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Cooling Methods for Broccoli
A Guide for Eastern Growers

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One of the selling points of locally grown broccoli is greater freshness. Delivering that freshness requires cooling the product close to freezing within hours of harvest and employing proper postharvest handling procedures. In eastern production, the availability of appropriate cooling is one of the most important requirements for a viable enterprise. Broccoli can be precooled by several different methods: vacuum cooling, hydrocooling, slurry icing (slush icing), forced-air cooling, top icing and room cooling. The appropriate method depends on specific constraints of the producer. This publication is intended to help the producer chose a method that best fits their constraints.

Cutting and field-packing broccoli. The cutting crew works in front of the mobile packing unit. Broccoli must be cooled as soon as possible after harvest to remove field heat and reduce respiration to optimize post-harvest quality. Photo: S.A. Sargent

WHY COOLING MATTERS

Broccoli must be rapidly cooled in order to deliver the quality buyers expect. The broccoli head, or crown, is made up of actively developing flower buds. Broccoli is best harvested when heads reach market size but are still firm and compact, with tightly closed, dark or bright green buds that show no signs of yellowing or discoloration. At this fast-growing inflorescence stage of development, broccoli has a high respiration rate (Toivonen and Forney, 2016) that continues after harvest and will cause a rapid deterioration in quality unless it is quickly cooled. The flavor and nutritional benefits of broccoli depend on preventing that burst of respiration that occurs in the hours immediately after harvest (Figure 1). The goal of rapid cooling is to lower respiration to preserve the flavorful sugars and healthy antioxidants that are quickly depleted at room temperature and above. The loss of sucrose and other nutrients occurs well before the harvested product begins to turn yellow. In fact, half to all of the sucrose in broccoli can be lost in about 6 hours if temperature is not maintained close to 32 °F (King and Morris, 1994; Downs et al. 1997; Page et al. 2001). Quickly lowering the respiration rate also slows toughening of the stalk and minimizes water loss, maintaining a firm crown longer.

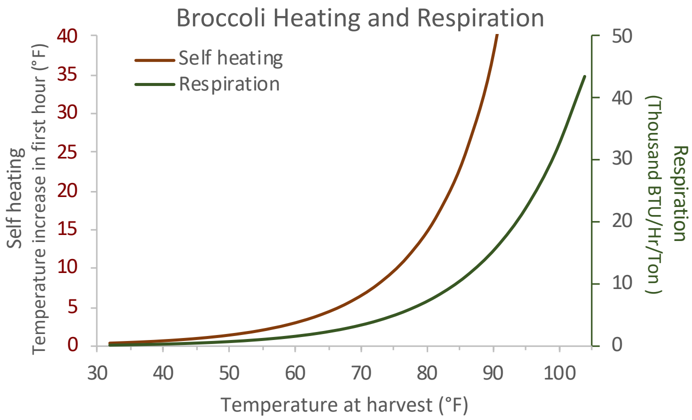

Figure 1. *Summer harvest requires harvesting while the broccoli is cool, and reducing the temperature quickly. Respiration by the uncooled product results in self-heating, raising the temperature even more. The rate of respiration also increases with temperature. This chart assumes harvest into containers and one hour travel time to the cooling facility.*

After cooling the broccoli close to the desired 32 °F storage temperature, it is also important to maintain that temperature in the cold chain until it reaches the customer. The cold chain is the unbroken series of practices that keep the cooled product continuously cold during storage and shipping to the final point of sale. For highest quality, relative humidity must be kept at 95 to 100 percent during handling and shipping operations. This will minimize moisture loss and resultant softening of florets (Figure 2).

Figure 2. *The packaging admonishes everyone handling this box to maintain the cold chain at 34 °F. Conventional measures used for other vegetables during storage and distribution are effective for broccoli.*

TEMPERATURE AND RESPIRATION

Broccoli is particularly sensitive to high field temperatures because it has a higher respiration rate than most vegetables. Respiration involves numerous enzymatic reactions, and the rate of these reactions is temperature-dependent. Within the normal ambient temperature range, the rate of respiration increases exponentially with increasing temperature. This relationship between temperature and respiration is described mathematically by the use of the temperature quotient (Q_{10}). The Q_{10} is how many fold respiration increases for each 10 °C (18 °F) rise in temperature. The Q_{10} value for many biological reactions, including respiration of many vegetables, is 2.0, that is, doubling. In contrast, the Q_{10} value for broccoli is much higher, with respiration increasing 3.8-fold. That high value means respiration is very high at field temperatures (Figure 1). Thus, it is very important to reduce the temperature of broccoli to as close to 32 °F as fast as possible to prevent loss of quality that occurs during prolonged exposure to higher temperatures once the head is cut from the plant (Forney and Rij, 1991; Wills et al., 1989).

Not only does harvested broccoli benefit from cold temperatures down to 32 °F, it is also very tolerant of contact with water and/or ice. Rapid cooling within an hour or two of harvest will result in an increase of more than two weeks of shelf life by minimizing water loss, softening, floret yellowing and toughening of the stem.

Broccoli quality decreases rapidly at temperatures above 32 °F. The respiration rate of broccoli at 32 °F is 19-21 mg CO_2/kg/hour and increases 10-fold at 70 °F. The time required to cool 1 ton of broccoli using 2 tons of refrigeration capacity when starting at different temperatures is shown in Figure 3. With a starting temperature of 70 °F, it takes 2.5 hours to decrease the temperature to 40 °F (Figure 3).

