers.

† Fruit scored on 0–5 scale; 0 = no damage, 5 = unmarketable.

In contrast to impact and compression bruising, vibration bruising is more serious when fruits are warm. This type of bruising can occur from fruit movement or rubbing during packing or transit, so cooling produce before it is packed will reduce the incidence of such injuries. Since many fruits are subject to vibration bruising during transit, and since none of the presently-used packing methods can completely immobilize fruit within the package, fruit not subject to chilling injury should be kept at low temperatures during transport.

Chilling and freezing of produce

The low temperatures that are important in protecting many commodities may damage others, especially tropical and subtropical fruits and vegetables. Such damage, commonly called chilling injury, occurs at temperatures above 32°F. Symptoms may include tissue darkening and drying, surface pitting, failure to ripen normally, off-flavors, or increased susceptibility to invasion by microorganisms. Some commodities may show chilling injury only after prolonged storage, while others may be injured by brief exposures to low temperatures. Thus, good temperature management must be based upon a complete understanding of commodity requirements. Some major temperature requirements of various California fruits and vegetables are discussed later, starting on page 33. Whatever the temperature management program, it must always protect the produce from freezing.

Fig. 8. Effect of different temperature regimes on the quality and deterioration of cherries.

Protecting produce temperature during marketing

Produce should be maintained as cold as possible without causing injury. The market life of produce is a function of time and temperature, with the degree of deterioration related directly to the length of exposure to higher temperatures regardless of when exposure occurs. Thus, effective protection of the produce requires efficient cooling and good temperature management throughout distribution.

Rapid marketing can minimize deterioration of produce, as in air transport of California strawberries to markets in the eastern U. S. and Europe. Contrary to some belief that such rapid marketing would eliminate need for refrigeration, tests with strawberries and cherries (fig. 8) indicate that even in a 2- or 3-day marketing period higher produce temperatures result in much greater loss (due to physiological deterioration, fruit rot, and desiccation).

Maintenance of continuous low temperatures may not be possible under all marketing conditions. Some produce handlers believe that re-warming will cause faster deterioration than would occur if produce was never cooled. However, tests have shown that refrigeration for only a portion of the distribution time was better than no refrigeration at all; even produce undergoing repeated cooling and warming deteriorated at a slower rate than non-cooled produce. Here again, deterioration was directly related to the length of exposure to higher temperatures regardless of the pattern of high and low temperatures. With chilling-sensitive produce, however, such temperature fluctuations could prove harmful if the produce received extended exposure to temperatures low enough to cause tissue injury.

Part II—THE COOLING METHOD

Room cooling

Exposure of produce containers to cold air in refrigerated spaces is a common cooling method (Sainsbury, 1961; Guillou, 1960). A simple and effective arrangement is to discharge cold air into a cooling room horizontally just below the ceiling. The air sweeps the ceiling and returns past the cooling produce on the floor (fig. 9).

This arrangement has several advantages:

- Produce may be cooled and stored in the same place, in which case there is less re-handling.
- Design and operation are simple.
- The ceiling is kept cold (radiation from a warm ceiling may measurably warm objects at floor level).
- Peak loads on the refrigeration system are less than with faster methods of cooling.

Room cooling has severe limitations:

- Cooling is relatively slow, particularly with less-open types of containers.
- Produce is sometimes shipped without adequate cooling, or shipment may be delayed.
- Sensitive produce may deteriorate measurably in the time required to cool it.
- More floor space is needed for a given output than with faster methods of cooling.
- Use of the same space for cooling and for

storage exposes stored produce to high air velocities and fluctuating temperatures which can cause serious water loss.

- Moving cooled produce to separate storage involves the same rehandling as for faster cooling methods, without their advantages.
- Produce in newer more-closed containers, or in containers tightly stacked on pallets, is particularly hard to cool in room coolers, and even less perishable products (apples or pears) may deteriorate to unacceptable levels before they are cooled.
- Moisture released by warm interior produce may condense and cause "sweating" of colder outside produce.
- It is difficult to maintain cooling control because of the many variables encountered.

Because of these limitations, increasing use is being made of faster cooling methods to protect more perishable produce and to facilitate shipping soon after harvest.

Best results from room cooling require:

- Enough refrigerated air volume to keep all parts of the room cold.
- Air velocity of 200 to 400 feet per minute (2 to 4 miles per hour) around and among cooling containers.
- Spaced stacking (or design) of containers to permit air flow between them.

Fig. 9. Fruit being room cooled in pallet frames. Frames assure uniform spacing for air circulation past pallet sides, and are often used to prevent damage to corrugated containers during multi-pallet stacking.

- Well-vented containers which cool almost twice as fast as closed containers at moderate velocities (200 to 400 feet per minute).

When cooling is complete, air velocity around containers should be reduced to the least that will keep them cool; 10 to 20 feet per minute is often sufficient.

Ceiling jets for room cooling

Air in a cooling room tends to follow the path of least resistance from air inlets to air outlets. Consequently, the interior containers in a large stack of containers may receive little air movement if another part of the room is empty; or, in a fully loaded room, most of the air may pass over the top of the produce. Better penetration into the stacks can be attained by directing the air downward through large sheet-metal or plastic nozzles in a false ceiling (fig. 10). To do this the floor should be marked for placement of loaded pallets in a rectangular pattern, with channels a few inches wide that intersect directly beneath the nozzles. Air from the nozzles then goes down to the floor and spreads in four directions through the channels. Such cooling is considerably faster than with undirected air circulation. (Advantages here should be weighed against added costs for the nozzle system and for the additional fan power required.)

Bays for cooling and storage

For cooling and storage, a single large space is sometimes divided into bays by wing partitions extending outward from the walls (fig. 11). Air is circulated independently in each bay, and provision is made in each bay for high air velocity for cooling, and for low air velocity for storage. Movement of produce from a cooling room to a separate storage is eliminated. Thus warm air from newly-introduced warm produce cannot contact cooled produce as it may if an undivided room is used for both cooling and storage. The open aisles in a divided cooling room commonly occupy more floor space than in an undivided cooler, but lots are more easily separated and more accessible. Bays may also be arranged for forced-air or pressure cooling.

Containers used in room cooling

During room cooling, some heat escapes from produce in containers by conduction through the produce and containers walls; the remaining heat escapes because of air movement within the container and through vents or openings in container walls (Guillou, 1962-68; Mitchell, *et al.*, 1971). Vented containers may not be needed if the produce will not be injured by relatively slow cooling—for example, cleats and bulges on wood boxes allow sufficient air circulation for

Fig. 10. A ceiling-jet room cooler. Pallets are placed so the four corners are skimmed by air blown from jets in the ceiling; resulting turbulence speeds removal of heat from produce.

Fig. 11. Cooling-bay design for room cooling. The room is divided into a series of small bays, each of which may be operated relatively independently for cooling and temperature maintenance. Air circulating through a bay returns to the heat exchanger without passing over other produce. Thus, cooled fruit is protected as warm fruit is added to the system.

marginal cooling of wrapped pears. Non-wrapped pears in vented telescope corrugated containers are cooled satisfactorily if adequately spaced on the pallet. Properly vented containers may be more closely stacked on pallets than non-vented or improperly vented containers.

When rapid produce cooling is required, containers should always be vented. Top and bottom side-slots are often provided on wood containers by use of narrow side pieces, and a center slot is sometimes added by using two narrow slats instead of one side piece. Corrugated containers can be vented by cutting holes or slots in the corrugated board. Roughly, venting 5 per cent of the side area of a corrugated container may be expected to reduce its cooling time by 25 per cent, and to reduce its stacking strength by only 2 to 3 per cent if vents are not in container corners. Since one of the functions of a produce container is to immobilize its contents, the effect of vents in making corrugated containers more subject to bulging may be more important than their effect in reducing stacking strength. Containers with less than 2 per cent venting area are not recommended because they do not cool much faster than non-vented containers.

Some corrugated containers have top and bottom vents to increase cooling (through a chimney effect) when stacked. Such vents help cool top and bottom containers but have no measurable

Fig. 12. Recommended corrugated container venting pattern for room cooling. With dimensions of $L \times 3/2 L$, and with vents centered at a distance of $L/4$ from each corner and $L/2$ apart, vents will be aligned when containers are cross-stacked.

effect on those in the middle of the stack, because the temperature difference between the inside of the stack and the room produces no measurable air movement through the column of produce.

Foam plastic boxes provide about the same heat insulation through their walls as do the two layers of corrugated board in the walls of telescope containers. Cooling rates for foam plastic and 2-layer corrugated containers are about the same if the venting is the same.

Vents of different shapes and sizes show no consistent differences in cooling rates if their total areas are equal. Vents less than $1/2$ -inch across are less effective and should be avoided. Also, vents should not be of a size and shape that can be easily blocked by produce. Larger objects cannot close vents near the corners of a box, but vents near the corners seriously weaken corrugated containers.

For best room cooling with corrugated containers:

- Avoid round vents if produce can be caught and block vent.
- Use a few large vents instead of many small vents.
- No top vents needed.
- Vents should be $1/2$ -inch wide or greater.
- Keep vents 2 to 3 inches from all corners.
- Vent area should exceed 2 per cent of the side area.
- For cross-stacking use vent arrangement illustrated in figure 12.

Cooling in rail cars or trucks

Total cooling in rail cars or in trucks has been largely abandoned except for a few commodities

such as cantaloupes and celery. The trend toward cooling before loading is apparently due to growing appreciation of the importance of prompt cooling, to improvement and availability of other cooling methods, and to the displacement of ice by mechanical refrigeration in rail cars and trucks (Mitchell, *et al.*, 1968). Additionally, the cooling requirement for warm, heavy loads is many times greater than the air circulation and refrigeration needed to maintain the temperature of already-cold loads. Cooling warm produce would add unreasonably to the size, weight, and cost of mechanical refrigeration systems in rail cars or trucks.

Cool-air circulation through mechanical means in rail cars and trucks maintains predetermined temperatures in precooled loads better than was possible with ice refrigeration—air circulation does not stop when the car stops, and the delay and uncertainty of re-icing are eliminated.

Finely-broken ice is sometimes blown on top of warm loads in which neither produce nor containers will be damaged by wetting; the ice supplements mechanical refrigeration during initial cooling of a warm load. As transport vehicles are presently designed, however, the load may be only partially cooled when mechanical refrigeration begins to discharge freezing air. Melted ice-water may then refreeze with the wet top-ice, forming a blanket that blocks further air circulation through the load and leaving produce only partly cooled. Interference with air circulation may be minimized by top-icing in windrows down the center of a transport vehicle and against the walls, thus allowing air to enter the load freely through the valleys (Kasmire, 1971). Cantaloupes in wood crates have been satisfactorily cooled in less than 24 hours by combining this method of icing with operation of fans and mechanical refrigeration in rail cars. Portable auxiliary fans have not increased air flow through the load sufficiently to significantly speed cooling under these conditions (Kasmire and Parsons, 1971).

Where fast cooling is needed, flooding an ice-water slush over a load in a rail car may be an improvement over top-icing. If the ice-water can reach all parts of the load, cooling rates should be similar to those in hydrocooling with 32°F water. The operation should be continued for the length of time and with the same flow rate required to hydrocool the same produce. This system can be considered as an application of batch-type hydrocooling.

Cooling fruit for controlled-atmosphere storage

Modern flushing or scrubbing techniques for removing oxygen from the storage-area atmosphere makes it possible to cool fruit for controlled-atmosphere storage the same way as for conventional storage. Since fruit is placed in controlled-atmosphere for long-term storage, rapid cooling (as for conventional storage) can

be particularly beneficial. Fruit can be cooled as quickly in a controlled-atmosphere storage as in any room used for both cooling and storage if adequate air circulation and refrigeration are provided. Separate cooling facilities allow tighter stacking and require less refrigeration and fan capacity in storage.

The method by which oxygen is reduced in controlled-atmosphere storage has some effect on the fruit and on the refrigeration capacity. Allowing fruit respiration to consume excess oxygen while in storage uses sugars and other materials in the fruit and releases heat, which is then added to the peak load on the refrigeration system. Burning storage-room oxygen with fuel also releases heat, but part of it is usually absorbed by a heat exchanger instead of by refrigeration, thus slowing fruit respiration more quickly. Flushing out oxygen with liquid nitrogen is the quickest way of slowing fruit respiration and also provides some refrigeration. To avoid freezing when liquid nitrogen is used, care must be taken to assure that the cold gas is mixed with warmer gas in storage before it contacts the produce.

