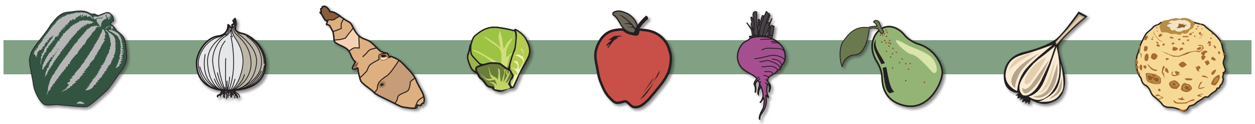
A4105

On-Farm Cold Storage

of Fall-Harvested Fruit and Vegetable Crops

PLANNING – DESIGN – OPERATION



Scott A. Sanford and John Hendrickson

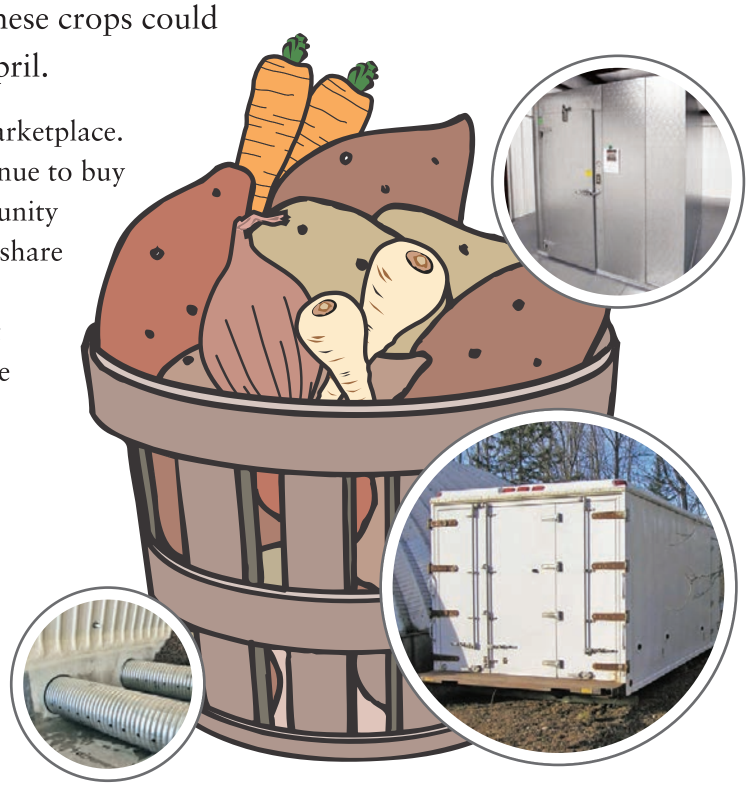
Winter crop storage can increase income and profit for growers by extending the marketing period for crops beyond harvest. Market potential for winter storage crops is large and growing. Demand for local (and organic) produce continues to outpace supply, and some food-conscious consumers are matching their diet to the seasonal availability of produce.

Many avid local food buyers lament the lack of local produce in co-ops and retail stores from December through April. Produce buyers indicate they would stock local produce if it were available.* The demand for crops such as carrots, beets, winter squash, cabbage, onions, garlic, and sweet potatoes in winter is significant and represents a largely untapped market for local growers. If growers had the appropriate storage facilities, all these crops could be successfully provided until March or April.

"Local produce could be provided successfully until March or April if growers had the appropriate storage facilities."

Retail stores represent just one portion of the marketplace. Restaurants and institutional food services continue to buy more and more local produce, and many Community Supported Agriculture (CSA) farms offer winter share boxes to their members. Collectively, the market potential for winter storage crops in the Midwest represents millions of dollars, especially given the large population bases in Kansas City, St. Louis, Detroit, Indianapolis, Chicago, Des Moines, Milwaukee, and the Twin Cities.

A December 2005 article by Laura Sayre on NewFarm.org discussed the effect of adding two, 8x12 ft cold storage rooms on Genesis



*Personal communication 2009: R. Williams, Co-op Partners; D. Lind, Viroqua Food Co-op; C. Halverson, Menomonie Food Co-op; A. Johnston, Williamson Street Grocery Co-op.

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Farm in northwestern New Jersey. They added a winter share to their CSA operation, and 140 members signed up for the 22-week winter season running from December 1 to May 1. This influx of members added about $60,000 a year to the farm's gross income.

Three growers in Wisconsin and one in Minnesota who currently grow winter storage crops report that income from these crops ranged from 16 to 25% of total annual sales. Bill Davison, formerly with the Madison Area Community Supported Agriculture Coalition (now FairShare CSA Coalition), indicates that only 4 of 42 member farms (9.5%) have facilities designed for winter storage of vegetables in 2010. The additional sales may allow small-scale growers to earn a full-time living from farming or reduce the need to work off-farm during winter.

If proper storage conditions are maintained, crops harvested in fall can be stored in bins or bulk piles for 2 to 12 months depending on the crop. Large growers may have one or more storage facilities optimized for the post-harvest requirements of a single crop. In contrast, small growers have unique issues with winter storage, because they often grow a wide variety of vegetables that have different storage requirements and varying post-harvest market life. Small growers will group crops with similar storage requirements in the same facility. For example, carrots, beets, cabbage, rutabagas, parsnips, and turnips all require the same storage conditions, about 32°F and high humidity, but potatoes require a higher temperature of 40 to 50˚F with high humidity. Onions require about 32˚F but dry conditions, while winter squash store best at 50 to 55˚F and dry conditions. Depending on the mix of crops, growers may need two, three, or four storage rooms to meet the variety of post-harvest storage requirements.

Growers who have cold storage facilities use a wide variety of types, ranging from commercially purchased walk- or drive-in coolers to retired refrigerated truck bodies ("reefers"), rooms built inside an existing barn (often using conventional wood-framed construction methods), and root cellars buried in the ground. However, reefers, renovated rooms, and root cellars often lack cooling and ventilation controls to maintain proper storage conditions necessary to ensure produce quality. In addition, improvised solutions can increase overhead and labor costs due to inefficient use of space.

The number of storage crops, amount of each crop, time period of storage, storage requirements of each crop, and financial resources will impact the type and size of storage facility that best fits a grower's needs. Planning and siting a storage facility should also consider the movement of equipment and personnel to minimize handling and labor costs. There are some important differences between a refrigeration system for crop storage and a system used in a walk-in grocery store or beer cooler that can affect the success of storing produce.