If the core temperature gets high enough, a 2-ton refrigeration capacity cannot lower the temperature of the broccoli. Respiration will cause the broccoli to get warmer while it is moved from the field to the packinghouse. In the field, broccoli has latent heat (field heat) resulting from the actual atmospheric temperature. It also has heat produced by respiration. As the starting temperature increases, refrigeration takes longer to remove the latent heat and reduce respiratory heat. This heating is one reason that summer harvest may only be possible early in the day. In this situation, large amounts of stored ice are necessary to provide the very high heat removal needed initially.

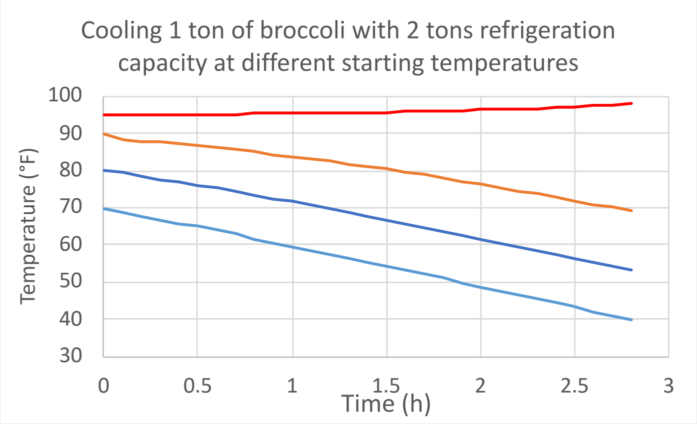

Figure 3. *If the starting temperature is too high, direct refrigeration may not be able to keep up. Time required to cool 1 ton of broccoli at four different initial temperatures using 2 tons of refrigeration. Each color represents a different starting temperature. These cooling times don't follow the 7/8 curve (discussed on page 4) because refrigeration, not heat transfer, is limiting.*

Minimizing Field Heat

Harvesting broccoli when it is cool, and keeping it cool, avoids the need for a lot of additional cooling, as shown in Figure 3. The first step is to harvest broccoli in the early morning after lower night temperatures have cooled it and removed much of the field heat and before sunrise results in field heat accumulation in the crowns. Second, it is helpful to make frequent trips from the field to the cooler to minimize produce warming. Third, using shaded areas for temporary field storage will reduce the accumulation of field heat by minimizing storage time in the open field, where temperatures are higher. Cooling should begin as soon as possible after the crowns arrive at the cooling facility. The higher the initial core temperature is at harvest, the greater the energy demand is for cooling the product to slow down respiration and prevent loss of quality (Figure 3).

COOLING OPERATIONS

To maximize the shelf life of highly perishable vegetables like broccoli, it is essential to remove the field heat and get the temperature close to 32 °F as quickly as possible. The rate of temperature decrease varies with the product being cooled, packaging, incoming core temperature, cooling method and cooling conditions. A rapid decrease in temperature does not damage broccoli; however, the cooling medium cannot be below the freezing point of broccoli (approx. 31 °F). If broccoli cannot be cooled to the desired 32 °F because of high temperatures or limited heat-removal capacity, the priority should be to remove most of the field heat. Getting the broccoli down to 45 °F or even 50 °F reduces the respiration rate significantly, and further cooling down to 32 °F could be achieved in cold storage. This approach may be useful when there are multiple incoming harvest lots over a short period of time. It is important to note, however, that the slower the cooling time, the faster moisture loss and degradation of nutrients will occur.

The most commonly used cooling methods include slurry icing, hydrocooling, forced-air cooling, vacuum cooling, top icing and room cooling. The speed of cooling varies among these cooling methods. Hydrocooling and vacuum cooling are more rapid than forced-air cooling with large volumes of air used per unit volume of product. Top icing and room cooling (with limited air movement) are slower and require longer cooling times. For a specific cooling system, the rate of cooling is determined by product temperature, cooling medium temperature and the product to be cooled.

The time required to cool a product may be estimated by the technique of half-cooling time. The half-cooling time is the time it would take to reduce the product temperature by half. Charts have been developed for most products using combinations of product and cooling-medium temperature to predict half-cooling times under different cooling methods, product size, packaging, and container type (Stewart and Couhey, 1963; Thompson et al., 2008). The thickness of the product influences the half-cooling time. The cooling time is faster if the medium moves through the head. For bunch cut, the stem is usually the thickest part, and slowest to cool (Figure 4).

Figure 4. *Broccoli is harvested as crown cut and bunch heads. Crown cut broccoli (a) typically has smaller spaces between the branches than bunch (b). If cold water and ice can get in those spaces, the heads cool down faster. (Photo: T. Björkman)*

For most products, it is necessary to decrease the core temperature to lower than one half of the difference between the starting product temperature and the initial coolant temperature. That temperature reduction can be achieved by leaving the product in the coolant until its temperature is reduced by half. It requires three half-cooling times to reduce the temperature of the product by 1/2, then 3/4, and finally 7/8 of the initial temperature (for example, 77 °F initial product temperature to cold room air temperature of 40 °F). This is often referred to as the 7/8 cooling principle (Figure 5). Of course, the time required and the actual temperature drop to reach 7/8 cooling varies with the initial product temperature, the product properties and the cooling conditions (container/packaging, initial product temperature, cooling system utilized, etc.). Cooling times for forced-air cooling, hydrocooling and slurry icing are shown (Figure 6).