Cooling with package icing

Packing finely-broken ice in containers with produce is one of the oldest cooling methods and should be one of the most effective, but tests of commercial operations have shown that often this does not do the job properly. Although

Fig. 13. Vacuum cooling tube being loaded with lettuce. Doors are sealed before cooling, and cooled produce is removed from the other end.

there may be enough ice in the containers to cool the produce, often as much as three-fourths of it is melted by exposure of packed containers to hot weather (Kasmire, 1971). Open storage and handling of ice before packing also results in considerable melting. Labor costs for packing, water damage to containers, unsatisfactory cooling, extravagant use of ice, and development of alternative cooling methods have resulted in a general decline in package icing.

Produce should be cooled from 95°F to 35°F by melting an amount of ice equal to 38 per cent of the produce weight. There is sufficient space within most packed produce containers to include this amount of ice, plus a margin for controlled loss. Mechanization of the icing operation has been under development, and better-insulated containers may also be designed.

Vacuum cooling of vegetables

Leafy vegetables are cooled on a large scale by enclosing them in air-tight chambers and pumping out air and water vapor, thus cooling by evaporation of water from produce surfaces (fig. 13). Air and water vapor may be pumped away with steam-jet pumps, or water vapor may be condensed on refrigerated surfaces while air is pumped away mechanically. The volume of water vapor released in the vacuum is over 200 times the volume of the same weight of outside air. Packed produce can be cooled quickly and uniformly in large loads by this method, but container walls or other barriers that retard water-vapor escape from the produce can seriously slow cooling (Harvey, 1963).

Measurement of produce temperature in a vacuum cooler is important. A gauge that measures absolute pressure in the chamber gives a direct indication of the boiling temperature of water in the chamber, and is probably the most reliable guide to managing a vacuum cooler. A temperature probe inserted in a sample of the produce and connected to an indicator outside the chamber will indicate cooling of exposed produce, but produce in the interior of the load may be considerably warmer, particularly if air is present. The value of a wet-bulb thermometer (which measures the boiling point of water in a vacuum) is limited by air leaks into the system which may raise the actual boiling point of the water considerably above the wet-bulb reading.

Vacuum-cooling equipment is costly and requires skilled attendance—to be economically feasible there must be a large daily and annual output of cooled produce. Thus a vacuum cooler must either be located close to a long-season production area or made portable so it can be moved to locations where there is such production. (Steam-jet coolers are adapted to portability because of their simplicity and because their operation does not involve connected load charges for the electrical motors used to operate mechanical pumps and refrigeration equipment.)

Lettuce cools almost as fast as a vacuum can be established, but a 25- to 30-minute cooling cycle is common, based on the relation of pump and refrigeration capacity to the size of the vacuum chamber. Produce having relatively less area exposed for evaporation of water is not so well adapted. In addition to leafy vegetables, some asparagus, cauliflower, celery and sweet corn are sometimes vacuum cooled commercially, although they cannot be as rapidly cooled as lettuce (which makes their cooling cost greater).

Vacuum cooling causes a water-vapor loss in produce equal to about 1 per cent of the produce weight for each 11°F of cooling. Concentration of this loss on the smaller surface of non-leafy produce may impair its fresh appearance. Spraying water on produce before vacuum cooling may therefore be desirable for reducing water loss and preserving appearance. Evaporation of surface water will also produce faster cooling for a short time if evaporation from produce is slow. Most non-leafy produce is well adapted to hydrocooling or to forced-air cooling, and these methods are usually cheaper than vacuum cooling.

Hydrocooling of produce

Fruits and vegetables may be cooled rapidly by bringing them in contact with moving cold water (Bennet, 1963; Kasmire and Parsons, 1971; Lipton and Stewart, 1959; Pentzer, *et al.*, 1936; Perry and Perkins, 1968; Tousaint, *et al.*, 1955). Hydrocooling removes no water from the produce, and may even revive slightly wilted produce. Efficient hydrocooling requires that:

Fig. 14. Hydrocooling produce in bins. Fork-lift places bins on moving conveyor. Bins then pass through the tunnel and chilled water rains upon and around the bins, thus passing through the produce.

Fig. 15. Shower-type hydrocooler. Recirculated ice water is pumped to an elevated flood-pan and allowed to rain through the produce.

- Water should move over the surfaces of the produce.
- Water should contact as much of the surface of each fruit or vegetable as possible.
- Water must be kept as cold as feasible without endangering produce—near 32°F except for chilling-sensitive commodities.

Conveyor hydrocoolers are the most common type of hydrocooler. In this type, produce in bulk or in containers is carried on a conveyor through a shower of water (figs. 14, 15). If the mass of produce is deep (a foot or more) the water may “channel” (pour through larger openings where least resistance to flow is encountered) and come in contact with only part of the lower surfaces. Channeling may be avoided by providing a heavy shower over a shallow depth of produce, or by proportioning the shower and the drainage from the bottom of containers so that the containers will be partly or entirely filled with water. Drainage must be sufficient to keep the water in the containers moving, and to remove all water before containers leave the hydrocooler.

In one test, a standard 4-foot × 4-foot bin of peaches was showered with a flow of 10 gpm (gallons per minute) per square foot of bin area. The peaches cooled in 24 minutes when the bin was filled with water and fruit immersed, but 30 minutes were required when no water filling occurred. In other tests, flows of as little as 2 gpm per square foot through immersed fruit produced cooling equal to 5 gpm per square foot through drained fruit. However, there was little difference in cooling rates when flows of 10 or 15 gpm per square foot were used on either immersed or drained fruit.

If a bin is to be filled with hydrocooling water, most of the bottom vents must be blocked. In the peach test, for example, filling the bin with a 10 gpm per square foot water flow required that only ten 1-inch holes be placed in the bin bottom. Because of difficulties in adjusting

Fig. 16. Required conveyor load for continuous hydrocooling. Conveyor load and produce cooled may be multiplied or divided by any convenient factor. Example: to cool 8.5 tons per hour, cooling time 40 minutes, would require a conveyor load of 5.7 tons. This can be provided by any convenient combination of length, width, and depth of load.

bottom vent openings to allow water filling, it is often easier to speed cooling by increasing water flow rate through the produce.

An alternative arrangement to showering is to convey submerged produce (in bulk or in containers) through a tank of cold water. This brings water in contact with all surfaces, but means must be provided to keep the water circulating among the individual fruits or vegetables, not merely moving around the containers or the mass of produce. Since motion of the produce through the tank is seldom sufficient to do this, propellers or pumps must be provided to circulate the water. Conveying may be troublesome, particularly if the produce tends to float and so must be held down. If the tank becomes jammed with produce, the operation must be temporarily stopped. Cleaning of the tank is difficult and serious produce damage may occur.

The amount of hydrocooler conveyor area is important and must not be underestimated. If, for example, a hydrocooler takes 45 minutes to cool cantaloupes from 94°F to 40°F with 34°F water, the hydrocooler must be large enough to hold, at one time, the maximum quantity of cantaloupes that will be loaded into it in 45 minutes, assuming the 34°F water temperature is maintained (fig. 16).

Many commercial hydrocoolers are inefficient simply because of lack of insulation. Tests have shown that less than half of the refrigeration supplied to most conveyor-type hydrocoolers is used to cool the produce—the rest is lost through insufficient insulation. Therefore, better insulation of hydrocoolers themselves may be needed (enclosing them in insulated spaces is well justified).

The room-type or “batch” hydrocooler has no conveyors and so is more easily insulated. Containers to be cooled (bulk produce is not used in this system) are stacked in rooms and may be left there in temporary storage; at least two rooms are usually provided, so that one can be cooling while the other is emptied and filled. Even though only half the floor space is used at any one time for cooling, floor area in this type of operation is much less expensive than floor area in a conveyor operation, and the total space occupied is not necessarily more than for the latter. Ice-water is showered over the produce as in a conveyor hydrocooler. Batch-type hydrocoolers appear to be well adapted to some operations but have not been commonly used.

Any hydrocooling system places a relatively short heavy demand on its refrigeration capacity while it is operating, but uses no refrigeration at other times—except perhaps to cool a fresh supply of water. This heavy peak demand often combined with a relatively short operating season is best met by ice refrigeration. Water may be chilled by flowing through broken ice in a tank or trough, which should be sufficiently wide and deep to allow water to flow between ice blocks forced to the bottom by ice piled above the water level. Water is not sufficiently cooled if it flows under ice floating on the surface. Strainers should be easy to clean and large enough that they do not have to be cleaned often. A succession of screens, from coarse- to fine-mesh, reduces accumulation of trash on the fine-mesh screens which are the ones most apt to restrict flow. Because of contamination of the recirculating water by dirt and microorganisms, it is often recommended that fresh water be used daily. Thus, the entire system should be easy to drain and clean.

The problem of purchasing and handling ice can be eliminated by using an ice-accumulator refrigeration system, in which mechanical refrigeration of moderate capacity freezes ice on coils in a water tank. The system can operate 24 hours a day, if necessary, making ice that melts off when the produce load is heavy. The freezing of water ice around the coils tends to concentrate accumulated dirt in the remaining unfrozen water. Much of this accumulated dirt can be drained off when there is a maximum load of ice on the coils with a minimum loss of refrigeration (see page 22 for further information on ice-accumulators, and page 28 for design calculations).

Checking hydrocooling operations

The water-cooling effectiveness (H) of a hydrocooler can be calculated if the temperature of the water entering (t_e) and leaving (t_o) the cooling coils or ice bunker is known, using the

$$\text{formula: } H = \frac{(t_o - 32)}{(t_e - t_o)}$$

Fig. 17. Estimated refrigeration requirement for hydrocooling. Here 30 tons of produce per hour, cooled at 40°F, requires approximately 360 tons of refrigeration, assuming a normal hydrocooling efficiency of 50 per cent. (Add two-thirds the weight of wood, one-fourth the weight of aluminum, or one-eighth the weight of steel if containers are run through hydrocooler; multiply refrigeration load by two-thirds for a well-insulated hydrocooler.)

If H is greater than 4, ice contact is poor, possibly because:

- Ice is floating, allowing water to bypass the ice.
- Water velocity over ice or cooling coils is too low—if so, propellers may be needed to increase water turbulence for better cooling.
- Inadequate ice surface is available in too small an ice compartment, or cooling-coil surface is inadequate.

If H is less than 4, ice contact is satisfactory and poor cooling of the produce is due to some other factor, such as:

- Inadequate refrigeration—figure 17 can be used to estimate the amount of refrigeration required to cool produce.
- Inadequate water circulation—if water is cooled more than 2°F in passing over the cooling surface, water flow is inadequate (for shower-type hydrocoolers, minimum water flows of 10 to 15 gallons per minute per square foot of hydrocooler area are recommended).
- Conveyor speed is too fast, so that produce does not remain in hydrocooler long enough.
- Water channeling through the product—water must be moving over the surface of the produce for efficient cooling; increasing water flow (or, in extreme cases, redesigning the hydrocooler) may be necessary.
- Excessive refrigeration loss caused by inadequate insulation of the hydrocooling unit.

Fig. 18. Air flow in forced-air (pressure) cooling. Placement of containers and proper use of baffles blocks air return everywhere except through side vents in containers. Thus, air is forced to pass through containers and around produce to return to exhaust fans. As air is exhausted from the center chamber, a slight pressure drop occurs across the produce.

Forced-air (pressure) cooling

Produce can be air-cooled rapidly by producing a difference in air pressure on opposite faces of stacks of vented containers (Guillou, 1963; Par-

Fig. 19. A well-mounted, efficient single blower can be used to circulate air through both produce and cooling medium in forced-air cooling. Blower is mounted in wall, lined with foam plastic for a wall seal, and equipped with a permanently mounted fabric cover (shown at top of foam plastic wall seal).

Fig. 20. Pallet loads of strawberries are placed at the two sides of the wall blower so as to allow a plenum (air-chamber or passageway) for air being drawn through produce to the blower.

sons, *et. al.*, 1970, 1972). This difference forces air through the stacks and carries produce heat away primarily by flow around the individual fruits or vegetables in the containers (figs. 18–22), rather than by flow around the outside of the containers (as in room cooling).

In forced-air cooling, cooling speed can be regulated by adjusting the volume of air. Rapid cooling can be accomplished with adequate refrigeration and a large volume of air flow per unit of produce. Using a large air volume to speed forced-air cooling reduces area of floor

Fig. 21. Forced-air cooling unit in operation with pallet loads of strawberries. The fabric cover in front seals the air-return plenum, and air is thus forced to pass through side slots of containers and around the fruit in order to return to blower. The blowers used in this procedure are controlled by time clocks.