This guide will help you plan, design, specify equipment, and operate a cold storage facility tailored to your specific requirements. The first section looks at the economics of storing fall-harvested produce. The economics of stored crops is different than that of summer-harvested produce, because the added costs of the facility, labor, shrinkage, and risk need to be factored into the selling price. Examples of the economics of several growers of different sizes are provided as a reference.

"Many growers may need two, three, or four storage rooms to meet the different storage requirements of a variety of crops."

The second section covers planning issues – how many storage rooms, how big, where they should be located, and crop storage environmental requirements.

The third section discusses different types of storage facilities, their advantages and disadvantages, and some constructions methods.

The fourth section covers environmental controls, refrigeration, humidification, and air exchange for a storage facility. There is a short section on reducing energy use for cooler operation and a discussion on material handling which is aimed at reducing excess labor costs and making sure the containers used for storage efficiently fit the cooler space. Food safety is covered briefly, because the cooler can be a source of food contamination if facilities and equipment are not kept clean and sanitized.

Examples of what other growers are doing can be valuable in formulating your own plans. Case study summaries of seven different fall-harvested crops from four different farms are provided as a reference. A brief summary is provided for each of the major storage crops grown in the Midwest with useful information that can help with planning and management. At the end is a reference section that should be useful for getting more in-depth information.

Winter storage crop economics

Growing crops for winter storage is very similar to growing for immediate sale or short-term storage. The main differences in production include selecting varieties known for their storage qualities, taking extra care to avoid disease issues that may reduce storage life, and harvesting when the crop is fully mature. None of these production factors are likely to significantly impact production costs. For the experienced grower in a northern climate, deciding to grow, store, and sell crops through the winter is mostly a consideration of markets, storage and post-harvest handling facilities, and labor availability during the months of November through April.

Having a readily available market for storage crops is the first and primary consideration. Options include winter farmers' markets, CSA programs, restaurants, schools, hospitals, retail stores, and wholesale distributors. All markets have expanded in most areas over the past decade given the demand for local produce beyond the traditional bounds of the standard "growing season." The number of farmers' markets operating through the winter is increasing; many CSA members relish the opportunity to stay connected to the source of their food; and chefs, food service professionals, and grocers increasingly see the merits of buying locally-grown products year-round.

However, the existence of a potential market does not mean that marketing and selling winter storage crops is easy nor does it guarantee that it is profitable. In addition to doing some market research, it is important to consider the additional costs and benefits of selling storage crops through the winter (Table 1).

Individual growers may recognize or experience additional costs or benefits beyond those discussed here, but these are good starting points to consider when deciding to pursue a winter storage crop enterprise.

A significant factor to consider is capitalization costs, though they will be reduced for farms that are very small-scale or have existing winter harvest capacity. Building an insulated and at least

Table 1. Costs and benefits of growing winter storage crops.

Costs	Benefits
Construction of new storage facilities	Extends use of existing storage facility assets
Increases energy costs	Expands gross sales
Increases labor costs	Provides the ability to offer year-round employment to dedicated employees
Affects quality of life by allowing less down-time for your business after a long growing season	May eliminate the need for the grower to work an off-farm winter job
Fewer available products may result in smaller average delivery volume to some customers	Helps maintain contact and sales with customers year-round
Increases expenses and administrative overhead costs	Improves cash flow during the winter

Table 2. Facilities and equipment for storage crops.

Items	Comments
Insulated storage area	There are many options for storage areas, from in-ground root cellars to large-scale coolers and everything in between.
Heated and insulated workroom	Plan to heat a room to at least 60˚F.
Tanks for soaking roots	Soaking loosens dirt clinging to roots and makes subsequent cleaning easier.
Miscellaneous post-harvest equipment	These items include regular and roller tables, scales, packing equipment, and various other items.
Hand truck, pallet jack, forklift or skid-steer loader	Most winter storage crops are heavy. It is best to move them using a hand truck, pallet jack, or forklift rather than carrying them by hand. This equipment requires a flat, concrete floor in the cooler and work area.
Harvest bins, pallet bins, and totes	While some growers store crops like carrots or potatoes in bulk piles, containers are generally more effective and efficient for small to mid-scale growing operations.
Brush, batch, or barrel washer	When growing winter crops in significant volume, brush or barrel washers provide an efficient and effective way to clean the harvest.
Mechanical harvester	These tools include carrot, beet, and parsnip lifters; potato and onion diggers; conveyers for assisting with harvest of cabbage and winter squash; and other devices.

minimally heated facility is a virtual necessity in northern climates. Table 2 lists various facilities and equipment that might be required depending on the size of the growing operation.

The list in Table 2 is oriented toward larger operations, but even smaller-scale growers will need adequate storage facilities and an efficient means for handling and washing produce. All facilities will also need to be heated to allow employees to work comfortably and to avoid the risk of freezing produce or water lines. Small operations can use a hand truck in the place of a pallet jack for moving boxes or totes instead of large bins. A hands-free wash station in which a foot peddle or a motion sensor turns on water can replace barrel or brush washers. Keep in mind that the amount of produce that can be effectively and profitably processed by hand is limited.

Mechanical harvesters, vegetable washing equipment, and sorting lines can improve efficiency for many operations, but they also increase capital costs.

The cost of coolers depends on the size, wall thickness, and other options such as doors and floors. The cost of a new cooler with refrigeration ranges from approximately $5,200 for a cooler measuring 6 ft wide x 8 ft long x 8 ft tall (5.33 ft wide x 7.33 ft long x 7.66 ft high inside) to approximately $23,000 for a cooler measuring 20 ft wide x 30 ft long x 12 ft tall (19.33 ft wide x 29.33 ft long x 11.66 ft high inside). This translates to a cost of $40 to $132 per square foot ($ft^2$) of floor area or a cost of $3.50 to $17.25 per cubic foot ($ft^3$) of volume.

Figures 1 and 2 provide an approximate value of the cost (per square foot and per cubic foot) of a cooler with refrigeration but without a floor. Costs in addition to this would include a concrete floor, freight for the cooler materials, installation, light fixtures, humidifier, and any racking (shelving) desired. When creating a budget for a cooler, check the cost based on both square footage and cubic volume, and use the greater value.