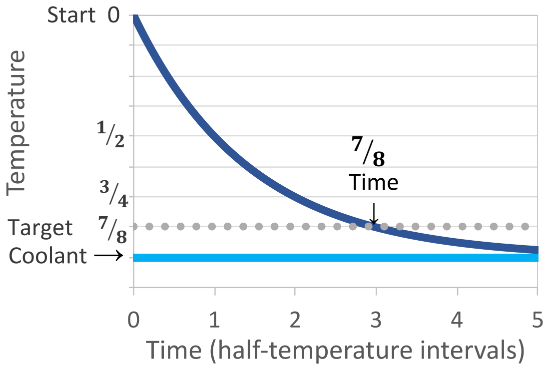

Figure 5. *An idealized cooling curve where the rate of cooling is limited by heat transfer from broccoli to the cooling medium. Three half-cooling times reduces the product temperature 7/8 of the way to the coolant temperature.*

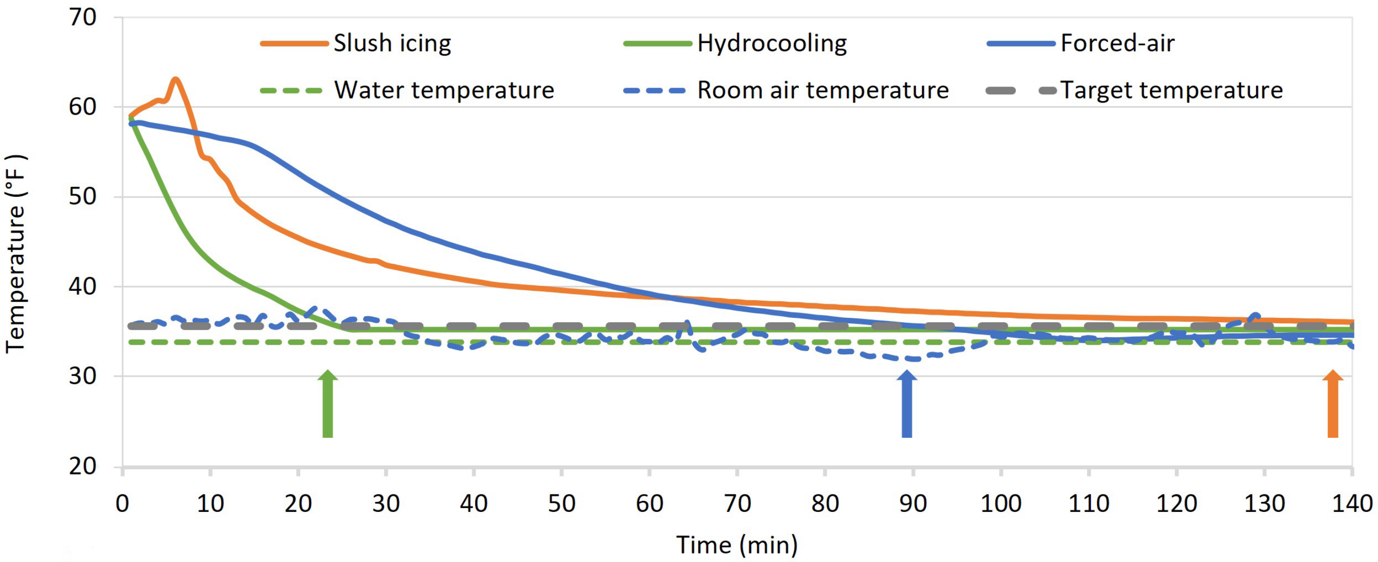

Figure 6. *Actual cooling curves for broccoli crowns using slush icing, hydrocooling or forced-air cooling. The broccoli started at 60 °F and was cooled with a medium at 34 °F to reach a target temperature that is 7/8 of the way to the medium temperature, that is 37 °F. Arrows indicate the time that the core of the broccoli reached the 7/8 temperature. The water for hydrocooling remained a constant 34 °F. The room air for forced-air cooling was set to be 34 °F, but the temperature was warmer at first because the refrigeration capacity limited heat removal from the air (Theodore, 2019).*

Containers/Packaging

The method and rate of cooling of broccoli depends on the packaging used. Therefore, coordinate the selection of harvest and shipping containers with the precooling, storage and shipping methods so that they are efficient and meet buyer requirements. Crown-cut broccoli (Figure 7) is typically packaged in 20-pound containers, which may be waxed, corrugated fiberboard cartons, plastic field lugs or reusable plastic containers (RPCs). Broccoli crowns are especially susceptible to mechanical damage during harvest and handling operations; therefore, caution is necessary to minimize drops/impacts into field containers and to ensure that the container isn't too deep, so as to avoid crushing of the crowns on the bottom layer. Bunched broccoli with stalks (Figure 8) is typically packaged in containers with 14-18 bunches per waxed corrugated fiberboard carton, weighing approximately 21 pounds.