Fig. 22. Forced-air cooling in bins prior to packing. The central plenum here is blocked with plywood panels which cover the top and back openings of the stack. Air is thus forced to pass through container side vents and around produce to reach exhaust blowers. Blowers should be stopped when cooling is completed. Each station in this installation is capable of cooling 60 tons of produce.

space needed by produce being cooled for a given rate of produce handled, but increases the cost of air circulation and may require a larger refrigeration system.

Forced-air cooling usually cools in one-fourth to one-tenth the time needed for room cooling, but still takes two to three times longer than hydrocooling or vacuum cooling. Room coolers can sometimes be converted for forced-air cooling, but such conversions will usually only speed cooling by a factor of 2 to 3 (compared to the time required with conventional air circulation).

A forced-air cooler should be designed and operated to substantially reduce or stop air flow through the produce as soon as it is cooled—continued flow may cause serious water loss from produce unless humidity is near the saturation point. For forced-air cooling design details, see page 29.

Shelf-type forced-air coolers

This special application allows small lots and incomplete pallet loads of produce to be efficiently cooled. Single pallets are placed side by side against a plenum (air-chamber or passage-way) usually in one row on the floor and in one

or two rows above on elevated brackets or shelves (fig. 23). The interior of the plenum is under suction or, in some coolers, under pressure. Dampers at each pallet position are opened by contact with the pallets, allowing air to be either drawn inward or forced outward through the stacked containers on the pallet (fig. 24). Dampers can be arranged to open only as high as the stack of containers on the pallet, allowing stacks of various heights to be cooled without adjustments or loss of air.

The same idea may be used to cool produce in pallet bins. Bins with slatted or screen floors are used. When each bin is placed it opens a damper connecting the plenum with the space beneath the floor of the bin and between its sills. Air from the room is drawn down through the produce in the bin and into the plenum.

Produce placed in a shelf-type cooler starts to cool immediately, merely by being put into position. No attendance is needed except to remove the produce when cooling is completed to avoid excessive desiccation. Every pallet or bin is accessible for removal at any time and may be immediately replaced by another, allowing virtually continuous use of all the cooling positions. These advantages must be weighed against the costs of shelves, dampers and floor area in relation to the volume of material being cooled.

Fig. 23. Shelf-type of forced-air cooler for cooling strawberries. Floor space utilization, which is not efficient with this system, is increased by use of pallet shelves. Pallet loads of varying heights can be accommodated.

Width of container stacks for forced-air cooling

In forced-air cooling, downstream produce (produce furthest from start of air flow) is warm-

est because it is contacted by air that has been warmed as it passes through the stacks. However, for any given air flow per unit weight of produce, the downstream cooling rate is not significantly affected by length of the air path through

Fig. 24. Damper arrangement for shelf-type forced-air cooler allows each pallet to be cooled independently. Dampers are opened as lever at bottom of each damper panel is depressed when pallet is placed on shelf.

the produce. Wider stacks, which simplify handling and reduce the floor area occupied by air channels, are therefore possible without delaying the cooling of downstream produce, although static pressure required to move the air increases rapidly as stack-width is increased.

Shipping containers are commonly stacked three-wide on pallets and placed so that air flows through the stacks across the pallet width. Arrangements that provide longer air paths through the containers save space but also require higher air pressure and result in more uneven cooling. Shorter air paths allow faster cooling and less air pressure but require more floor space (fig. 25). One plant in Arizona stacks grape boxes two-wide on pallets which are then conveyed through an air-cooled tunnel; the air-flow is large enough to cool the fruit from 90°F to 40°F in 1 hour. In one Mexican plant, tomato boxes are moved by hand trucks and placed in single stacks against air slots in the wall of air-return plenums for forced-air cooling.

Stacks 1-foot wide permit flow of a large volume of air for fast cooling with low static pressure (fig. 25). However, 60 per cent of the floor area is occupied by air channels, which means that this system is practical only if that much area can be economically given to the channels. Such a short air path has been utilized for certain conveyor-type coolers, coolers using vertical air flow, or coolers where containers are placed against air vents in a wall.

Most forced-air coolers utilize stacks 3 or 4 feet wide; reasonably good cooling rates are attained with moderate static pressures, and these widths make economic use of floor space. Floor space may be more efficiently used with stacks 6 feet or more in width, but static pressure requirements are then usually unreasonably high for efficient cooling of downstream produce. Wide stacks should be used only for some special reason, such as package and produce combinations needing only unusually low static pressure in relation to air flow.

Exposure of stacked containers for forced-air coolers

Containers stacked for forced-air cooling should be arranged so that the tops of the stacks are exposed directly to the source of cooling air. Air that leaks into a stack is then added to the flow through the downstream boxes. This tends to offset the slower cooling of the downstream boxes that results from their receiving the warmest air.

If tops of stacks are exposed directly to the air return, some air then leaks out of the top of the stack, thus decreasing flow through downstream boxes; downstream boxes then receive both the least and the warmest air, and this tends to make cooling very uneven (fig. 26).

Vertical air flow through produce in bulk, or in top and bottom vented containers, has advanced,

Fig. 25. Cutaway view of forced-air cooling of stacks showing static pressure (head) requirement and floor area utilization to achieve similar cooling with different stack widths.

tages, though it has not been generally used. Air channels for vertical air flow are above and below the produce and may be of ample size without adding to the floor area. The high cost of grating or of vented floors with adequate air passages beneath them has been an objection. Relations of air flow to cooling rate, static pressure, and length of air path are the same for vertical as for horizontal air flow.

Containers for forced-air cooling

In forced-air cooling the packing method and the containers must permit a satisfactory volume of air flow with a reasonable pressure difference across the stack (Mitchell, *et al.*, 1971; Wang and

Fig. 26. In forced-air cooling the top of the stack should be exposed directly to the source of cooling air so that boxes receiving the least air also receive the coldest air. Tiers should be spaced $\frac{1}{2}$ - or $\frac{3}{4}$ -inch apart to allow cold air that passes between the boxes to mix with the warmer air that passes through them. Dotted line shows position of dampers when not in use for forced-air cooling.

Tunpun, 1968). Packs in which spaces between fruits or vegetables are occupied by packing material (such as paper wraps on pears) are not suitable to forced-air cooling; film bags or liners prevent air from passing through a pack and also are not suitable for forced-air cooling. Fruit packed in plastic trays will cool satisfactorily if the containers are designed to let air pass both over and under each tray. Grapes packed in vented lidded containers cool well by forced-air despite their compact mass. Air passing between unlidded trays of strawberries makes good contact with the berries as it eddies over and among them, making them one of the most satisfactory crops for forced-air cooling.

Adequately vented containers are essential in this method of cooling. For moderately fast cool-

ing of multiple-tier arrangements of corrugated paper containers, containers should have at least 4 per cent of their side areas vented. Cooling with a given air flow is somewhat slower with small vents because more of the air is forced between containers and less flows through them. Small vents are more difficult to line up during stacking, but the chief objection to them is the very high static pressure required to force an air flow adequate for rapid cooling through them. For example, solid-sided wooden grape boxes require about 10 per cent longer to cool with the same air flow than do slatted-side boxes, and the static pressure required for cooling solid-side boxes is about double that needed for slatted-side boxes.

Small differences between similar containers sometimes have considerable effect on their cooling behavior in forced-air cooling. New container designs and produce packs must be tested under measured air flow and static pressure conditions before any close prediction of their cooling times can be made. (For further information on design calculations see section beginning on page 29.)

Conduction cooling of produce

Water loss from produce during cooling and storage may be prevented by using virtually vapor-tight containers. Although cooling by conduction of heat through such containers is slow, their cooling rate is satisfactory for slowly-respiring produce if a reasonable portion of the container surface (all sides of the container, for example) is exposed to cold air. Apples and pears packed in perforated-film liners (which allow some gas exchange but little water-vapor loss), and produce packed in nonvented curtain-coated containers, are examples of conduction cooling practices.

Grapes can be packed in wooden boxes having moisture-resistant, unvented liners, or in wax- or plastic-coated corrugated containers, with pads inside the containers that slowly release sulfur dioxide. Fruit deterioration is retarded by the released sulfur dioxide, by the naturally slow respiration of grapes, and by the effect of the vapor barrier in the containers in restricting moisture loss from grapes and stems. Because of these packing modifications, cooling time need not be as short as in the usual grape packing methods (Gentry and Nelson, 1964).

Humidity in a storage area cooled by dry coils would be quite low if all the produce in it were packed to prevent escape of moisture. If this is done low humidity is not objectionable, and moisture-induced weakening of corrugated containers is slowed.

Controlling humidity

Humidity in a produce cooler or storage area depends on the balance between losses and gains of water. Moisture in the air is usually not more than may be gained or lost in a few minutes

(O'Brien and Gentry, 1967). If gains and losses do not balance, air humidity soon changes until they do. Most water is lost from condensation on cooling surfaces, although absorption of moisture by containers, packing materials, walls, floors, and ceilings may sometimes be important. Water may be gained by evaporation from produce, by evaporation from water used to cool air in a packed cooling tower (see page 21), or by fog sprays (see below).

Air circulation should be sufficient to limit the temperature rise of humidified air. Relative humidity (RH) in cooling or storage is reduced by about 4 per cent for each 1°F rise in air temperature. Condensation may sometimes be reduced by use of large, effective cooling surfaces operated at a close-to-air temperature. The figures immediately below give calculated values for water condensation in a cooling plant with a return air temperature of 35°F.

WATER CONDENSATION ON COOLING SURFACES					
ΔT (°F)*	RH of return air at 35°F				
	95	90	80	70	60
	Condensation (gallons per hour per ton refrigeration)				
20	0.5	0.4	0.4	0.3	0.2
10	0.5	0.4	0.3	0.1	0
5	0.5	0.4	0	0	0
4	0.4	0.3	0	0	0
3	0.4	0.2	0	0	0
2	0.3	0	0	0	0
1	0	0	0	0	0

* ΔT here is the temperature difference between the air returning from the cooling room and the cooling surfaces over which that air will pass.

In California, cooling surfaces are usually designed to operate (when under full load) at about 10°F below air temperature in storages and 20°F below air temperature in coolers. Relative humidities of about 70 to 80 per cent may be expected under these conditions, and cooling surfaces will have heavy condensations of water evaporating from the produce. Larger cooling surfaces (three to six times larger and more efficient than usual) operated at 3°F below air temperature could reduce evaporation and condensation by half with 90 per cent RH. Cooling surfaces operating at 1°F below air temperature under full load, and at 95 per cent RH, would have to be 10 to 20 times as large and effective as those commonly used.

Usually, dry containers and pallets absorb considerable moisture from produce after it is cooled to within a degree or two of air temperature; air humidity may fall to low levels at this time unless water is added to the system.

Humidifying with fog spray

Humidity in coolers and storages may be kept at proper levels by using fog sprays to offset con-

densation of water on cooling surfaces. The quantity of water to be added, and the resulting condensation on the cooling surfaces, can be estimated from the text table on this page. Adding 1 gallon of water per hour per ton of refrigeration will offset condensation under severe conditions, and will allow a margin for absorption of water by dry interior surfaces at the start of an operating season (correspondingly more frequent defrosting of cooling surfaces will be required). Fog sprays raise RH and reduce water loss from produce; condensation accompanying their use also increases effectiveness of the cooling surfaces, and evaporation of the fog cools the circulating air.

Nozzles using compressed air to atomize the water and discharging between 1 and 2 gallons of water per hour, and between 1 and 2 cubic feet of air per minute at air pressures of 40 to 60 pounds per square inch, can be used in most situations. Larger nozzles may be used where there is room for their long spray plumes to dissipate. Fog spray does not settle out of moving air, but it may create a nuisance by collecting on surfaces against which it impinges. It is cheaper and less troublesome to change pulleys on an air compressor, so that it maintains satisfactory pressure on the nozzles while operating continuously, than to use a start-stop system with an air tank and a pressure regulator in the line to the nozzles. Only a small air-chamber is required to absorb pulsations in the air supply.

A humidistat which automatically starts and stops the water supply is sometimes used, although manual regulation of a continuous water supply is often more satisfactory. The humidistat must be very carefully adjusted and maintained to sense humidities above 90 per cent, and it will behave erratically if temperature varies. Also, starting and stopping the full spray volume makes a room alternately too wet and too dry. With manual regulation, a heavy spray may be used when the refrigeration load is heavy, or to dampen the interior surfaces of a cooler or storage area at the start of the season; when the load is light, a fine spray will maintain a steady, high humidity. Minor changes in the character of the spray are commonly needed only twice a day in coolers or active storage areas, and much less frequently in storage areas to which new produce is not being added in great quantity.