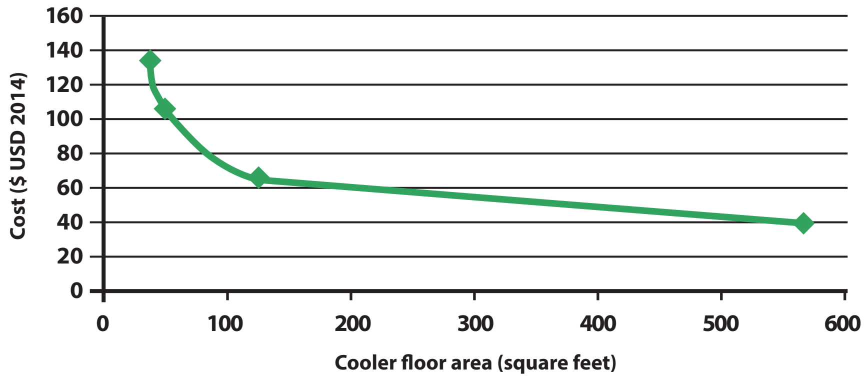

Figure 1. Cooler cost per square foot.

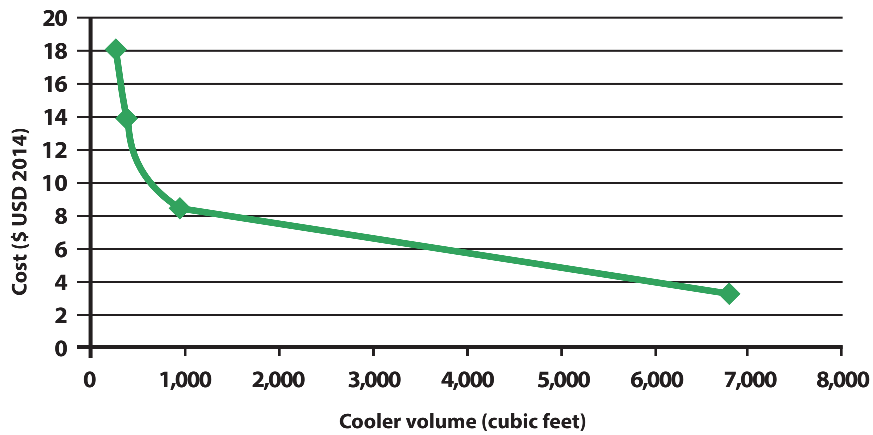

Figure 2. Cooler cost per cubic foot.

Another important cost for storage crops is "shrinkage." Shrinkage is the amount of stored produce that is not fit for market. For storage crops, this is not only the amount of the harvest that is culled based on quality characteristics including size, shape, and uniformity, which will be similar to produce harvested for immediate sales, but also the amount of produce that spoils during storage or needs to be trimmed. The amount of shrinkage can vary widely based on crop variety, production practices, crop condition at harvest, harvest and post-harvest handling practices, storage conditions, and duration of storage. See Table 3 for the relative amounts of shrinkage across different crops reported by Wisconsin and Minnesota producers.

Storage crops will have added costs over products sold shortly after harvest, so it is logical that the price you get for those products should reflect the additional costs. Anecdotal evidence suggests that labor, post-harvest losses, and storage costs for storing and marketing vegetables through the winter may result in a 20% increase in cost. If winter sales are a new enterprise for you, there may also be marketing and delivery costs to include in your overall budget. Whether the market can bear a higher price should be considered when developing a marketing plan for winter storage crops.

In many cases, producers are able to charge a higher price at winter farmers' markets, because there is less supply or competition in the market-place. Wholesale accounts may be more resistant to higher prices, though buyers at restaurants or retail stores with a strong preference for local produce or strong personal relationships with

Table 3. Amount of shrinkage for common storage crops.

Crop	Crop Loss (%)	Source of shrinkage
Carrots	3 - 10	Mostly culls based on size and shape
Beets	5 - 10	Black spot and rot
Winter squash	20 - 40	Rot and disease; not selling within the typical storage time
Onions	20 - 30	Spoilage and disease
Cabbage	10 - 40	Spoilage and disease
Potatoes	6 - 12	Soft rot, scabbing, knobbing, and greening

Source: John Hendrickson, 2013 survey of six growers.

farm suppliers may be able to absorb or pass along these added costs to the final consumer.

When determining an acceptable price and measuring profitability, a grower should factor in all costs of growing, harvesting, washing, storing, packaging, marketing, selling, and delivering their goods to market, in addition to general overhead expenses. One useful tool for documenting costs and tracking profitability is Veggie Compass (www.veggiecompass.com), a spreadsheet tool developed at the University of Wisconsin-Madison in partnership with growers. When using Veggie Compass to assess the profitability of winter storage crops, it is best to treat each stored crop as a separate product rather than including them with the same crop sold fresh during the growing season. Due to handling and storage costs, storage crops may require a higher price in order to be profitable.

As explained, one very important consideration in developing facilities for winter storage crops is assuring proper temperature and humidity conditions. Proper environmental control is essential to maintain optimal quality, which lengthens storage life, reduces income loss due to shrinkage, and directly improves the bottom line. Nearly all winter storage crops are sold by the pound, as opposed to bunches or by volume. Improper storage conditions will cause excessive moisture loss, reducing the weight of the produce and, in turn, the revenue from its sale. A profitable winter storage crop enterprise should factor in the necessary capital improvements to ensure near optimal storage conditions so that the crop and the profits do not shrink as the result of moisture loss.

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The overall profitability of storage crops obviously depends on a great many factors and is likely to vary from farm to farm depending on markets, pricing, yields, scale of operation, labor, and other variables. Table 4 provides profiles of several farms in Wisconsin and Minnesota.

Table 4 suggests that on the small-scale farm where the owner might be doing all the additional work of marketing, packaging, and delivering, the costs of winter sales might be very modest compared to the additional gross sales generated. On larger farms, winter sales will likely demand supplemental hired labor that brings with it the necessity of management, payroll expenses, and overhead. Selling high volumes will also demand more efficient means to handle the product, increasing capital investment costs.

These examples also suggest that the capital costs of a modestly sized additional storage unit would be recovered relatively quickly based on gross sales potential. However, it is a mistake to confuse how quickly the cost of a capital investment can be recovered with how profitable a winter storage crop enterprise might be on an individual farm. To determine the latter, one needs to create a complete enterprise budget and then use record-keeping to measure the performance of the enterprise over time.