Figure 7. *Crown-cut broccoli harvested into waxed container, cooled and shipped with ice. This box still contains some ice on arrival in the grocery store.*

Figure 8. *Bunched broccoli was once the standard, and remains a significant form in some markets. Photo: T. Björkman*

Crowns and bunches may be individually overwrapped with shrink-wrap film. To maintain quality, broccoli should be cooled to 32 °F before it is film wrapped. If applied in the field, the film will reduce contact of the coolant to the heads and increase cooling time. Florets (Figure 9), once cooled, are typically packed in either 10-pound or 5-pound film bags for food service and institutional markets or in 1- or 2-pound bags for consumers.

Forced-air cooling has fewer constraints on packaging because no water is used. However, the packaging must have enough ventilation for the air to be forced between the heads to efficiently cool the produce. Containers used for forced-air cooling should have approximately 5 percent sidewall vent area to accommodate adequate airflow (Wang and Tupin, 1968; Mitchell et al., 1971). Top icing, hydrocooling and slurry icing are water-based and need waterproof packaging to maintain durability during cooling (Boyette and Estes, 1992; Boyette et al., 1992; Thompson, 2016). Corrugated cartons are traditional; for water-based cooling they must be waxed, which prevents them from being recycled. For air or vacuum cooling the boxes don’t need wax but must have sufficient strength to maintain integrity in high relative humidity environments. Reusable plastic containers (RPCs) are water-tolerant and well ventilated. However, their adoption has been limited because they are difficult to sanitize, may be misplaced, and need to be backhauled. RPCs can be leased, which removes several barriers to use of these containers.

Figure 9. *Florets in 5-pound film bags are a common form for food-service use, and a standard in wholesale markets. Photo used with permission of Gold Coast Packing, Inc. Santa Maria, California.*

TYPES OF COOLING

Slurry icing

With slurry icing (slush icing, liquid ice), a mixture of water and ice flakes is either injected through vents or handholes without opening or removing packages from pallets (Boyette et al., 1989) or is poured on the top of the open container before sealing. The water has two functions: a) it maintains or stabilizes the temperature of the ice at 32 to 33 °F, so as to not freeze the broccoli, and b) it serves to distribute the ice throughout the carton. The slurry is injected within a matter of seconds, encasing the crop (Figure 10). Once injected, the cartons can be immediately loaded onto a refrigerated trailer and shipped. The ice cools the broccoli in about 140 minutes (7/8 cooling time), and the resultant water serves to keep the broccoli moist, minimizing water loss (Theodore, 2019). Slurry icing was long considered the best method for cooling broccoli (Cantwell and Suslow, 1999); however, large-scale producer-shippers are increasingly using forced-air cooling or hydrocooling for shipping long distances. Ice in shipping containers significantly increases the weight of a load; also, the melting water can be a potential food safety issue.

Slurry icing results in better distribution of ice in the packed carton than does top icing (see page 13), which leads to improved product cooling due to the increase in product contact. Slurry icing is an efficient method when large amounts of produce need to be cooled relatively quickly. The equilibrium temperature of the water-ice slurry is 32 °F. This method uses 11 to 28 pounds of ice per carton of broccoli (Thompson et al., 2008; Kauffeld et al., 2010), depending on how much ice needs to be in the box when it is shipped. While this method is considered one of the most effective at removing field heat, it may be more than what is required for producers who have customers within 12 hours of shipping time and don't need long-term temperature control from ice melt. Slurry icing was found to be the best method to reduce fresh weight loss and to preserve green color. It was also best at reducing yellowing, discoloration and shriveling when broccoli is cooled as compared to room cooling, forced-air cooling and even hydrocooling (Kochhar and Kumar, 2015). Broccoli cooled with slurry icing can be stored for 18 days with stalk or up to 15 days without the stalk (Kochhar and Kumar, 2015).

Figure 10. *Slurry icing encases broccoli in ice. The box is full immediately after icing (bottom). After shipping, some of the ice remains (top). The amount of ice remaining in the box can be regulated by changing the proportions of ice and water. Individual ice particles are so small that they are distributed within each head, as well as around it. This method provides very rapid precooling because of the good contact. Simply top icing can look similar but the uneven distribution makes it ineffective for precooling broccoli. Photo: C. Theodore*

To accomplish slurry icing, the ice must be finely ground into water in a mixing tank, and the proportion of ice to water adjusted to produce the desired temperature drop and residual ice. There are three methods for applying slurry ice to broccoli.

1. Single, open-top containers on a conveyor belt pass beneath a stream of ice slurry, rapidly filling while turbulence mixes ice with the heads (Figure 11). The water drains after the box has moved past the filler, which increases throughput, and the containers are palletized.

Figure 11. *Slurry icing reusable plastic containers. The proportion of ice in the slurry can be varied depending on how much cooling and residual ice are needed. The cold water is sanitized and reused. Photo: T. Björkman*

2. Palletized containers receive a mixture of water and ice pumped from a hose into the openings of each container (Figure 12). This method is fast, effective and does not require opening any of the containers or removing them from their pallets. On average, two workers can add slurry to a pallet of 30 containers of broccoli in about five minutes (Boyette and Estes, 1992). Such a system costs $100,000 to $200,000.