Air expansion commonly cools nozzles by 2 or 3 degrees and so they need protection against freezing even if the surrounding air is near but not below 32°F. Nozzles and water lines can be protected by wrapping them with electrically-heated tape.

One type of pneumatic-atomizing nozzle mixes air and water outside of the nozzle (see schematic of external and internal mixing nozzles in figure 27). Air is discharged beside the water nozzle, creating a suction that allows water to be supplied at a pressure of 1 or 2 pounds per square

inch above or below atmospheric pressure, depending on whether a heavy or a light spray is needed. If they receive water from a common supply, nozzles of this type must all be on the same level to avoid significant differences in water pressure. Water-supply lines must be large enough to avoid significant friction, and must be laid out to avoid formation of air pockets (which will not be blown out by low water pressure). External mixing nozzles are often arranged to syphon water from small tanks in which the water level is controlled by float valves. This makes no provision for changing the water supply to regulate the weight of the spray, so a better arrangement is to admit water from any convenient supply to the nozzles through a needle valve. The valve may be adjusted to provide heavy or light spray by regulating the flow of water rather than its pressure. External mixing nozzles are best adapted to installations in which the simple control system is an important advantage, and in which the water supply may conveniently be laid out to minimize friction and to avoid the formation of air pockets.

Another type of pneumatic nozzle mixes the air and water inside the nozzle, before they issue from a common orifice (see diagram of internal mixing nozzle, figure 27). Water is supplied at a pressure close to that of the air, rendering friction in water lines and differences in elevation of

nozzles much less important than with external mixing nozzles. Also, any air pockets are blown out of the water lines by the high water pressure, thus allowing formation of air pockets to be disregarded in the pipe layout.

There are compensating disadvantages to this arrangement, however. Interconnection of air and water supplies in the nozzles can allow contamination from the air lines to be blown back into the water lines in case of failure of the water pressure. Public health regulations require fail-safe protection of back-flow from such a system into the general water supply. Moreover, the pressure in many water supply systems may not always be adequate to force water into nozzles against the 50 or 60 psi pressure needed for good atomization. A satisfactory method is to supply water to internal mixing nozzles with a small piston pump drawing water from a tank filled from a general supply by a float valve. A variable speed drive on the pump allows volume to be adjusted for a heavy or light spray. Spray adjustments are more positive and stable if water and air are supplied at fixed volumes rather than at fixed pressures, as is sometimes recommended. Internal mixing nozzles are generally most satisfactory in larger installations, where using a pumped water supply is not a serious objection and where it is advantageous to avoid the large, carefully laid out water piping or small tanks at each nozzle which are necessary for external mixing nozzles.

Fig. 27. Preferred fog-spray nozzle arrangements for produce coolers and for storage areas. Positive control of air and water volumes allows stable adjustments for heavy or light sprays.

EXTERNAL MIXING NOZZLES

INTERNAL MIXING NOZZLES

A third type of fog nozzle discharges water through a minute orifice at a pressure of 400 to 600 pounds per square inch, thus providing satisfactory atomization without use of air. Elimination of the air system is offset to some extent by the cost of a high-pressure water pump and extra-heavy water pipe and fittings. No adjustment of spray volume is possible here, and the tiny nozzles are more subject to stoppage than are larger ones.

A spinning disc atomizer is sometimes used in produce coolers and storages. Water is atomized by the velocity with which it is thrown from the edge of a rapidly revolving disc, and a small air blast is provided to discharge the spray. Each unit (capable of humidifying a small room or zone within a larger room) costs several hundred dollars but is complete in itself and needs only inexpensive electric and water connections. This type of atomizer merits consideration if only one or two units are needed.

Packed towers for cooling and humidity control

Spray-system regulation and maintenance is eliminated if air in a cooler or storage area is cooled by contact with showering cold water in a cooling tower containing a packing material. Air moving upward in the tower can be brought to within a degree or less of the temperature of the water supply, and close to 100 per cent RH.

Fig. 28. A packed cooling tower in which cold water is sprayed over packing and air counter-flows through tower for cooling.

Various types of packing material can be used to produce good contact between air and water in a limited space. In California, an arrangement of horizontally-stretched plastic filaments is widely used. Wood-slat or plastic demisters remove water droplets from the air, which enters the cooler or storage in ideal condition (fig. 28). Prefabricated towers can be purchased complete with fans, packing, and demisters, or they can be constructed from purchased materials and components.

Ice accumulators used with packed towers

Packed cooling-tower systems can be supplied with cold water from a tank containing mechanically refrigerated coils on which ice forms when the refrigeration load is light and melts when the load is heavy. Since the refrigeration system can operate continuously, it needs only a fraction of the capacity that would be needed if it were required to cool an entire day's production during a few hours on a hot day. (Provision is often made for cooling the water with purchased ice in case of failure of the mechanical system.) Water must be circulated in the tank by a propeller, or agitated with air, to melt ice evenly. As an alternative arrangement, a refrigerated coil may be used over which water flows from above, and which accumulates ice. This system occupies more space than a coil in the tank but good heat transfer between water and ice is assured without special agitation.

A device that senses the thickness of the ice and stops or starts the refrigeration system accordingly is needed. To operate efficiently, freezing of ice on the accumulator coils must be stopped while ample open channels for water circulation remain between coils. Air temperatures below 32°F may be obtained by adding a freezing inhibitor to the water; the inhibitor must be nontoxic because of possible carryover of droplets to the produce (food and environmental protection aspects should always be checked). Resistance of hardware to corrosive effects of the inhibitor should also be considered. The solution must be neutralized if sulfur dioxide reaches it from grape fumigation. Such a solution is calculated to lower the RH of the air by about 1 percentage point for each 2 degrees that temperature is lowered.

Using ice bunkers as a source of coolant

Initial costs and fixed charges for an ice bunker are usually a small fraction of those for a comparable mechanical refrigeration system, and the ice bunker is simple to operate and maintain (Guillou, 1960). On the other hand, the daily cost of ice is usually several times the cost of power needed to operate a mechanical system. For a short season the total annual cost for an ice bunker can be less than for a mechanical system. Some operations may best be done by combining a smaller mechanical system to oper-

ate throughout the season with an ice bunker to carry a short peak load.

An ice bunker should cool return air at least half-way to ice temperature. Failure to do this may be due to any of these conditions:

- The ice may be fused, channeled or in too-large blocks, or not deep enough; a 5- or 6-foot depth is about minimum for good cooling.
- Warm air can leak into the bunker or the ducts; look for leaking ice hatches.
- The bunker can be poorly insulated, especially if exposed to the sun; ordinary concrete has little insulating value.
- The bunker may be too small; its horizontal area should be about 1 square foot for each 100 cubic feet per minute of circulating air.

A room may remain warm in spite of adequate air cooling in the bunker because of:

- Inadequate fan capacity for the amount of warm produce being cooled or for size of plant.
- Air circulation restricted by high water in the bunker or some other obstruction; pump strainers and pumps should be readily accessible for cleaning and servicing while there is ice in the bunker.
- Excessive warm air entering through doors; using an air curtain (consisting of an air flow directed across an open door) allows as much heat leakage as leaving 10 to 25 per cent of the door area open, and may be useless if badly adjusted or if exposed to winds or drafts.

Recirculating melt water by showering it over ice reduces channeling and ice-cone formation, raises RH, and greatly improves cooling. However, the additional cost of an adequate shower system partially offsets the low-first-cost advantages of an ice bunker. A reasonable operation would provide a shower of 0.25 gallons per minute per square foot of bunker—with an air flow in the ice bunker of 100 cfm per square foot of bunker, thus cooling the air through the same temperature range that the water is warmed.

Ice refrigeration maintains high RH only when air temperature is close to ice temperature. Ice tends to maintain the dew point of the air near 32°F, resulting in 88 per cent RH if air is 35°F but only 78 per cent RH if air is 38°F. Using salt to lower ice temperature will considerably lower the RH. Fog-spray humidification in ice-refrigerated coolers greatly reduces water loss from produce being cooled, thus improving its appearance.

Liquid nitrogen and liquid and solid carbon dioxide as coolants

Liquid nitrogen, liquid carbon dioxide, and solid carbon dioxide (dry ice) are sometimes used in rail cars and trucks, both as refrigerants and to modify the atmosphere (see page 10 for discussion of this modification).

There is a direct relationship between cooling

effectiveness of these materials and that of water-ice. Thus the quantity of the materials needed for a given cooling situation can be easily calculated. Vaporizing 1 pound of liquid nitrogen or liquid carbon dioxide and warming the vapor to 32°F absorbs as much heat as melting 1.2 pounds of water-ice. Vaporizing 1 pound of solid carbon dioxide and warming the vapor to 32°F absorbs as much heat as melting 1.8 pounds of water ice.

These materials usually cost much more than water ice and thus are quite expensive for ordinary refrigeration. However, a spray of any of them quickly cools air in a vehicle to far below freezing, and thus makes them uniquely valuable for cooling interiors of frozen-food trucks after truck doors have been opened. The same materials can also be used to cool produce rapidly. This fast cooling, plus the atmospheric modification provided by nitrogen or carbon dioxide, may justify the higher cost. When cooling fresh produce, the cold gases must be diluted with warmer air to raise their temperature to a safe level before they reach the produce and cause freezing. As with any other cooling system, resulting cold air will cool the produce only if it is effectively circulated through the load. Sufficient circulation is not assured by either the generated volume of gas or natural convection within the vehicle. The cold gas that is introduced is dry but will become saturated by only a fraction of the moisture that would be condensed on the surfaces of heat exchangers supplying the same refrigeration by other methods. Thus the use of these materials as coolants will not necessarily aggravate the problem of maintaining a satisfactory RH.

Liquid carbon dioxide boils below the freezing point of the solid unless under pressure. Consequently, part of the vapor given off by the liquid often solidifies as it expands, so pipes and nozzles through which the vapor flows must be arranged to avoid clogging.

Choosing the cooling program

The choice of a cooling method involves several factors, including produce perishability, ambient environment, packing method, speed of marketing, and the effect of other protective services. Available cooling methods include various forms of air cooling and, for certain commodities, hydrocooling, vacuum cooling, package icing, and top icing. The time of cooling may be: immediately after harvest; before, during or after packing; during storage or transit; or even in a split cooling regime (partial cooling before packing and final cooling after packing). Decisions must be made as to: whether rapid cooling is necessary, either to protect produce or aid in shipping; what final temperature produce should be cooled; how much temperature variation can be tolerated during holding or transport of produce; and what special conditions may be necessary during cooling (as, for exam-

ple, fumigation, humidification, or atmosphere modification). Interrelationships between cooling, handling of produce, growth and spread of microorganisms and the package, the packing, and the marketing procedures must be considered—each decision may influence or be influenced by other distribution practices.

Effects of cooling method on produce and its handling. Air-cooling is widely used, and such systems can be relatively trouble-free if properly designed and operated. Rapid or slow air-cooling methods are available, and produce can be cooled at any point in the handling program. However, blockage of air circulation by containers and packing materials can be difficult to overcome unless care is taken, and can result in slow cooling and uneven produce temperatures. Fortunately, it is possible to arrange packing methods, package design and packaging materials, and stacking patterns and air-distribution systems to achieve efficient air cooling.

Vacuum cooling is rapid but requires a fairly large produce-surface to mass ratio for efficiency, so its use is restricted to a few commodities such as leafy vegetables. Because cooling is by water evaporation this method causes some shriveling and wilting, although this may be partially overcome by thoroughly wetting produce prior to cooling. Evaporation from damaged tissue can quickly desiccate small injuries, thus making them more prominent.

Several cooling methods, including hydrocooling, package icing, and top icing, bring produce into contact with water, and this may be an advantage in eliminating water loss, or even in returning some water lost by wilted produce. Hydrocooling is especially attractive where handling speed is important. However, wetting of some commodities can create problems which overshadow these advantages. Contamination of water by microorganisms can be difficult to control; wherever water enters wounds or open cavities it can cause greater losses due to fungal decay, and fungicidal treatments may be needed to lessen this problem. With some commodities wetting may result in other types of injury, including surface browning and intensification of russetting. Wet commodities are also more difficult to sort and grade, and some packaging materials may be damaged from wetting.

Hydrocooling is sometimes credited with another advantage that may be more potential than real. Continuous-flow cooling can be made an integral part of the packing line—if produce can be moved from the field directly through a hydrocooler and packing line, rehandling costs normally associated with cooling are eliminated. This saving is achieved only if the harvest and packing operations are precisely synchronized. As such a situation never lasts for any sustained time, these savings are not achieved for an economically feasible period.