Along with traditional hoop houses, winter storage crops offer another option for extending the growing, marketing, and selling season. With planning, preparation, appropriate infrastructure, available markets, and management, winter storage crops can be an important component of a fresh market farm business.

Table 4. Profiles of example farms selling storage crops.

	Farm A	Farm B	Farm C	Farm D
Cubic feet of storage space	812	6,000	17,374	22,400
Type of facility	Root cellar, room attached to a house	4 storage rooms	3 storage rooms	2 storage rooms
Crops	Roots, alliums, squash, cabbage, sweet potatoes	Roots, alliums, squash, cabbage	Roots, alliums, squash, cabbage, sweet potatoes	Cabbage, carrots, butternut
Winter labor	Owner (2-4 hrs/wk)	Owner + 1 part-time employee (30 hrs/wk)	Owner + 5.5 employees (part-time and full-time) (80-90 hrs/wk)	Owner + 8 employees (part-time and full-time) (280 hrs/wk)
Major market (Secondary market)	**CSA** (Direct wholesale)	**Direct Wholesale** (CSA and farmers' markets)	**Direct Wholesale** (Distributor and CSA)	**Direct Wholesale** (CSA)
Gross sales	$14,400	$85,000	$136,000	$250,000
Gross sales per cubic foot	$18	$14	$8	$11
Estimated annual capital cost*	$817	$3,317	$5,081	$5,992

*Assumes 15-year storage facility life, 7% return on investment.

Planning

The first step in planning a storage facility is to determine what crops are going to be stored, their quantities, time period of storage, method of storage (in bins or bulk piles), environmental conditions required for each crop, and storage compatibility with other crops. Crops should be grouped according to the environmental conditions required for optimal storage and by crop compatibility. For example, ethylene-producing crops should not be stored with ethylene-sensitive crops, and crops that will emit and absorb odors must be stored separately.

Next, determine the size of storage space required for each environmental condition. Space utilization is important to keep your investment costs low.

A cooler with pallet bins stacked high and close together will require about 2.5 to 3 ft^3 of cooler volume for each bushel of crop stored (Bartsch, 1986). A bushel equals 1.24 ft^3.

Based on this rule of thumb, there is 50% space utilization for a densely-packed cooler. A walk-in cooler with isles or racks and baskets on the floor may hold considerably less than 1 bushel per 3 ft^3. When calculating space requirements, it is important to account for overhead clearances of 12 to 18 in., 4 to 6 in. between the sidewalls, and 8 to 10 in. between end walls and any containers of product to facilitate air circulation. Details about calculating storage container requirements can be found in the *Material Handling* section.

Storage facility location and layout

The location of the storage facility should be carefully considered to ensure convenient access from fields to the processing or packaging area and to the loading dock. The location may be influenced by the location of other buildings, driveways, roads, topography, water drainage, and utilities (electric, water, etc.) as well as local zoning ordinances. Ideally, the processing and packaging area is adjacent to the storage facility and under the same roof to avoid fighting the elements when moving the crop from storage to packing to market during winter (Figures 3 and 4).

Expansion is another factor to consider when selecting the facility's location. Successful businesses often outgrow their facilities faster than imagined. Considering how to double or triple the size of the facility during the initial planning phase will reduce potential future costs and inefficiencies.

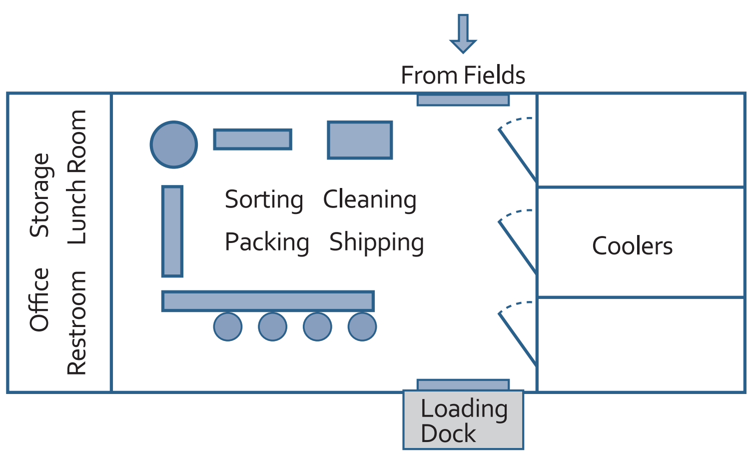

Figure 3. Example floor plan of storage facility with coolers adjacent to a combined processing and packaging area and a shipping location.

Farms with higher volumes might consider installing a cooler with one door that opens to a post-harvest staging area, where crops coming from the fields can be cleaned, sorted, and bulk-packaged for long-term storage, and a second door that opens to the processing and packaging area, where crops are prepared and packaged for delivery to market (Figure 4). This configuration can help reduce traffic congestion and improve workflow. On small farms, both of these stages may occur in one area (Figure 3).

Floors should be hard and smooth; concrete works best. This allows the use of wheel carts, hand trucks, pallet jacks, and forklifts to move boxes, totes, or pallets of produce easily. All floors should be sloped to a drain for easy cleaning.

Further information about building plans for storage facilities can be found in the *Additional Resources* section at the end of this document.

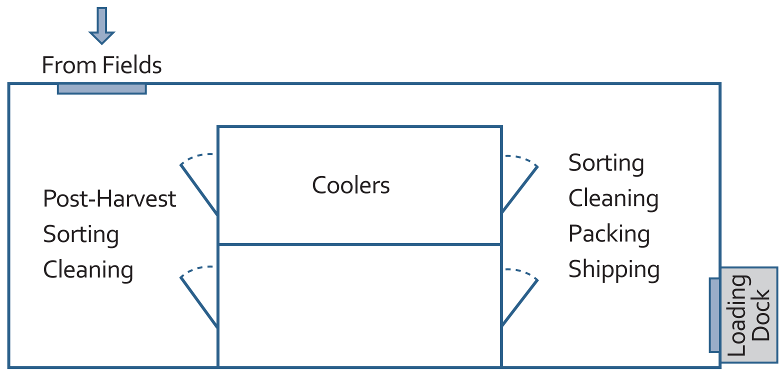

Figure 4. Example floor plan of a storage facility with a post-harvest processing area, coolers, packaging area, and loading dock in series to facilitate high-volume throughput.