Figure 12. *Manual slurry icing of palletized cartons. Photo: S.A. Sargent*

3. An automated slurry-ice method involves placing one or several pallets of broccoli in an enclosed container (Figure 13) that is rapidly filled with a slurry of water and ice and then drained, leaving excess ice (Figure 10) in the cartons of broccoli (Boyette and Estes, 1992). This method, which requires the use of a clamshell cooler, can be accomplished by one worker. The clamshell cooler has a very high capital cost (greater than $500,000) and is mainly used at facilities that cool many truckloads a day.

All of these systems require large quantities of ice, which is typically made on-site with mechanical ice makers and ice storage bins.

Figure 13. *Pallet slurry icing of broccoli packaged in waxed cartons. Used with permission of Cool Jet Pty Ltd. (Source: http://www.postharvest.net.au/postharvest-fundamentals/cooling-and-storage/cost-of-cooling-a-case-study-with-broccoli).*

Hydrocooling

Hydrocooling also uses water and ice to remove heat. The initial investment in hydrocooling is higher than for slurry icing, but the energy use is much more efficient. Since the water is recirculated, it must constantly maintain sanitary conditions to minimize cross-contamination of crowns with microbes that cause decay or human illness. (See details in Food Safety sidebar on page 10.) Packages used in hydrocooling must allow vertical water flow and tolerate water contact (Thompson, 2016). Corrugated fiberboard dipped in wax is popular, as are reusable plastic containers and plastic bins. Wood containers are not recommended because they cannot be sanitized adequately to prevent cross contamination and are not recyclable.

Hydrocooling flows chilled water over produce via shower or immersion, rapidly removing heat (Thompson, 2016). The 7/8 cooling time is determined by the thickest part of the product, which is the stalk. For hydrocooling, the 7/8 cooling time is about 20 minutes, or about five times faster than forced-air cooling (see page 1). Hydrocooling has the capacity to cool large amounts of broccoli quickly, which is attractive for large-scale producers as it can allow for greater harvesting and marketing flexibility. However, it is only 20 to 40 percent as energy-efficient as vacuum cooling or forced-air cooling.

Types of hydrocoolers:

Continuous hydrocoolers allow produce in bins or cartons, moving at a rate of approximately 1 foot per minute, to pass along a conveyor under a shower of chilled water with flow rates as great as 200 gallons per minute (Thompson et al, 1998).

Batch hydrocoolers are enclosed and do not have conveyors (Figure 14); instead, bins or cartons on pallets are placed into the enclosure where large quantities of chilled water are flooded over the top, collected at the bottom, re-cooled and recycled. Depending on the model, one to eight pallets can be cooled at a time. These are generally smaller and have a lower initial investment cost than conveyor units; however, this design can cause non-uniform cooling.

Immersion hydrocoolers are large, shallow, rectangular tanks that hold moving chilled water. Crates or boxes are loaded into one end of the tank and moved by a submerged conveyor to the other end where they are removed. Crushed ice or vapor-compression refrigeration systems cool the water, while a pump is used to move the water. Immersion hydrocooling is nearly twice as efficient at cooling broccoli as conventional shower hydrocooling, as measured by the amount of heat removed per unit of energy used. (Thompson et al., 2002).

Figure 14. *Palletized field lugs cooling in a shower hydrocooler. Photo: S.A.Sargent.*

FOOD SAFETY REQUIREMENTS

The following discussion about agricultural water — specifically, agricultural water used during harvest, packing and holding activities — is informed by the Produce Safety Rule of the 2015 Food Safety Modernization Act (FSMA PSR) (www.fda.gov/food/guidanceregulation/fsma/ucm334114.htm). Ice as agricultural water is covered under Subpart E (note that compliance dates have been extended). Sample testing is discussed at 21 CFR §112.44, and a discussion of recirculated water can be found at 21 CFR §112.48.

Broccoli is often hydrocooled or iced to remove field heat and maintain temperature in storage and transport. Water used for precooling, for making ice or slurries; or for washing broccoli, hands or food contact surfaces is considered agricultural water. Agricultural water used during harvest, packing and holding must be safe and of adequate sanitary quality. Water sources should be tested to confirm they have no detectable generic *Escherichia coli (E. coli)* in a 100 milliliter (mL) sample (21 CFR §112.44) and to rule out any other hazards of concern (for example, chemical contaminants).

Ice used in postharvest cooling is also agricultural water and is thus subject to requirements of the FSMA PSR. Accordingly, machines, bins, tools and any other surfaces the ice contacts must be clean prior to use and regularly cleaned and sanitized as part of an established sanitation program.

Water that is used for hydrocooling or ice slurries is often recirculated, passing through multiple cartons of broccoli before being discharged. Recirculation introduces the risk of cross-contamination by both plant and human pathogens. Therefore, recirculated water must be managed to ensure it is safe and sanitary (21 CFR §112.48). Keeping the water sanitary requires several steps. First, change the water on an established schedule. Monitor the water visually for build-up of organic material. Maintain constant sanitary conditions by using an FDA-approved sanitizer labeled for this use. The cut end of the broccoli stalk is particularly susceptible to infection by bacteria and other pathogens. Maintain and monitor the water temperature to minimize infiltration of microorganisms into the broccoli. These efforts will reduce the risks not only from human pathogens but also from plant pathogens, often resulting in better shelf-life.