Typically, produce flow from the field is in-

dependent of the packing operation. Thus some provision must be made for produce accumulation between harvest and packing. If, under these conditions, the hydrocooler is an integral part of the packing line then the warm produce must be unloaded and held at ambient temperature while awaiting cooling and packing—and no savings in handling are achieved.

If the hydrocooler is separated from the packing line, produce can be cooled as it arrives from the field and held in cold storage for later packing. In such storage, various types and amounts of produce can be accumulated for more orderly operation of the packing facility. If produce is hydrocooled before storage it will have better temperature protection, which helps compensate for any extra handling needed.

If field deliveries for continuous-flow cooling systems exceed receiving capacity, the produce must either be speeded through the system (resulting in incomplete cooling) or must remain warm while awaiting cooling. By contrast, most stationary air-cooling installations have a much greater receiving capacity than continuous-flow systems, so cooling can be started immediately although it will proceed slowly during the time that refrigeration demand exceeds capacity.

Determining the speed of cooling produce. Rapid cooling is essential for highly perishable fruits and vegetables, and for less perishable produce when harvest temperatures are extremely high (grapes grown in desert regions, for example). Slower cooling methods usually involve simpler facilities (less refrigeration and air flow capacity) and less handling of the produce and thus cooling costs can be less.

Rapid cooling enables a shipper to thoroughly cool and load his produce on the day of harvest. During periods of short supply, or periods of declining prices, this enables a shipper to protect the quality and condition of his produce while responding to these market conditions.

Although rapid cooling has been said to “shock” a commodity, this idea has never been substantiated in tests. When injury has been found, it was related to something other than speed of cooling—for example, water damage from hydrocooling, or freezing injury from use of too low a temperature.

Not all fast cooling methods will cool the produce at the same speed. Vacuum cooling (for leafy produce) and hydrocooling are the fastest methods that can be used. Forced-air cooling can be almost as fast if a large volume of air (several cfm per pound of produce) is used, but somewhat slower cooling (using reduced air-flow rates) may satisfy the needs of the produce and the shipper and be substantially less expensive (fig. 29).

When to cool

Typically, harvested fruits and vegetables in California are cooled after packing, but recent handling and packaging changes have created

Fig. 29. Comparison of the speed of cooling peaches by different methods; average fruit-pulp temperatures. (Guillou, 1960.)

interest in the possibility of cooling before packing. One reason for this interest is industry concern with excessive produce deterioration prior to packing. Delays between harvesting and packing sometimes exceed a day, and during such delays produce can deteriorate through ripening, moisture loss, and growth and spread of microorganisms. Unless delays can be eliminated, cooling before packing may be the only practical method to reduce deterioration. Careful management may minimize such delays so that only a fraction of the produce would require cooling prior to packing.

Cooling of produce in containers after packing is often difficult because of the insulating effect of wraps, shims, pads, and liners around the produce. Additionally, the problem is sometimes aggravated by tightly stacking nonventilated containers on pallets, by generally poor air circulation, or by insufficient refrigeration capacity. By cooling in relatively-open harvest containers before packing, better contact between produce and cooling air or water is obtained.

Cooling before packing involves the total product, including culls and material diverted to alternate outlets (canning, freezing or drying, for example). Unless cooling of diverted material helps prevent spoilage or deterioration or facilitates processing, additional cooling cost must be charged to the packed produce. If 20 per cent of the produce is diverted, cooling cost of the packed produce increases by 25 per cent; a 50 per cent diversion would double cooling cost. Cooler capacity must be large enough to accommodate produce that is to be shipped and produce that is diverted.

Some rewarming of cooled produce will occur during subsequent packing operations, and this can result in increased operating costs and reduced protection for produce (fig. 30). For ex-

EFFECT OF PRODUCE DIVERSION ON COOLING COST OF PACKED PRODUCE IN PREPACK COOLING

Per cent of gross weight diverted from packing	Gross produce weight (in pounds) needed to provide 1 ton packed produce after diversion	Cooling cost factor*
0	2000	1.00
10	2222	1.11
20	2500	1.25
30	2857	1.43
40	3333	1.67
50	4000	2.00

* To obtain actual cooling cost, multiply this factor by the basic cooling cost per ton of produce. For example, if a cooling operation costs \$10.00 per ton and 30 per cent of the produce is diverted to culls or elsewhere, the total cost per packed ton of produce would be $\$10.00 \times 1.43 = \14.30 .

ample, if produce is exposed to air 40°F warmer than it is, and to a 3 mph breeze, it can warm more than 25°F in 30 minutes. If produce temperature had originally been reduced by 40°F, this warming would nullify over 60 per cent of the initial cooling.

Only careful sorting during picking can control the amount of produce diverted during packing. However, partial cooling of the produce before packing followed by complete cooling after packing can substantially slow deterioration and reduce costs. With a reduced produce-air temperature difference, produce rewarming will be less.

Refrigeration losses of cooled produce can be reduced by enclosing the packing facility to reduce air movement. Air conditioning of the

Fig. 30. Effect of delays in packing and air movement on rewarming of exposed apricots, nectarines, peaches, pears and plums. (Mitchell, 1969.)

packing facility can substantially reduce produce-air temperature differential. As an alternative, dumping and palletizing operations can be done in refrigerated areas to shorten the time that produce is exposed to ambient temperatures. Some new mechanized packing methods greatly speed the packing operation, thus reducing produce exposure time.

Cooling after packing will continue to be used because of lower cooling costs that can be achieved, but these lower costs will result in greater economy of operation only if produce quality is adequately protected. Therefore, shippers must carefully manage harvest and packing operations to minimize delays before cooling. Cooling speed and uniformity in the packed containers can also be increased by using forced-air cooling, by proper venting of containers and use of packing materials that do not restrict air flow through the container, and by proper palletizing of containers (see pages 14-19.)

Measuring temperatures

Just as temperature of coolant air or water cannot be determined by measuring coil temperature, so produce temperature cannot be determined by measuring temperature of surrounding air. Therefore, good temperature management depends upon accurate temperature measurements taken in the produce and in the cooling facility.

Equipment for measuring coolant temperature. The choice of heat-measuring instruments will depend on the needs for versatility, the completeness of measurements required, and the degree of automation desired.

Wall-mounted mercury- or alcohol-filled glass-

stem thermometers provide good temperature measurement at low cost; long-stem types can be read more accurately. Thermometers having remote-sensing devices allow measurement of coolant temperatures in inaccessible locations. The simplest of these cost little more than a good standard glass-stem thermometer. Recording thermometers which use bulbs for remote sensing of temperatures up to 200 feet away from the indicator can be obtained with as many as four sensing bulbs for multipoint recording. They are fairly precise, and relatively inexpensive (a few hundred dollars, based on 1972 prices). For installations where more sensing positions are required, thermistor probes or thermocouple wires connected to a recording thermograph are used, with the latter being generally more economical and requiring less maintenance. Such a system combined with a 12- to 24-station recording thermograph costs between \$1,000 and \$2,000 (based on prices in 1972).

Equipment for produce temperature measurement. Inexpensive pocket thermometers having alcohol- or mercury-filled glass stems are made with pointed tips for easy insertion into produce. A cold fruit or vegetable may absorb sufficient heat from a warm thermometer to significantly change the temperature in the area of the measurement; to prevent such errors the thermometer's temperature should first be lowered by a preliminary insertion into the fruit or vegetable, and actual temperature measurements should start with subsequent insertions.

Bi-metallic dial thermometers (units that measure temperature by differential expansion of two different metals) for manual measurement of produce temperatures are easily read under difficult light conditions, but are not necessarily more accurate than glass-stem thermometers. Bi-metallic thermometers with dials large enough for accurate reading generally cost between \$10.00 and \$15.00 (1972 prices).

Thermistor thermometers are easier to use than pocket bulb thermometers. Thermistor probes enclosing a hypodermic needle tip can be purchased for use with small produce or hard-to-reach locations. Because this probe is small, temperature equilibration with the produce is generally not necessary. (A thermistor probe and dial indicator cost between \$100 and \$200 in 1972). Thermistor probes are easily damaged and must be carefully protected.

Any of the multi-station recorders used for coolant temperature measurement may also be used for measuring produce temperatures. With such equipment, probes may be installed to record both coolant and produce temperatures simultaneously.

Calibration of temperature-measuring equipment. All temperature-measurement equipment should be calibrated at least once a year to assure accuracy. Accuracy can be easily checked by submerging the sensing unit in an ice water

bath. The bath should contain a mixture of ice and water, should be well agitated continuously, and should be free of contaminants (distilled ice and water). Any deviation of water temperature from 32°F in such a mixture will be due to contamination or incomplete mixing. The sensing unit should be held in the water out of contact with ice or container until it equalizes with the water temperature. Many instruments have adjustments to allow for simple correction of calibration—if adjustment is not possible, a label which specifies the temperature correction that must be subsequently applied to all measurements should be attached to the instrument.

Measuring coolant temperatures. In a room cooler, temperature measurement is needed at several locations to locate fluctuations or variations occurring in the room. Temperature-sensing units should not be placed on outside walls because heat from outside will cause erroneous readings. In a forced-air cooler, sensors should be placed to measure incoming air temperature. To evaluate the effect of doors or hallways on the cooler, additional sensors should be placed near them.

In a hydrocooler, the temperature of water contacting the produce should be measured. Variations may exist at entry and exit points of the water, so measurements should be made at both.

Measuring temperatures in vacuum coolers poses a special problem, and is discussed in the section on vacuum cooling.

Measuring produce temperatures. The most important decision to be made in measuring produce temperatures is whether to judge cooling sufficiency by the average temperature of the produce or by the warmest temperature in the batch or mass of produce.

If temperature of produce in a batch can be expected to equalize before the warmest produce in that batch deteriorates materially, then the average temperature should be used. Such a condition could be expected to exist when bulk produce is being mixed during packing, or when small containers are to be mixed during subsequent loading.

If temperature variations in a batch can be expected to continue for a prolonged period, with consequent danger of deterioration of warm produce, then the temperature of the warmest produce should be used. This condition could be expected if produce is cooled and stored in large bulk bins for some time before packing, or if packed containers are stacked on pallets for cooling and subsequent shipment as palletized units.

Adequate estimates of the average temperature of a batch of produce may be obtained by collecting temperature measurements in a grid pattern within the batch whether it be a large bulk bin, a pallet load of containers, or a larger collection of either. Several measurements should

be taken top to bottom, side to side, and end to end within the batch.

In determining temperature of the warmest produce in a batch, it is helpful to understand the cooling pattern of the facility. The position of the warmest produce may vary from system to system and can be affected by the type of container used.

Ambient temperatures of the air around a batch of produce will give little indication of the temperature of the produce at its core or pit where cooling is slowest (cooling rate at produce surface may be many times greater than cooling rate at a depth of only 1/2 inch into produce tissue). Thus, temperatures should be taken at the core or pit position.

In room cooling, temperature measurements should be taken of produce near the center of the container, as that is the slowest cooling position. Similarly, it is important to select containers from the center of a pallet load of produce. The warmest temperature to be found, then, should be the core temperature of produce in the center of a container located in the center of a pallet load of produce.

In forced-air cooling, downstream produce at the closed end of the return channel will cool most slowly if the system is supplied with uniformly cold air in one direction. Thus, temperature measurements at this point are most important in determining proper cooling. Additional measurements at other positions are useful in determining the cooling pattern.

Produce at the bottom of the shower is slowest to cool in a shower-type hydrocooler, and should be checked to determine completeness of cooling. In submersion-type hydrocoolers, random temperature checks of produce should be sufficient.

Temperature measurement is time consuming, but it is a valuable management tool for evaluating the efficiency of the operation and must be routinely done to assure that good cooling has been accomplished.

Measuring temperatures in transit. Typically, temperatures in transit are recorded by a small portable thermograph mounted in the air space above the load (such units are generally rented on a per-trip basis). Although records so obtained can be helpful in determining external temperature to which some of the produce has been exposed during transit, they do not indicate temperature changes occurring in the load of produce. They can be especially misleading if air circulation through the load is restricted, as for example by a blanket of refrozen ice (under such conditions the air over the load may be quite cold while the mass of produce in the center of the load is warm). If desired, several thermographs can be located in containers occupying different positions in the load. During prolonged transit these thermographs would provide a close estimate of the temperature of the produce surrounding them. Such records are normally most useful when studies are being

conducted on containers, cooling, or loading. These portable thermographs can best be calibrated in a constant temperature chamber by comparison with an instrument of known accuracy.

A good temperature-measurement program for fresh produce calls for the following:

- Routinely measure and record coolant temperatures.
- Routinely spot check and record temperatures of produce as it leaves the cooler, regardless of your confidence in the facility.
- Check accuracy of temperature-measuring equipment and note corrections, at least

once a year—equalize the temperature of the bulb of glass-stem thermometers by inserting point of thermometer into an individual piece of produce before starting actual measurements.