Number of coolers

The number of coolers will depend on the number of crops (or storage-compatible groups of crops), environmental conditions required for each crop, and how long they are to be stored before marketing.

There are three general temperature and relative humidity (RH) ranges used to store commonly grown horticultural crops: (1) cold and humid, 32°F and 90 to 95% RH; (2) cold and very humid, 32°F and 95 to 98% RH; (3) cold and dry, 32°F and 60 to 70% RH. Table 5 lists these temperature and humidity ranges and the crops that fall into each. Some crops, such as those shown in Table 6, require specialized storage conditions.

Controlling temperature, humidity, and air circulation is extremely important to prevent crops from dehydrating or decaying. The recommended storage temperature for many fall-harvested vegetable crops is near 32°F, including carrots, turnips, beets, parsnips, and cabbage. This may only be a degree or two above the freezing point of the produce, so the cooler needs very good air circulation to prevent "cold spots" that cause freezing. Space should be left between the walls and bins to allow air to circulate. It is also essential for the cooler to have an evaporator unit designed for a 1 to 2°F maximum temperature

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drop across the heat exchanger. The reason will be discussed later in this publication.

For crops such as potatoes, chilling injury can occur if the rate of cooling (internal tuber temperature drop per day) is too fast or the final storage temperature is too low.

Holding produce at higher temperatures or lower humidity than the optimal conditions will reduce storage life, increase shrinkage, and reduce quality of the produce. The USDA's Agricultural Handbook No. 66, *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks* is one of the best sources of information on optimum storage conditions, use of controlled atmosphere (CA) storage, ethylene production and sensitivity, respiration rates, physiological disorders, and storage diseases (Gross et al., 2004).

Table 5. Common environmental conditions for winter storage crops.

Environmental condition	Crop	Typical storage time (months)
Cold and humid		* = controlled atmosphere
32-36˚F, 90-95% RH	**Apples**	2 - 4 3 - 12*
	Horseradish	8 - 10
	Jerusalem artichoke	12
	Pears	2 - 5 8 - 9*
	Turnips	4 - 5
Cold and very humid		
32-36˚F, 95-98% RH	**Beets**	4 - 5
	Brussels sprouts	1
	Cabbage	5 - 6
	Carrots	5 - 9
	Celeriac	6 - 8
	Leeks	2 - 3
	Parsnips	4 - 6
	Radishes	1 - 2
	Rutabagas	4 - 6
Cold and dry		
32-35˚F, 60-70% RH	**Garlic**	2 - 12
	Onions (sweet)	4 - 7
	Onions (pungent)	6 - 10
	Shallots	2 - 3

Source: Gross et al., 2004.

Table 6. Environmental conditions for specific winter storage crops.

Environmental Conditions	Crop	Typical storage time (months)
40-50˚F, 95-98% RH	**Potatoes (late crop)**	2 - 12
55-59˚F, 85-90% RH	**Sweet potatoes**	4 - 7
40-50˚F, 40-50% RH	**Dry beans**	6 - 10
50-55˚F, 50-75% RH	**Winter squash (acorn, buttercup, butternut, and Hubbard) and pumpkins**	2 - 3

Adapted from Kitinoja, 1999 and Wilson, 1999.

Permits

When building or renovating, municipal or county government permits may be required for construction, electrical, plumbing, or sewage installation. In some areas, agricultural facilities are exempt from certain permit requirements and building codes. However, it is often to a grower's long-term advantage to follow building codes when renovating or building a storage facility, because repurposing or renovating in the future may be expensive or not allowed if the building is not already to code. Codes have been developed to ensure the safety of those working and visiting farm facilities; they are not meant to impede progress.

If a grower plans to do some of the construction themselves, it is important to understand the current building code requirements, as they could affect grants or loans for the construction. For example, a grower installed the lights in a packing shed and ran all the wiring in steel conduit. However, current electrical code required plastic conduit in wet environments to avoid the long-term corrosion problems experienced with steel conduit. Because the wiring did not meet code, the grower was not eligible for an energy efficiency grant, and he had the added expense of replacing the conduit and rewiring.

Types of storage facilities

Storage can be as energy efficient as a root cellar, as simple as a refrigerator, or as sophisticated as a prefabricated walk-in cooler or a high bay drive-in cooler – the workhorses of the industry. This section will evaluate the pros and cons of each type of storage facility.

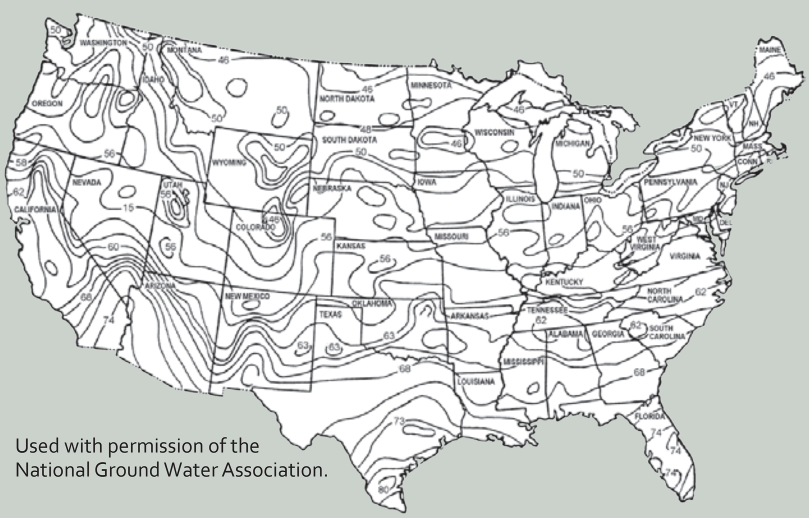
Root cellars

Root cellars have long been used to store late-season crops and provide food through the winter, such as potatoes, turnips, rutabagas, cabbage, winter squash, onions, carrots, apples, and beets. Some crops only last a few months, while others remain edible until spring or longer.

A root cellar is a room that is built in the ground with the walls and often the ceiling covered with earth. The temperature control for a root cellar is provided by heat exchange from the earth surrounding the storage space, and, in some cases, by natural air exchange through vents. The ground temperature will vary with location and is usually close to the average annual temperature 5 to 7 ft below the surface. In the Midwest, the ground temperature can range from about 45°F in northern Minnesota, North Dakota, and the Upper Peninsula of Michigan to about 60°F along the southern borders of Kansas, Missouri, and Illinois. See Figure 5 to estimate the ground temperature for your location. It may be too warm for optimal long-term storage of some crops and too cold for others.