The water used to clean food-contact surfaces is also agricultural water and must also be safe and sanitary. Proper cleaning of surface involves all of the following steps:

- Rinsing to remove loose soil.
- Scrubbing with a detergent to loosen remaining soil.
- Rinsing with water to remove soil and detergent.
- Sanitizing with an approved anti-microbial solution (sanitizer), following the label.
- Drying (often air drying).

FSMA PSR guidance outlines the expectation that food contact surfaces be visually clean prior to use — in this case, prior to contact with fresh produce. Those surfaces include harvest knives, worker hands, boxes, reused containers, conveyors, slurry tanks, ice machines, shovels, etc.

Broccoli cooled in hydrocoolers loses less physiological weight and green color than room- or forced-air cooled broccoli (Kochhar and Kumar, 2015). Also, hydrocooled broccoli yellows, discolors and shrivels less than broccoli cooled with room or forced-air cooling. Similar to slurry-iced broccoli, hydrocooled broccoli can be stored at 32 °F for 18 days with stalks and 15 days as crowns (Kochhar and Kumar, 2015). One of the main negative aspects of hydrocoolers is the inconsistency of cooling within poorly vented crates or cartons (Boyette and Estes, 1992).

Some hydrocoolers use salt in the cooling solution so that it can be held near 32 °F without icing up. However, salt must be used with caution on broccoli because it can corrode equipment, dehydrate the broccoli and will freeze the broccoli if the solution is colder than 31 °F (Thompson et al., 1998). Food grade salt must be used for this purpose (James and James, 2014).

Forced-air cooling

Forced-air cooling uses high velocity, refrigerated air as the cooling medium, drawing it through produce packed in cartons or crates. The 7/8 cooling time is about 90 minutes (Figure 6). Forced-air cooling can be added to most cold room facilities with a relatively small investment in high-capacity fans (Callahan and Chamberlin, 2018), although additional refrigeration capacity may have to be added to accommodate the higher cooling demand. If the room refrigeration system cannot maintain the setpoint for air temperature, more refrigeration capacity is necessary.

Forced-air cooling is the most common method for removing field heat from produce. It is adequate to bring the temperature to 40 to 48 °F, with the remaining heat being removed over time during subsequent storage at 32 °F, which is the target for broccoli. Simply reducing the temperature setpoint below 32 °F in the cold room does not work because ice will cover the cooling coils. To further increase the shelf life, another technology can be used to remove that heat more rapidly before storage.

Tunnel cooling is the most common type of forced-air cooling (Figure 15). It consists of two rows of packages, bins or pallets arranged in parallel to form an air-return channel (Thompson et al., 1998). A tarp is placed over the top of the two rows, forming the tunnel. A fan at the rear of the tunnel pulls air from the tunnel, reducing the pressure and in turn drawing air through vent openings in the produce containers along the sides of the tunnel. This method is effective for cooling larger batches of produce. Tunnels typically have between four and 24 pallets of product, although the longer the tunnel, the more likely there will be lower airflow rates moving farther from the fans. The variable airflow rates along the tunnel create nonuniform cooling within the load. Forced-air cooling is moderately efficient, removing 1.5 times as much heat as the energy used for cooling. Typical cooling times are 1 to 2 hours, depending upon the room temperature.

Figure 15. *Forced-air or tunnel cooling. Top: Tunnel formed by pallets in cold room. Bottom: Tarp lowered to cover tunnel; yellow arrows indicate airflow through sides of pallets. Photo: S.A. Sargent*

A **cold wall system** (Figure 16) is useful if cooling too few pallets to build a tunnel. This method requires more space and labor than tunnel cooling because each pallet is cooled individually. A cold wall is built by placing individual pallets or stacks of packages in front of the opening in a negative-pressure plenum wall (Thompson et al., 1998). The plenum wall has lower pressure in the space adjacent to the cold-storage room, which causes cold air to move across the product and into the adjacent space. From there it is recirculated back to the refrigeration coils and re-cooled. Air is pulled through the stack into the opening.

Figure 16. *Cold wall with several single pallet cooling bays. Photo: S.A. Sargent*

Optimizing Air Flow in Forced Air-Cooling Systems

Forced-air cooling time is controlled by volumetric airflow rate and product diameter. The airflow rate is typically 100 to 400 cubic feet per minute (cfm) per ton of product (Flockens and Meffert, 1972; Gan and Woods, 1989). Containers used for forced-air cooling should have approximately 5 percent of the total sidewall area as vent (open space) to accommodate sufficient airflow (Wang and Tupin, 1968; Mitchell et al., 1971). Forced-air cooling has a lower capital cost than other methods for facilities that already have cold storage. Forced-air cooling causes more water loss, yellowing and shriveling to broccoli than hydrocooling or package icing (Kochhar, 2015). In-room humidifiers can reduce moisture loss by maintaining 90 to 95 percent relative humidity.