- Take temperatures from the slowest-cooling positions (produce in the center of containers at the center of pallets in room cooling, or the downstream position in forced-air cooling).
- Measure core or pit temperatures of produce.
- Remember that air temperatures tell little about inner temperatures of produce.

Part III—DESIGN CALCULATIONS

Hydrocooler dimensions and water flow

The following calculations are useful for preliminary design of a hydrocooler or for checking the capacity of an existing unit. Substitute the expected temperature of mechanically refrigerated surfaces, where used, for 32°F in these calculations.

Given or assumed:

P = maximum weight of produce to be cooled per hour (tons)

t_1 = highest expected initial produce temperature (°F)

t_2 = highest allowable final produce temperature (°F)

t_e = highest expected temperature of water through the load (°F)

S = seven-eighths cooling time (minutes) from table 3 (page 39) for other tests

E = efficiency in use of refrigeration =
 $\frac{\text{heat removed from the product}}{\text{heat absorbed by ice or cooling surface}}$
 use 0.50 for ordinary open installation or 0.75 for enclosed and well insulated

Calculate:

F = remaining fraction of initial product-to-coolant temperature difference

$$F = \frac{(t_2 - t_e)}{(t_1 - t_e)}$$

T = cooling time (minutes) from S , F and figure 35 or 36.

C = conveyor capacity (tons)

$$C = \frac{PT}{60}$$

L , W and D = length, width and depth of load on conveyor (all in feet) to give capacity C to suit containers, nature of produce and available space for the cooler

w = water circulated (gallons per minute)—10 LW to 15 LW , depending on nature of produce)

$$t_e - t_o = 1.8 \frac{P (t_1 - t_2)}{wE} \text{ where } t_o \text{ is the temperature of water leaving the ice or cooling surfaces}$$

where t_o is the temperature of water leaving the ice or cooling surfaces

$\frac{(t_e - 32)}{(t_e - t_o)}$ = a measure of the effectiveness of contact of the water with the ice of cooling surfaces; compare with figure 31.

If $\frac{(t_e - 32)}{(t_e - t_o)}$ comes out more than 4, the expected cooling could be accomplished even with poor contact of water with ice or cooling surfaces. If good water contact with ice or cooling surfaces can be assured, choose a lower t_e and repeat the calculations, which will give a shorter cooling time and allow a smaller conveyor capacity.

If $\frac{(t_e - 32)}{(t_e - t_o)}$ comes out less than 1, the expected cooling could be accomplished only with exceptionally good water contact with ice or cooling surfaces. To assure attainment of the expected cooling, choose a higher t_e or a larger w and repeat the calculations.

Intermediate values of $\frac{(t_e - 32)}{(t_e - t_o)}$ may be used,

depending on estimated effectiveness of water contact with ice or cooling surfaces
 V = conveyor speed (feet per minute)

$$V = \frac{L}{T}$$

$$\text{Refrigeration load (Btu/per hr)} = \frac{1800 P (t_1 - t_2)}{E}$$

$$(\text{tons of refrigeration}) = \frac{P (t_1 - t_2)}{6.7E}$$

$$\text{Ice melted per hour (tons)} = \frac{P(t_1 - t_2)}{160E}$$

Fig. 31. Diagram of water temperature cycles in hydrocoolers. Water cooled by ice or by mechanically refrigerated surfaces at 32°F. Water flow in relation to refrigeration load: ample water flow: $t_e - t_o = 1^\circ\text{F}$; marginal water flow: $t_e - t_o = 2^\circ\text{F}$. Contact of water with ice or refrigerated surfaces: water well cooled: $\frac{(t_o - 32)}{(t_e - t_o)} = 1$; water fairly well cooled: $\frac{(t_o - 32)}{(t_e - t_o)} = 2$; water poorly cooled: $\frac{(t_o - 32)}{(t_e - t_o)} = 4$.

If containers are run through a hydrocooler, about two-thirds of the weight of wood or one-fourth the weight of aluminum or one-eighth the weight of steel should be added to the weight of the produce for calculations.

These calculations assume t_e to be midway between the temperatures of the water leaving the cooling surfaces and returning to them.

Air channel dimensions in forced-air coolers

Static pressure losses in air channels beside stacks of produce being cooled by forced-air may result in uneven cooling if the channels are not wide enough (Guillou, 1963; Haerter, 1963). Figure 32 shows friction and velocity pressure losses in a forced-air cooler.

- Friction loss in a forced-air cooler supply channel is reduced by "peeling off" of air as it enters the load, and may be roughly estimated as equal to one-half of the velocity pressure. Maximum reduction in effective static pressure in this channel is usually at the open end, where the reduction is equal to the velocity pressure.
- Friction loss in a return channel is increased by the blocking effect of the air as it leaves

the load and may be roughly estimated as equal to one and one-half times the velocity pressure at the open end. Friction loss and velocity pressure at the open end combine to raise the effective static pressure at the closed end of this channel by roughly two and one-half times the velocity pressure at the open end.

- The least effective static pressure across the load is at the left end in the figure. It is reduced by the amount of the combined maximum losses in the channels. Figure 33 shows approximate static pressure losses in supply and return channels in relation to the air velocities at the open ends.
- Best division between supply and return channels of a given space allotted to channels is a complicated problem. The bottom figure 32 is calculated for a ratio of supply to return channel air velocities of 0.7. This makes losses in the two channels about equal. One channel is sometimes much shorter than the other in the direction of air flow, in which case the shorter channel can profitably be made narrower. Figure 34 shows calculated best ratios of channel widths, measured in the direction between

Fig. 32. Static pressure losses in air channels of a forced-air cooler.

Fig. 33. Static pressure losses at open end of supply channels and closed end of return channels beside produce being cooled by forced-air.

channels, in relation to ratio of channel lengths.

- Figure 32 and the following analysis apply to parallel- or cross-flow channels. Counter-flow would require that one channel diagram in figure 32 should be turned end-for-end.
- This analysis is based on published tests and analyses of losses in slotted air ducts used in building ventilation. The velocity pressure effects in these ducts are the same as in forced-air cooler channels. The effects of possible incorrect estimates of friction can be judged by examination of figure 32. The effect of uneven static pressure on cooling rate can be estimated from the forced-air cooling times given in table 4.

Shelf-type coolers commonly require consideration of pressure loss in one channel only—the room serves as the other channel.

Cooling calculations

Cooling times and temperatures. Exact calculations of time and temperature relationships in produce cooling involves characteristics which are seldom known, but satisfactory estimates for design and operation of cooling facilities can be based on assumption of logarithmic cooling (Guillou, 1960). Figure 35 has been constructed on this assumption, and figure 36 shows a way of using a log-log slide rule to estimate cooling times and temperatures.

Use of seven-eighths cooling time. Many of the calculations and much of the data in this publication are designated by the time for seven-eighths cooling (fig. 37). This is the time to cool

produce through seven-eighths of the initial produce-coolant temperature difference (or to one-eighth of its initial value).

The following is useful for rough estimates of expected seven-eighths cooling times and temperatures:

Remaining fraction of initial produce to coolant temperature difference

$\frac{1}{2}$ $\frac{1}{4}$ $\frac{1}{8}$ $\frac{1}{16}$ $\frac{1}{32}$ $\frac{1}{64}$

Multiply seven-eighths cooling time by

$\frac{1}{3}$ $\frac{2}{3}$ 1 $1\frac{1}{3}$ $1\frac{2}{3}$ 2

This approximation is reasonably good if the average temperature of the mass of produce being cooled is considered. As cooling begins, however, the most exposed produce cools faster and the most protected produce cools slower than the above indicates (fig. 38).

Seven-eighths cooling times are three times as long as half-cooling times (which are commonly used). Seven-eighths cooling, like half-cooling, is the same for a given produce exposed in a given way regardless of temperatures of produce and coolant. Seven-eighths cooling times and temperatures are quite practical estimates of cooling in commercial operations, and are more easily understood than half-cooling times.

Seven-eighths cooling time can be measured directly and has a physical meaning only when

Fig. 34. Ratio of air-channel widths for least static-pressure loss, in relation to total channel width, for parallel or cross flow in channels between produce stacks cooled by forced-air (not counter flow).

Fig. 35. Chart for estimating cooling times and temperatures. Each diagonal line represents seven-eighths cooling in the time at which it crosses the seven-eighths cool line. Example: Produce cools in a test to 0.08 of initial produce-to-coolant temperature difference in 30 hours, seven-eighths cooling time is 25 hours, so would cool to one-fourth of initial temperature difference in 16 hours.

Fig. 36. To use log-log slide rule for cooling calculations set any cooling time on the B scale beneath the corresponding fraction of initial temperature difference on LL00 scale. All other cooling times and fractions of initial temperature difference will then correspond. Setting shown is for seven-eighths cooling in 3 hours or one-half cooling in 1 hour.

Fig. 37. Cooling curve needed to achieve seven-eighths cooling in 9 hours.

Fig. 38. Time and temperature relationship in cooling produce.

a coolant temperature is constant (fig. 37). It is a general measure of exposure of produce to coolant, however, and is useful in calculations whether coolant temperature is constant or varying, as is explained below.

Calculating the momentary cooling rate. In designing cooling systems, it may be necessary to know the rate at which a batch of produce will be cooling at some specific time. The maximum rate when the cooling of a warm batch is started is particularly important, since this determines a peak refrigeration load. Using:

$$\begin{aligned} S &= \frac{7}{8} \text{ cooling time (hours)} \\ (t - t_o) &= \text{product to coolant temperature difference (°F)} \\ R &= \text{momentary cooling rate (°F/hours)} \\ 2.08 &= \text{natural logarithm of } \frac{1}{\frac{7}{8}} \\ R &= \frac{2.08(t - t_o)}{S} \end{aligned}$$

This applies whether coolant temperature is constant or varying, and may also be used to estimate *S* from test measurements of *R* and $(t - t_o)$.

Cooling coefficients. Cooling rates are sometimes designated by a cooling coefficient—this is the temperature reduction in degrees per hour divided by the average temperature difference be-

tween produce and coolant. For example, produce cooled 40°F in 10 hours would have cooled at an average rate of 4°F per hour. If the average temperature difference between produce and coolant over the 10-hour period had been 16°F, the cooling coefficient would have been 4°F per hour

$$\frac{4^\circ\text{F per hour}}{16^\circ\text{F}} = 0.25^\circ\text{F per hours } ^\circ\text{F. Neglecting}$$

departures from idealized logarithmic cooling, the cooling coefficient is the same for any period of a cooling operation or at any moment. Therefore, using *C* for cooling coefficient (°F per hour °F):

$$R = C(t - t_o)$$

In practice, cooling coefficients may vary considerably as cooling progresses, and should be measured over about the same cooling ranges as those to which they are to be applied.

Test results with variable coolant temperatures may be applied to operations with constant coolant temperatures, or the reverse, by the relation between cooling coefficient and seven-eighths cooling time:

$$C = \frac{2.08}{S} \quad \text{or} \quad S = \frac{2.08}{C}$$

Part IV—COOLING DATA

Cooling and storage requirements for California fruits and vegetables

The tables which start on page 35 summarize environmental information for most fresh fruits and vegetables grown in California, but because of climatic, varietal and cultural differences there may be variations from the data. (Where exceptions are known, they are noted in parentheses on the tables.) Because handling requirements for these commodities are often complex, the reader is referred to ASHRAE Guide and Data Book (1971) and to Lutz and Hardenburg (1968) and Whiteman (1957) for more complete information; see "References" for literature indicated.

Ideal holding temperatures. The temperatures shown in table 1 (page 35) are those generally considered as optimum for the commodity. Unless produce is subject to chilling injury it is recommended that it be held as closely to its freezing point as possible without danger of freezing. Many commodities respond best if held at 32°F or below. Storage near the freezing point is possible only if temperature fluctuations of the cooling system are not great enough to permit freezing.

Relative humidity. An RH of 90 to 95 per cent is recommended for most fresh commodities that can be held near 32°F (table 1). However, most commodities can be held at this high RH only if uniformly cooled to near 32°F. At higher pro-

duce temperatures, such high RH can speed development of rot organisms. Low temperature and high RH combined can reduce moisture loss enough to eliminate shrivel and drying problems for many commodities.