Harvested produce is "alive" during storage; crops are continuously respiring, consuming carbohydrate reserves, and producing heat, CO_2, water vapor, and, in some cases, significant amounts of ethylene – the ripening hormone. Fruits and vegetables are continuously losing moisture from respiration and transpiration, which varies inversely to the relative humidity of the air in the facility. Without humidity control, which root cellars usually lack, the crop may become soft and develop skin that appears shriveled, perhaps making it unmarketable even though it may still be edible.

Many root cellars are small and do not have access for pallet jacks, forklifts, or even hand-carts to promote easy material handling. Transporting even a modest amount of produce in and out of a root cellar by hand is both inefficient and laborious. The cost of carrying out such work is significant.



Used with permission of the National Ground Water Association.

Figure 5. Ground temperatures in the continental U.S.
(See Appendix A on page 82 for a larger version.)

Modern root cellars

Modern root cellars can be designed to capitalize on the concept of earth contact to reduce cooling costs while facilitating efficient material handling. To accomplish these goals, a modern facility differs from a traditional root cellar in two key ways. First, a modern root cellar must have an active environmental control system. This may include supplemental refrigeration, ambient cooling from controlled ventilation with outside air, or some combination as well as humidity control.

Second, a modern root cellar must also have one end of the cellar at grade, so produce can be transported into and out of the facility by pallet jack or forklift. Ramps are not ideal, as they become slippery when wet or icy. This requires that the facility be built into a hill or soil mounded up on the walls to have contact with the earth for heat transfer. The walls of the cellar can be poured or block concrete construction. If the walls are longer than 20 ft, they will usually require a pilaster or T-wall to prevent the weight of the surrounding soil from causing the wall to rotate inward and potentially collapse. Check local or state building codes for requirements.

The root cellar building shown in Figure 6 may look like a home, but the basement has earth contact on most of three sides. Insulation on the exterior walls and horizontally underground keeps frost away from the walls and allows the earth to moderate the temperature in the basement. The facility has an aboveground level that can be used for office space, an employee locker or lunchroom, tool storage, or living space. Such a facility can be built without the upper level, but the additional cost of the upper four walls and an insulated floor deck is an economically efficient way to increase usable space.

Figure 6. Modern root cellar in the lower level, below office or living space. Food Farm in Wrenshall, MN. (Courtesy of Janaki Fisher-Merritt)

WALL INSULATION

The walls of a modern root cellar should be insulated on the exterior with closed-cell rigid foam board to a depth of 2 to 3 ft below grade. At this depth, closed-cell foam board insulation should also be laid horizontally to cover the area up to 8 ft out from the wall (Figure 7). This prevents frost from penetrating the earth adjacent to the walls, so heat from the ground can provide temperature moderation in the root cellar. The R-value of the vertical cellar wall should be a minimum of R-25 (5 in. of rigid closed-cell foam board). R-value is the thermal resistance factor or rate at which a material transfers heat – a higher R-value will conduct less heat. The vertical insulation must be securely fastened to the wall to prevent it from being dislodged as the backfilled earth settles. A foam adhesive can be used to attach the foam board to the concrete wall and to attach foam board to foam board. A nail with a washer can be used to anchor the foam to the sill plate if needed. A brick ledge on the outside of the wall can also be used to provide support, but this feature adds to the cost of constructing the wall.

Two inches of extruded polystyrene foam board is recommended for the horizontal insulation in the ground. The horizontal foam board should have a 25 pounds per square inch (psi) compression strength rating if it will be necessary to

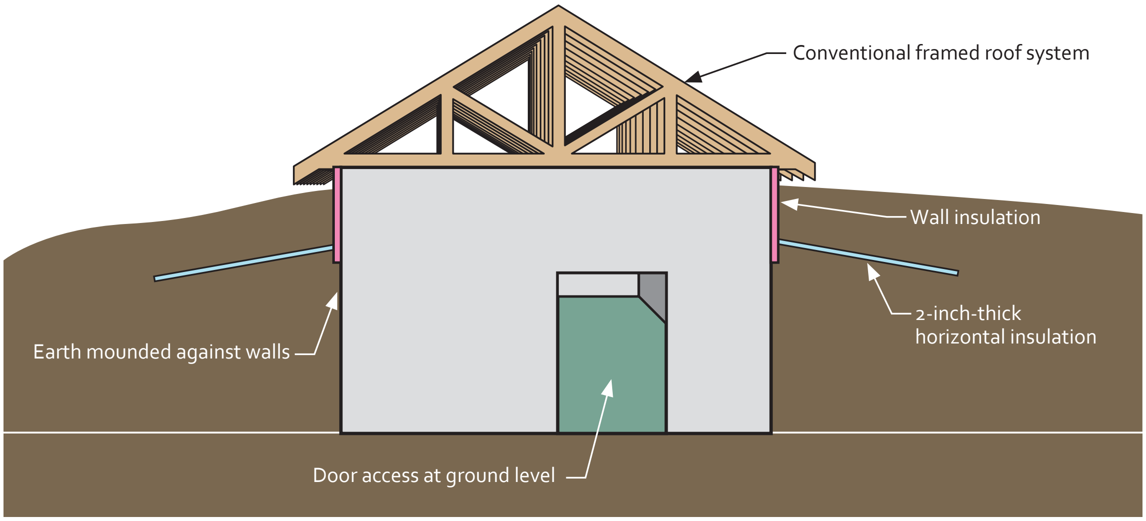


Figure 7. Cross-section of modern root cellar construction. (Sanford)

drive equipment on the ground covering the insulation. The horizontal foam should be laid at 6 in. above the bottom of the vertical insulation on the wall. This will prevent a break in the insulation once the ground has settled. To minimize the impact of settling soil on the foam board, backfill to the level of the vertical wall insulation and pack or allow settling before installing the horizontal wall insulation.

Any exposed foam insulation must be covered to prevent deterioration from sunlight and damage from rodents and lawnmowers. Some options include covering the foam with a mesh and applying a concrete coating (stucco), applying an adhesive-backed rubber or fiberglass sheeting (such as Protecto Bond® or Nudo GroundBreaker™), covering with a veneer material, or fastening standard building siding over the wall.