Hydrovac cooling

Figure 17. *Vacuum chamber for four pallets. The vacuum pump and mechanicals are on the left, the chamber on the right. The whole unit can be shipped on a flatbed trailer. Used with permission of Quik-Cool Australia Pty Ltd.*

Vacuum cooling (Figure 17) is the process of placing broccoli into a hermetically sealed, metal container and removing much of the air to reduce the pressure in the container. It is the fastest and most energy-efficient cooling method (Wang and Sun, 2001). The low pressure reduces the boiling point of water to below room temperature, causing it to rapidly vaporize (Thompson et al., 1998). This vaporization results in evaporative cooling that lowers the broccoli temperature. Broccoli will wilt from that loss of water, so a small amount of additional water needs to be supplied. When water is added to vacuum cooling, the process is called hydrovac cooling**.** Evaporative cooling causes a water loss of 1 percent per 10 °F cooled (Barger, 1963), but broccoli can only lose 2 percent of water to be remain marketable.

Hydrovac cooling does not follow the usual cooling curve because the rate depends on evaporation of water rather than heat transfer. While this method does not have a 7/8 time, a comparable 40 °F reduction takes about 30 minutes. The water evaporation rate depends on how quickly the vacuum pump removes water vapor (Sun and Zheng, 2006). A typical setup will cool the product 1 to 2 °F per minute. Vacuum pumps typically reduce the internal pressure to 4.6 mmHg, causing water to vaporize. The process of changing from the water phase to gaseous phase removes heat from the crop. If held at 4.6 mmHg long enough, broccoli can cool all the way to 32 °F (Thompson, 2016). Broccoli pre-cooled to 42 °F with this method can then be stored at 32 °F for up to 15 days (Boonprasom and Boonyakiat, 2010).

Hydrovac cooling is spatially uniform, which is an advantage over methods where ice or flowing cold water does not reach the center of the container or broccoli head. Vacuum cooling is energy efficient, removing 1.5 to 2.5 times as much heat per energy used as room cooling (Thompson et al., 2002) or about 0.2 kWh per carton. The capital cost of the equipment is high (Boyette et al., 1989; Thompson, 2016), but trailer-mounted units can be leased for the growing season on the East Coast. The units come in capacities of six or 24 pallets.

ICE *VERSUS* DIRECT REFRIGERATION AS A COOLING SOURCE

Removing field heat requires around 1 ton of refrigeration per ton of product if the broccoli is cooler than 65 °F. However, the high respiration rate of summer-harvested broccoli can strain the capacity of the refrigeration unit. For example, if the broccoli has reached 100 °F, just offsetting the increased heat from respiration requires 2½ tons of refrigeration (30,000 BTU/h, using 8 kW of power.)

Ice can be valuable as a source of cooling because it can provide the very large cooling capacity needed initially in removing field heat. It can be made continuously on site and stored, or purchased. As a general estimate of ice needs for cooling summer broccoli, 2 tons of ice are required per ton of broccoli cooled. Ice is required for slurry icing as previously discussed and is commonly used in top-icing for many crops, including broccoli. Ice can be purchased in either block-ice form or as chips or flakes. Chip or flake ice makers are more energy efficient and require less labor than block ice-making equipment. However, chipped or flaked ice is less easy to transport than block-ice; therefore, large-scale growers may prefer to install their own ice-making equipment depending on their production size (Boyette and Estes, 1992). If it is less expensive for growers to buy block ice, they can also purchase ice crushers to facilitate the production of smaller pellets of ice for slurry. Chips should be no larger than 3/8 inch so that they can penetrate voids between the broccoli heads (Boyette and Estes, 1992).

Purchased ice can be a practical alternative to on-site icemaking or additional refrigeration. If a great deal of cooling is required only on a few days a year, that cooling can be supplied with purchased ice stored in an insulated room on the farm. Growers close to a supplier of flake ice can take advantage of that option. Sanitary conditions must be maintained as previously described.

Top Icing

Top icing for broccoli involves putting 2 to 4 inches of crushed ice on top of the broccoli in each box (Figure 18). This can be performed by hand or by machine, depending on operation size (Thompson et al., 2002). While top icing is the simplest icing approach, it has significant drawbacks. Because the heat transfer to the broccoli in the bottom of the box is low, 7/8 cooling cannot be achieved with this method. Is should therefore only be used on pre-cooled produce. Ice alone can freeze the top crowns because broccoli freezes at 31 °F whereas the ice may be at 20 to 25 °F. Both problems are avoided by using an ice-water slurry.


Top Icing – must be tolerant to freezing temps

Figure 18. *Top icing, although somewhat effective for maintaining cooled crops, should not be the primary cooling method. Photo: S.A. Sargent*

Figure 19. *Flaked ice being blown on top of the cold crop as it is loaded into the refrigerated trailer. Photo: S.A. Sargent*

Top icing provides inconsistent cooling, being effective mostly with the top layer of broccoli, but not deeper in the package (Boyette and Estes, 1992). Heat transfer is inefficient, so broccoli heads that are at summer field temperature (greater than 80 °F) and not in direct ice contact may not cool at all. Some initial cooling can be achieved by adding ice weighing 20 to 30 percent of the produce weight (Thompson et al., 2002) and having the meltwater cool the lower layers of broccoli.