Chilling temperature. Chilling injury can take several forms, including surface pitting, tissue discoloration, increased susceptibility to microorganisms, altered flavor or texture, and loss of ability to ripen. Table 1 shows temperature at which chilling injury can occur in some commodities. Often such information may not be precisely known, and thus is in parentheses. For some commodities a wide temperature range has been reported. Chilling injury is often found only for some varieties or for produce grown under certain climatic conditions. Chilling injury is a time-temperature function, and thus it may be possible to hold some commodities safely for short periods at temperatures below those found to cause chilling injury. Holding temperature requirements may also vary according to ripeness of the produce.

Highest freezing temperature. The freezing points shown in table 1 are the highest noted for any test of that commodity (Whiteman, 1957), with many varieties having been observed to have lower freezing points. Because of limitations of test data readers should be aware that some varieties may have freezing points higher than those shown here for a commodity. The freezing point of a commodity is influenced by

the level of soluble solids. Fruits or vegetables having low-soluble solids content may freeze at temperatures usually considered safe for them. Freezing has occurred at temperatures not generally harmful in Bartlett pears containing low-soluble solids, with freezing occurring first among the least ripe pears in the lot.

Maximum market life of produce. There is a maximum time that one can expect a product to remain marketable under good storage and distribution conditions, with considerable variations resulting from varietal, seasonal, or handling differences. To obtain the longest market life, it is essential that the produce be properly handled before as well as during storage. Often special treatments noted in the "comments" column are essential to maintaining maximum market life for a particular commodity.

Removing heat of respiration

All fresh commodities respire, with heat being produced as one of the products of that respiration. Many studies have been conducted to determine the amount of heat produced by the produce, when held at specific temperatures. In table 2 (page 38) this information has been converted to show the refrigeration required to remove heat of respiration.

Produce cooling times by method of cooling

The results of many tests of the speed of cooling various commodities are available (tables 3 and 4, pages 39-41). As has been noted in the discussion of seven-eighths cooling on page 30, it is possible to develop constant values for cooling times if the produce and its exposure conditions remain constant. Using this procedure, data from various tests have been compiled and seven-eighths cooling times estimated for a few commodities, packing methods, containers, stacking patterns and cooling methods. (For other information on containers see figures 40 and 41, pages 42, 43.)

The temperature of an exposed product or container is reduced to one-eighth of its initial elevation above a constant temperature coolant in approximately the times indicated in tables 3 and 4. Small differences in containers, packing or exposure can make considerable differences in cooling rates. These figures are offered only as a guide.

Useful constants

One ton of refrigeration is the heat absorbed by melting water ice, or given off by freezing water ice, at a rate of 1 ton in 24 hours. This is 288,000 Btu per day, 12,000 Btu per hour, and 200 Btu per minute.

Melting 1 pound of water ice absorbs 144 Btu. Vaporizing 1 pound of water absorbs 1,073 Btu at 32°F, 1,035 Btu at 100°F.

Vaporizing 1 pound of dry ice and warming the vapor to 32°F absorbs 264 Btu (equal to melting 1.8 pounds of water ice). Vaporizing 1 pound of liquid nitrogen or 1 pound of liquid carbon dioxide and warming the vapor to 32°F absorbs 175 Btu (equal to melting 1.2 pounds of water ice).

Approximate compressor horsepower per ton of refrigeration:

Evaporation temperature °F	Condenser temperature °F		
	95	115	135
	Horsepower per ton		
30	1.1	1.5	2.0
20	1.3	1.8	2.4
10	1.5	2.1	2.7

For fans working against pressure (not applicable to free discharge):

Air horsepower =
$$\frac{\left(\frac{\text{cubic feet}}{\text{per minute}}\right)\left(\frac{\text{static head, inches of water}}{6370}\right)}{1}$$

Shaft horsepower =
$$\frac{\text{air horsepower}}{\text{fan efficiency}}$$

Fan efficiency is usually from 0.40 to 0.70 for pressure fans.

In water pump calculations:

Water horsepower =
$$\frac{(\text{gals per. min.}) (\text{head in ft.})}{3960}$$

Shaft horsepower =
$$\frac{\text{Water horsepower}}{\text{Pump efficiency}}$$

Pump efficiency is usually between 0.50 and 0.70.

The shaft horsepower delivered to a fan or pump is converted to heat in the air or water and adds to the refrigeration load at a rate of:

1 horsepower = 2,540 Btu per hour = 0.21 tons of refrigeration

If the motor is in the air stream the entire electrical input of about 1 kw per horsepower is converted to heat in the air stream at a rate of:

1 kw = 3,413 Btu per hour = 0.28 tons of refrigeration

This figure applies also to heat from lights or other electrical equipment.

Specific heat of fruits and vegetables: 0.85 to 0.95 Btu per pound °F, average 0.90 Btu per pound °F

Specific heat of wood and paper: 0.30 Btu per pound °F

Specific volume of air at 35°F: 12.50 cubic feet per pound

Density of water at 35°F: 62.40 pounds per cubic foot, 8.3 lb/gallon

Density of ice in blocks: 56 pounds per cubic foot

Volume of ice in bunkers: 50 to 60 cubic feet per ton

If either the velocity or the velocity pressure of air is known, the other can be determined by use of the graph shown in figure 39 (page 41).

TABLE 1
COOLING AND STORAGE REQUIREMENTS FOR CALIFORNIA FRUITS AND VEGETABLES

Commodity	Ideal holding temperature <i>degrees F</i>	Relative humidity <i>per cent</i>	Chilling temperature <i>degrees F</i>	Highest freezing temperature <i>degrees F</i>	Maximum life	Comments
Apple..... (chilling-sensitive varieties)	30-31 (38-40)	95	(36-38)	29.3	2-8 months (varietal)	Some varieties, including Yellow Newtown, McIntosh, some Jonathan, and some Grimes Golden subject to chilling injury. Controlled atmosphere used for long storage.
Apricot.....	31-32	95		30.1	2-3 weeks	Ripen at 65-75°F.
Artichoke.....	32	90-95		29.9	1 month	
Asparagus.....	32	95		30.9	10 days	
(if stored).....	(36)		(36)		(2-3 weeks)	
Avocado.....	40-55	85-90	40-55	31.5	1 month	Chilling injury if kept more than 10 days below 36°F.
(Fuerte var.).....	(45)		(40)			Ripen at 60-75°F.
Beans, lima.....	32-40	90		31.0	1-2 weeks	Shell for longest life.
Beans, snap.....	45-50	90-95	45-50	30.7	1 week	
Beets.....	32	95		30.3	3-5 months	Top for holding. Maximum life with tops attached is 2 weeks.
Berries:				(tops 31.3)	topped	
Bushberries.....	31-32	95		30.5	Few days	Cool promptly and thoroughly.
Blueberries.....	31-32	95		29.7	2-6 weeks	Cool promptly and thoroughly. Carbon dioxide used to supplement refrigeration in transit.
Strawberries.....	32	95		30.6	1-2 weeks	
Broccoli.....	32	90-95		30.9	2 weeks	
Brussels sprouts.....	32	90-95		30.5	2-5 weeks	
Cabbage.....	32	90-95		30.4	1-4 months	Storage life depends on variety and season of harvest.
Carrots.....	32	95		29.5	1-5 months (varietal)	Top carrots for best market life. Maximum life with tops attached is 2 weeks.
Cauliflower.....	32	90-95		30.6	2-4 weeks	
Celeriac.....	32	90-95		30.3	3-4 months	
Celery.....	31-32	90-95		31.1	2-3 months	
Cherry, sweet.....	30-32	95		28.8	2 weeks	Carbon dioxide sometimes used to supplement refrigeration during transit.
Citrus:						
Grapefruit.....	58-60	85-90	50		4-6 weeks	Curing for 3 days at 70°F sometimes used to counteract low temperature breakdown.
Lemon.....	58-60	86-88	58	29.4	1-4 months	Storage at 32-40°F is possible if market period is less than 1 month. Cure at 72-78°F and 85-90 per cent RH for 6-10 days. Ventilation needed to remove ethylene and other volatiles.
(immediate marketing).....	(32-40)					
Orange.....	38-44	85-90	37	29.7	3-6 weeks (3-4 weeks)	
(Some Valencia).....	(48)					
Tangerine and other						
Mandarins.....	32	85-90		30.1	2-4 weeks	Some varieties chilled at 32°F.
(some varieties).....	(38)					

(table continues)

TABLE 1—*Concludes*

Commodity	Ideal holding temperature	Relative humidity	Chilling temperature	Highest freezing temperature	Maximum life	Comments
Corn.....	32	90-95		30.9	Few days	Chill quickly and thoroughly to prevent conversion of sugar to starch.
Cucumber.....	45-50	90-95	50	31.1	2 weeks	Waxing used to reduce weight loss.
Eggplant.....	45-50	90	50	30.6	1 week	Waxing used to reduce weight loss.
Figs, fresh.....	31-32	90-95		27.6	1 week	
Garlic, dry.....	32	65-70		30.5	6-7 months	
Grapes.....	30-31	95		28.1	1-6 months (varietal)	Periodic fumigation used for disease control.
Greens, leafy.....	32	95		32	Few days to 2 weeks	Freezing point very close to 32°F for some types of greens. Should be cooled quickly and thoroughly.
Horseradish.....	30-32	90-95		28.7	10-12 months	
Kohlrabi.....	32	90-95		30.2	2-4 weeks	
Leeks, green.....	32	90-95		30.7	1-3 months	
Lettuce.....	32-33	95		31.7	2-3 weeks	Vacuum cooling generally used for prompt removal of field heat.
Melons:						
Casaba.....					4-6 weeks	
Crenshaw.....	45-50	85-90	45-50	30.5	2 weeks	Hold partially ripe melons above 50°F.
Persian.....					2 weeks	
Honeydew.....	45-50	85-90	45	30.3	3-4 weeks	Gas with ethylene at temperature above 65°F for ripening. Gassing time depends upon initial maturity.
Cantaloupe.....	32-40	85-90	40	29.9	1-2 weeks	Storage temperature of honeydew & cantaloupe depends on maturity and length of storage. Chilling possible below about 40°F.
Watermelon.....	40-50	80-85		31.3	2-3 weeks	
Mushroom.....	32	90-95	40	30.4	5 days	
Onion, dry.....	32	65-70		30.6	1-8 months	Market life depends on variety and season. Cure with warm, moist air circulation until 3-5 per cent weight is lost.
Onion, green.....	32	90-95		30.4	Few days	Sensitive to chilling injury below about 50°F
Okra.....	45-50	90-95	50	28.7	7-10 days	
Olives.....	45-50	90	45	29.4	4-6 weeks	
Parsley.....	32	90-95		30.4	1-2 months	
Parsnips.....	32	90-95		30.4	2-6 months	
Peach and nectarine.....	32	95		30.4	2-4 weeks (varietal)	Handle like carrots. Internal breakdown can occur at 36-50°F. Ripen at 65-70°F.

Peas, green.....	32	90-95		30.9	1-2 weeks	tions. Very low solids pears (9 per cent solids) may be damaged at 29-30°F. Controlled-atmospheres may extend storage. Ripen at 65-70°F.
Pepper, sweet.....	45-50	90-95	50	30.7	2-3 weeks	Prompt, thorough chilling needed to maintain sugar. Fresh peas keep better if unshelled.
Persimmon.....	40	90		28.1	3-4 months	Waxed to reduce water loss. Sensitive to chilling injury below about 50°F.
Plum.....	(30)-32	95		30.5	1-2 months	Storage life depends on variety, maturity and storage conditions. Ripen at 65-70°F. Only high solids, well-matured fruits can be held at 30°F.
Pomegranate.....	32	90		26.6	2-4 months	Market life depends on condition and curing. Cure 4-5 days at 70°F. Store in dark. Store cured potatoes at 40°F. Without curing, hold at 50°F. Hold chip potatoes at 70°F.
Potato: Early, immature.....	40-70	90	38-40	30.9	2-5 months	Cure 45-60°F and high RH for 10-14 days. Store in dark. Condition chip potatoes for 1-3 weeks at 70°F just before use. Behave about as early apples such as Jonathan and Grimes Golden.
Late, mature.....	38-40	90	38-40	30.9	5-8 months	Top before storage.
Quinces.....	31-32	90		28.4	2-3 months	Wax to reduce weight loss. Handle as topped carrots. Handle as topped carrots.
Radish.....	32	90-95		30.7	3-4 weeks	Cool rapidly and thoroughly.
Rhubarb.....	32	95		30.3	2-4 weeks	May be cured 10-20 days at 80-85°F.
Rutabaga.....	32	90-95		30.1	2-4 months	Chilling may occur if held more than 1 week below 45°F.
Salsify.....	32	90-95		30.0	2-4 months	Cure for 4-7 days at 85°F and 85-90% RH.
Spinach.....	32	90-95		31.5	2 weeks	Ethylene sometimes used to ripen. Fastest ripening at 65-68°F. Slow ripening at 57-60°F.
Squash, winter and pumpkin	50-55	50-75	50	30.5	1-6 months (varietal)	Quality reduced on fruit held at 32-35°F. Top for extended storage. Store as topped carrots.
Squash, summer.....	32 or	90	(45)	31.1	1 week	
Sweetpotato.....	45-50	90			2 weeks	
Tomato: Mature green.....	55-60	85-90	55	29.7	4-6 months	
Firm ripe.....	55-70	85-90	50-60	31.0	2 weeks	
Turnip.....	45-50	85-90	45-50	31.1	Few days (3 weeks)	
Turnip greens.....	(32-35)	90-95		30.1	4-6 months	
	32	90-95		31.7	2 weeks	