ALTERNATIVE WALL CONSTRUCTION TECHNIQUES

Foam board insulation can also be sandwiched between interior and exterior layers of concrete similar to a precast concrete wall (Figure 8). The wall thickness on each side of the foam insulation

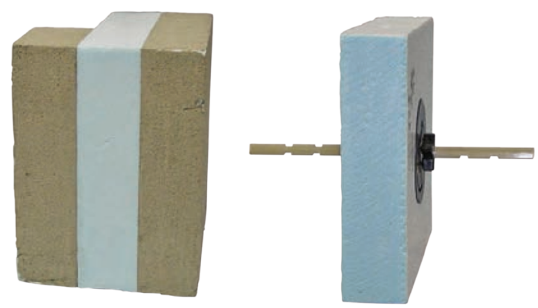


Figure 8. Center-insulated concrete wall (left) and insulation with concrete tie (right). (Sanford)

can be different. For a root cellar, an insulated wall should have a 6-in. concrete wall on the inside, 4 in. of foam insulation, and 2 in. of concrete on the outside for protection. This system has the advantage of thermal mass on the inside of the root cellar, an easy-to-clean interior surface, and the durability of a concrete external surface. The disadvantage of this system is that the insulation typically extends to the footings, thus lowering the heat transfer into the root cellar and reducing cooling. To maximize heat transfer from the surrounding earth, the insulated portion of the wall could be extended to only about 30 in. below grade and then built as a solid uninsulated wall to the footings. To reduce material cost, the wall could be tapered from a 12-in. insulated upper wall section to an 8-in. solid lower wall section. The disadvantage of a concrete exterior is that it results in a break in the insulation where the horizontal insulation intersects the exterior concrete face. This break could result in frost permeating below the insulation due to the high heat conduction rate of concrete.

Cellar walls can also be constructed using insulated concrete forms. These forms are made of foam and can be stacked to form a wall. The open spaces in the center of the forms are filled with concrete to produce a well-insulated, load-bearing wall (Figure 9).

Figure 9. Insulated concrete form.

While this method is expedient, insulated concrete forms have two disadvantages. First, insulation on both sides of the concrete reduces heat transfer from the earth. Second, the lower thermal mass of concrete on the inside of the cooler reduces the ability of the wall to store energy and moderate the cooler from large temperature swings. If the complete wall is built using insulated concrete forms, the cellar can be cooled with mechanical refrigeration for summer use, and an active heat transfer system can be used for fall or winter cooling as discussed below. Insulated concrete forms could be used for a hybrid wall, where insulated concrete forms are used for the upper section from the surface to about two feet below grade and solid poured concrete is used for the lower section. In all cases, the outside and inside of the foam must be covered to prevent degradation and to provide a washable surface required by FDA food safety regulations.

ROOF AND CEILING SYSTEMS

A traditional root cellar is entirely covered with soil, including the roof. However, this type of roof system is more costly, because it must support the weight of the earth and any live loads (items traveling over the top). Another disadvantage of a fully subterranean cellar is that the soil will freeze down to the roof in cold climates, because root cellars are typically not below the frost level and any ceiling insulation will reduce the transfer of ground heat through the roof.

A more cost-effective method is to build a conventional, truss roof system above grade and mound earth against the walls to within a foot or two of the roof. The roof needs to have adequate height above the ground to shed snow. In areas with deep snow or locations with windy conditions, snow loading due to drifting should be taken into account when the roof trusses are selected. A local supplier will be able to provide assistance on the correct truss selection. The trusses can be wood or metal. The area under the roof needs to be vented to remove moisture and reduce the heat load to which the cellar will be exposed. Venting can be done with roof, eave, or gable-end vents, the same types that are used in residential or commercial construction. If the cellar will be used during the summer, a power vent with a fan may be necessary to minimize heating under the roof.

CEILING INSULATION

The ceiling must be insulated with closed-cell foam insulation, either foam-in-place (FIP) or rigid foam board, with taped seams for rigid boards or a sealant for foam-in-place to provide a vapor barrier. There are three types of foam insulation that are acceptable: extruded polystyrene, urethane, and polyisocyanurate. Refer to the discussion on insulation types on page 24 for pros and cons of each. An insulation value of R-25 or greater is recommended. If rigid foam board insulation is used, the joints should be staggered and taped to reduce air and moisture migration into the insulation. A covering, such as corrugated steel or plastic composite, must be used on the interior to protect and help support the insulation. Fire codes usually require any foam insulation to be covered. Installing a corrugated steel ceiling and applying foam-in-place insulation before the roof is completed provides a well-insulated ceiling. The wall and ceiling joint should also be sealed to prevent humid air from infiltrating into the ceiling or wall cavities.

FLOORS

Floors in root cellars are typically uninsulated concrete to allow heat to transfer from the earth to regulate the temperature. The concrete floor also provides a hard, level surface for pallet jacks or forklifts and allows easy washing. The concrete should be 4 to 5 in. thick (4 in. for hand trucks and 5 in. for forklifts) and reinforced with rebar, wire mesh, or fiber filler. Use 3,000 psi-rated concrete for light loads (hand trucks) and 3,500 or 4,000 psi-rated concrete for floors with heavier loads such as a forklift. For more information, see the *Walk-in and Drive-in Coolers* section.

ACTIVE HEAT TRANSFER SYSTEMS

Using mechanical refrigeration in a root cellar is not recommended, because higher heat gain through the uninsulated walls and floor will increase energy costs. If a root cellar will be used for summer storage, then mechanical refrigeration will be needed, and the floor and walls should be fully insulated. The heat transfer rate from the earth isn't enough to remove field heat from summer-harvested crops. Insulating the walls and floor will greatly reduce the cooling from the earth during the cold months but will also reduce heat gain during the summer when the refrigeration is running.

If both the walls and floor are insulated, then earth-air heat exchangers (earth tubes) or a closed-loop water-glycol system can be used to provide heat transfer to or from the earth when desired. In an earth tube system, a pipe exits the root cellar, loops underground, and returns to the storage room. Air is forced through the pipe with a blower to facilitate the transfer of heat from the earth to the air and into the root cellar. Typically, multiple tubes are used with a 100 to 200 ft run per pipe. The amount of cooling and heating will depend on the size of the pipe, number of pipes, airflow rate, depth the pipes are buried, and ground temperature. The pipes could be buried along the root cellar foundation to reduce excavation costs. The pipes should be buried at least 6 ft deep or below frost depth.