The best use of top icing is to keep the broccoli cold and hydrated once it has been cooled to below 40 °F. Pre-cooled broccoli can be stored up to two to three weeks with top-ice cooling that maintains 32 °F. Many receivers are accustomed to seeing a considerable amount of ice in the carton, which is the practice when it is transported long distances. Other receivers want no ice at all because the meltwater is a slipping hazard for personnel in the storage area and potentially a food safety hazard. Flaked ice is also sprayed onto the tops of palletized products as they are being loaded into the refrigerated trailer, principally to maintain high relative humidity during transport (Figure 19). For general reference, it takes a 30-ton machine to produce 10 tons of ice in 8 hours. Growers should contact manufacturers for more exact information on equipment and operation costs for their ice needs.

Room cooling

The least efficient cooling method for broccoli is room cooling. It is used when other cooling methods are unavailable or when demand on the cooling equipment is so high that there is not time to bring the temperature below 40 °F. However, room cooling takes a very long time to cool broccoli. Room cooling occurs when produce at ambient temperature is placed in an insulated room equipped with refrigeration units to chill the air with evaporator coils and fans (Thompson et al., 2002). The 7/8 cooling time is over 12 hours. Therefore, this method is not effective for removing field heat from broccoli. Broccoli loses water, becomes yellow and shrivels faster with room cooling than other methods (Kochhar and Kumar, 2015). Broccoli will become limp with as little as a 2 to 4 percent loss of water (Hruschka, 1977; Hardenburg et al., 1986).

Room cooling requires conditions in addition to a low air temperature. Humidity should be maintained at 90 to 95 percent to prevent excessive water loss. Water can be resupplied to maintain humidity using misting nozzles putting water into the air above stored broccoli (Figure 20). Refrigeration units with large evaporator coils are necessary to allow operating near freezing without removing humidity or icing up (Boyette et al., 1989). The energy efficiency depends on how well the roof, walls and floor are insulated. In warm seasons, a poorly insulated floor can be a major energy cost (Ekman et al., 2016).

Mobile room coolers can be made from insulated trailers for small quantities (10 to 40 boxes) by modifying the temperature controller of the existing air conditioner with a device such as a Coolbot (storeitcold.com). This method can maintain a cold temperature, but is not suitable for removing field heat (Perkins-Veazie, 2012).

Room cooling requires 2.5 cubic foot refrigerated storage space for each 1.18-bushel container. To facilitate adequate air distribution throughout the room, ceiling height should be at least 18 inches above the highest stacking height intended for storage. The floor space should include 25 percent of total floor space for aisles and walkways, and 6 inches between produce containers and walls.

Figure 20. *Room cooling of broccoli. Note the mist nozzle above the broccoli. Some growers add mist nozzles to their cold room to minimize dehydration.*

Energy efficiency

The cooling methods vary widely in how efficiently they use energy to remove field heat. A large inefficiency is the icemaking process. A second inefficiency is that only a small proportion of the heat transfer is from the broccoli. Other losses include heat transfer into the building, respiration by broccoli that is cooled slowly and loss of cooled water. When considering alternatives for a new facility, it is worthwhile to estimate the energy cost with the specific equipment being considered, and to investigate energy-efficient engineering solutions that are appropriate to the site. Other scenarios showing how widely the energy use can vary depending on how the infrastructure is configured are described by Junge et al., 1986 and Ekman et al., 2016.

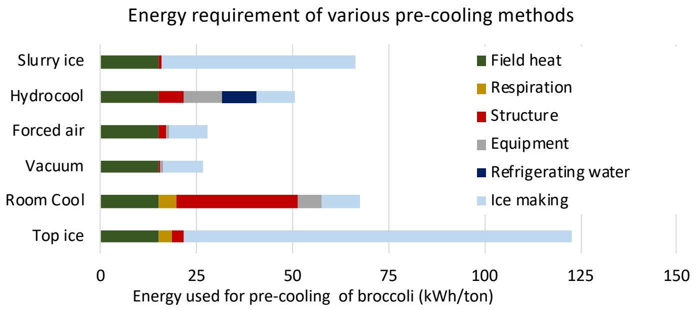

Figure 21. *The energy requirement for precooling varies widely, with the inefficiencies coming from various sources. The energy for removing the field heat itself (green) is the same for every technology and depends only on the starting temperature. The remaining energy heats or cools other things, such as the building, the surrounding air and soil, discarded cold water or ice.*

The approximate cost of cooling can be calculated from the local price of electricity. At a typical cost of $0.20/kWh, the energy cost can range from $5 to $25 per ton. Adapted from Ekman, 2017 with current assumptions.

Recommendations

- Cooling is necessary to maintain quality for highly perishable crops including broccoli.
- The best cooling method for any particular grower depends on the volume of broccoli harvested (small-, medium- or large-scale), distance to market (near or far) and funding available for equipment and upkeep. Figure 21 compares the energy costs of the various cooling methods.
- Packaging needs to be suited to the cooling method.
- The faster broccoli reaches reach 40 °F, the longer the quality of broccoli will be maintained in cold storage.
- Cooling times are available in tables in Couey (1963).
- Room coolers will be necessary for storage regardless of cooling method if there is a delay in shipping after harvest. Cold rooms should be kept at 32 °F and 95 percent relative humidity for preserving quality of the broccoli for up to 28 days. Storage life is shortened by as much as 14 days if coolers are at 41 °F (Cantwell and Suslow, 1997; Le Strange et al., 2010).
- Most packing facilities maintain storage at 32 to 33 °F, whereas retailers maintain their produce storage at close to 40 °F.

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