TABLE 2
REFRIGERATION NEEDED TO ABSORB HEAT OF RESPIRATION*

Produce	Tons refrigeration per ton produce†				
	Produce temperature (degrees F)				
	32	40	60	70	80
	<i>tons</i>				
Apples.....	0	0-0.01	0.01-0.02	0.01-0.03	—
Apricots.....	—	0.01-0.03	0.03-0.05	0.05-0.10	—
Artichokes.....	0.02-0.03	0.03-0.05	0.07-0.11	0.11-0.18	0.12-0.23
Asparagus.....	0.02-0.05	0.04-0.08	0.09-0.18	0.13-0.20	0.28-0.36
Avocados.....	—	0.02-0.03	0.05-0.12	0.06-0.26	0.09-0.33
Beans, snap.....	0.02-0.03	0.03-0.04	0.11-0.15	0.16-0.18	—
Beets, topped.....	0.01	0.01	0.02	—	—
Broccoli, sprouting.....	0.01-0.02	0.03-0.12	0.13-0.26	0.21-0.26	0.43-0.67
Brussels sprouts.....	0.02	0.02-0.04	0.05-0.10	0.07-0.13	—
Cabbage.....	0	0.01	0.01-0.02	0.02-0.04	0.04-0.05
Cantaloups.....	0	0.01	0.03	0.03-0.05	0.05-0.06
Carrots.....	0.01-0.02	0.01-0.02	0.02-0.04	0.04-0.07	—
Cauliflower, trimmed.....	0.01	0.01-0.02	0.03-0.04	0.06-0.07	0.06-0.11
Celery.....	0.01	0.01	0.03	0.05	—
Cherries, sweet.....	0	0.01	0.02-0.03	0.03	—
Corn, with husks.....	0.02-0.04	0.03-0.06	0.12-0.13	0.20-0.24	0.22-0.33
Grapefruit.....	—	0	0.01	0.01-0.02	0.02
Grapes.....	0	0	0.01	—	0.02
Honeydew and watermelon.....	—	0	0.01	0.01-0.02	0.02-0.03
Lemons.....	—	0-0.01	0.01-0.02	0.01-0.02	0.02
Lettuce, head.....	0-0.01	0.01-0.02	0.02-0.03	0.04-0.05	0.06-0.07
Lettuce, leaf.....	0.01-0.02	0.02-0.03	0.04-0.06	0.06-0.09	0.09-0.13
Oranges.....	—	0-0.01	0.01-0.02	0.02-0.03	0.02-0.03
Peaches.....	0	0-0.01	0.02-0.03	0.05-0.08	0.06-0.09
Pears, Bartlett.....	0-0.01	0-0.01	0.01-0.05	0.02-0.05	—
Plums.....	0	0-0.01	0.01	0.01-0.02	0.02-0.05
Potatoes, immature.....	—	0.01	0.01-0.02	0.01-0.03	—
Potatoes, mature.....	—	0-0.01	0-0.01	0.01	—
Strawberries.....	0.01	0.01-0.03	0.05-0.07	0.08-0.15	0.13-0.16
Tomatoes, mature green.....	—	0-0.01	0.01-0.02	0.02-0.03	0.03-0.04
Tomatoes, ripening.....	—	0	0.02	0.02-0.03	0.02-0.04

* Adapted from test reports. Reports vary widely because of varieties, growing conditions, maturity and treatment since harvest. 0 indicates less than 0.005; — indicates no data.

† The values shown here are the tons of refrigeration required to absorb the heat of respiration only. To convert these values to heat released by the product (as Btu per hour), multiply value shown by 12,000.

TABLE 3
ROOM COOLING AND HYDROCOOLING TIMES, USING DIFFERENT CONTAINERS
AND DIFFERENT PACKING METHODS AND STACKING PATTERNS*

Produce	Room cooling		
	Container, packing method, and stacking pattern	Seven-eights cooling times***	
		Average	Slowest
Apples.....	Unpacked, wood boxes in pallet loads†	—	2-3.3 days
	Packed, wood boxes in pallet loads†	—	6-8 days
Artichokes.....	In corrugated containers‡	24 hours	—
Grapes.....	In wood lugs, stacked solid on pallets§	—	30 hours
Nectarines.....	Packed in plastic tray pack containers stacked on pallets. Air velocity 400 fpm	—	—
	Wood container 20.5 per cent side vent area	—	12 hours
	Corrugated containers 10-13 per cent side vent area	—	12 hours
	Corrugated container 6 per cent side vent area	—	12 hours
	Corrugated container 1.9-3.4 per cent side vent area	—	27 hours
Pears.....	Forty-eight pounds in wood box, both wrapped and unwrapped, on pallet¶**	2.5 days	3-4 days
	Forty-eight pounds in non-vented, partial telescope corrugated container, on pallet	—	4 days
	Tight-fill in 12" x 18" x 10" high telescope container, 36 lb. two 1½" holes in each side, cross-stacked§‡¶	—	—
	54 containers per pallet ½" space between sides	2.5 days	4-6 days
	48 containers per pallet 3½" space between sides	2 days	3.6 days
	Tight-fill, 36 lb, cross-stacked 3½ per cent side vent, 1" spacing between containers¶	16 hours	23 hours
	Tight-fill, 36 lb, cross-stacked 5 per cent side vent, no space¶	24 hours	40 hours
	LA lug, 24 lb¶	16 hours	20 hours
	Wrapped in LA lug size corrugated container, 24 lb.¶	30 hours	39 hours
Plums.....	Tight-fill in 11" x 17½" x 8" high corrugated containers, 28 lb. cross-stacked on pallet	—	—
	No vent and no spacing between containers, cross-stacked¶	—	84 hours
	Four per cent vent area, 1" spacing between containers, cross-stacked	—	22 hours
	Four per cent vent area, no spacing, register stacked	—	18 hours
	Single 4-basket crate, 2 sides exposed§	—	27 hours
Fruit in 47" square bins			
Oranges.....	Twenty-four inch deep bin, no side vent**	33 hours	—
	Thirty inch deep bin, no side vent	45 hours	—
Plums.....	No side vents 24" deep††	—	24-46 hours
	Six ¾" x 16" slots on each side	—	23-40 hours
	Perforated metal bin ½" holes on 1" centers	—	18-33 hours
	Six ¾" x 16" slots on each side	—	20-32 hours
Hydrocooling			
Asparagus.....	In bunches immersed in flowing water‡‡	6 minutes	—
Cantaloupes.....	In bulk in commercial hydrocooler§§	45-60 minutes	—
Peaches.....	In 47"-square bins, 2' deep. Water showered in 150 gallons per minute per bin**	—	—
	Free drainage from slots in bottom	30 minutes	—
	Bin bottom with 10 1" holes allowed bin to fill	24 minutes	—
	In commercial hydrocoolers	33 minutes	42 minutes
Pears.....	150-size Anjou in open lug, water spray 4 gallons per minute per foot§	42 minutes	51 minutes
Sweet corn.....	In wirebound crates, immersion¶¶	—	—
	No agitation	46-84 minutes	—
	Agitation	28 minutes	—
	In wirebound crates, water shower 5 gallons per minute per square foot, free drainage	45 minutes	—

* Temperatures of exposed produce or containers were reduced to ½ of their original elevation above a constant temperature coolant in approximate times shown.

† Reference: Sainsbury, 1961.

‡ Reference: Guillou, 1962-68.

§ Reference: Guillou, 1960.

|| Reference: Mitchell *et al.*, 1971.

¶ Reference: Mitchell and Parsons, 1970.

** Reference: O'Brien and Gentry, 1967.

†† Reference: Mitchell and Mayer, 1971.

‡‡ Reference: Pentzer *et al.*, 1936.

§§ Reference: Lipton and Stewart, 1959.

||| Reference: Toussaint, *et al.*, 1955.

¶¶ Reference: Perry and Perkins, 1968.

*** Times are approximate and are to be used only as guides. Small differences in containers, packing procedures or exposure to the coolant can affect cooling rates considerably. A dash (—) in either column indicates that information is not available.

TABLE 4
AIR FLOW RATES AND STATIC PRESSURE REQUIREMENTS TO FORCED-AIR COOL COMMON PRODUCE*

Air flow rate and static pressure needed for various cooling times										
Hours needed to seven-eighths cool downstream produce										
1.5	2	3	4	6	9	12	18			
Air flow rate (cfm/lb. produce) and static pressure (inches of water)†										
Type of produce, method of air flow, and type of container										
Containers placed three-deep and in register†										
Artichokes in corrugated containers, 9 per cent side-area vented.....										
Grapes in lidded paper-wood laminated containers, no bottom cleat.....										
Grapes in lidded paper-wood laminated containers, ¾" bottom cleat.....										
Grapes in full telescope, 17½" x 15" x 6" container, 5.8 per cent side-area vented.....										
Grapes in partial telescope 17½" x 14" x 6½" container, 3.5 per cent side-area vented.....										
Cantaloupes in corrugated containers, 6 per cent side-area vented.....										
Nectarines (or peaches) in corrugated containers with plastic trays, 6 per cent side-area vented.....										
Peaches (or nectarines) in plastic trays in lidded wood lugs, 20 per cent side-area vented.....										
Pears in 12" x 18" x 9½" high corrugated containers										
(a) 2 per cent side-area vented.....										
(b) 5 per cent side-area vented.....										
Plums in 11" x 17½" x 8" high corrugated containers, 4 per cent side-area vented.....										
Strawberries in open crates on pallets.....										
Tomatoes in corrugated containers 10 per cent side-area vented.....										
Air flow is vertical through slotted bin bottoms										
Oranges										
2 ft. depth.....										
3 ft. depth.....										
4 ft. depth.....										

Bulk bins (47 inches square); air flows horizontally through slots in bin sides					
Plums, 3 per cent side-area vented					
Average fruit.....	0.7 (0.9)	0.4 (0.25)	0.20 (0.07)	0.10	
Slowest cooling fruit.....		1.0 (1.8)	0.6 (0.7)	0.4 (0.3)	0.20 (0.12)
Plums, 5-6 per cent side-area vented					
Average fruit.....	0.6 (0.4)	0.3 (0.13)	0.17		
Slowest cooling fruit.....		0.8 (0.7)	0.5 (0.25)	0.3 (0.12)	0.20

* Based on calculations of seven-eighths cooling of produce. Figures compiled from laboratory and field data. References: Guillou, 1967; Mitchell, *et al.*, 1971; Parsons, *et al.*, 1970. 1972; Parsons, 1972; Wang and Tunpun, 1968.
 † Static pressure shown is for air path through three tiers stacked in register. For other stacking, multiply static pressure by: 1 tier, 0.05; 2 tiers, 0.3; 4 tiers, 2.3; 6 tiers, 7.0.
 ‡ Figures not in parentheses are flow rates needed to cool in time indicated. Figures in parentheses are pressures needed to force air through stack. Figures are approximate only—small differences in container venting and stacking patterns can cause large changes in static pressure losses.

Fig. 39. Relationship between velocity pressure and air velocity at 35°F.

Fig. 40. **A.** Four-basket crate; partially unpacked crate of plums showing components. **B.** Corrugated telescope container used for many commodities. **C.** Wire-bound crate used for corn, celery and other commodities. **D.** Strawberry crate containing 12 baskets; normally lidded only on top crate: **E.** Cantaloupe crate. Fruit hand placed without other packing material. **F.** Pear box for place-packed wrapped pears; top lid budge is normal.

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Fig. 41. **G.** Standard wood lug used for many commodities including peaches, nectarines, tomatoes, and pears; pear lug often unlidded. **H.** Nectarine plastic-tray pack in corrugated lug—2 layers. **I.** Plastic-tray pack components for container. **J.** Corrugated lug with inset panels for air circulation when stacked. **K.** Grape lug; top liner is tucked down sides before lidding. **L.** Paper-wood laminated lug used for grapes and other fruits.

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