A closed-loop system using piping with a water-glycol solution and a liquid-to-air heat exchanger can also be used. The piping is laid in a trench below frost depth. A pump circulates the glycol solution through the underground loops and back to a liquid-to-air heat exchanger to transfer heat from the root cellar to the earth.

This system can eliminate some issues with condensation and the potential for mold growth in the earth tube system. Because the heat transfer rate between the earth and the pipe is slow, the system requires a large surface area to achieve adequate amounts of cooling and heating. The heat transfer area or length of pipe buried in the ground will vary depending on soil type. A deep pond can also be used as the heat sink for a water-glycol system. See the *Additional Resources* section for more information.

Refrigerators

Household or commercial refrigerators can be a low-cost alternative for short-term storage of small quantities of crops. However, they are not recommended for storing crops for more than a few weeks. Crops can be stored in small containers, packaged in bags, or stacked on shelves. Household and commercial refrigerators have a temperature range of 32 to 45°F which is within the storage temperature range for many crops. However, refrigerators typically do not have humidity controls, so packaging or bagging is required to preserve humidity. Adding a humidifier to a refrigerator will not work, because the dew point temperature across the refrigeration coils is too low allow for adequate humidity levels, and it will frost up heat exchanger coils.

Household refrigerators do not have the refrigeration capacity to cool crops rapidly enough when completely filled with warm produce or to keep produce cold when the unit is opened frequently. They use the cold air from the freezer to cool the refrigerator compartment, often resulting in uneven cooling. When trying to hold crops at cooler temperatures (<35°F), some areas in the refrigerator may be below 32°F and could damage produce. Rapid removal of field heat is important for maintaining quality and should be done prior to placing produce in a household refrigerator.

Commercial refrigerators have higher cooling capacities and evaporator fans that run continuously to enable rapid removal of field heat. This reduces the chance of freezing produce, but it also increases the dehydration of produce. The shelving in a commercial refrigerator is typically designed to carry heavier loads and have larger internal dimensions to better accommodate tote baskets used by growers. In addition, the refrigeration compressor in a commercial refrigerator can usually be replaced if it fails. In household refrigerators, replacing a failed compressor is very expensive compared to the cost of replacing the refrigerator. Refrigerators with glass doors will be more expensive to operate than units with solid, insulated doors due to higher heat gain.

Reefer truck bodies

Many growers store produce in retired refrigerated truck or trailer bodies, known as "reefers" (Figure 10). They are equipped with a refrigeration unit and have nominally insulated walls and doors. There are a few disadvantages to using reefer bodies for crop storage. First, these units are design to hold contents at the desired temperature as the truck travels from point A to point B, so the cooling capacity and airflow of the reefer refrigeration system are not adequately sized to handle field heat. Further, the typical reefer body will only have 2 to 3 in. of polyurethane foam insulation with an approximate rating of R-10 to R-15. Aging, possible damage, water leaks, missing insulation, warped doors, and poor or missing door seals will result in higher heat loss and gain as well as higher energy costs than a typical walk-in cooler. Depending on the location and how the reefer body is supported, it may be

Figure 10. Reefer truck body.

difficult to move items into and out of the box. Ideally, the reefer body should be set up and supported to allow a pallet jack or forklift to drive into the unit to move produce. If the reefer is elevated, large bins must be set into the unit using a forklift and moved into place using a pallet jack, which is labor intensive.

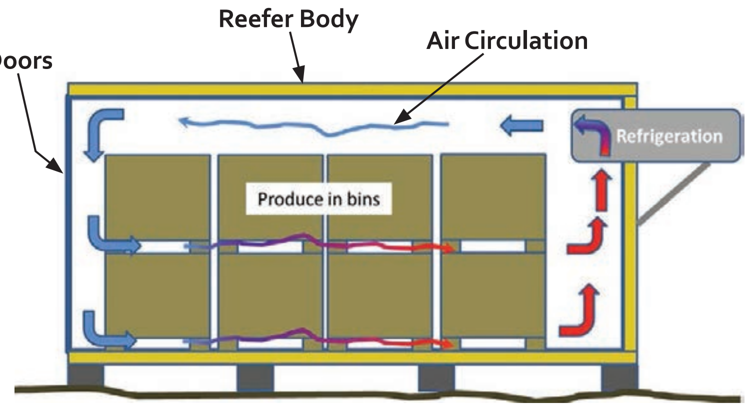


Figure 11. Reefer body air circulation.

Typically, a reefer body will be either 96 or 102 in. outside width and able to accommodate two 40 or 42 in.-wide bins side by side, respectively, with the recommended 4- to 6-in. gap between the walls and bins for air movement (Figure 11). Depending on bin height, the stacking height of bins in a reefer is limited to 2 or 3 in order to maintain acceptable headspace of 12 to 18 in. for adequate airflow. Floors of older reefers do not have channels for return airflow, which is a problem if produce is set directly on the floor. Stack bins on a pallet or similar false floor to cool produce if the floor is flat. A reefer body on a truck or trailer is a great option for maintaining produce quality during transport to market.

Walk-in and drive-in coolers

Walk-in or drive-in coolers are the workhorses of the industry and can be configured in a range of sizes to meet specific needs (Figure 12). The components of a walk-in cooler include: insulated walls, ceilings, and sometimes prefabricated floors; cleanable interior surfaces; an environmental control; a self-closing door with gasket; a lockable door latch; lighting; and the refrigeration system. The *Additional Resources* section at the end of this document also contains a wealth of information about walk-in and drive-in coolers to supplement the material provided here.

The size of containers should be considered when sizing a cooler in order to maximize internal use of space. Keeping in mind that the dimensions on specification sheets for coolers usually refer to the outside dimensions, make sure to use inside dimensions when sizing a unit and planning the internal layout. Coolers can be assembled from prefabricated panels or built in-place. Coolers located inside a building should have a minimum of 2 to 3 in. between the cooler panels and any adjacent wall, ceiling, or object to allow airflow over the panels. This will prevent condensation and the resulting deterioration of the panels. The 2007 Energy Policy Act specifies a minimum R-value of 25 for walls and ceilings, but R-30 or more is highly recommend and will reduce energy costs. Prefabricated insulated floors are available with cooler packages and will reduce heat gain, but insulation can also be installed under a concrete pad to eliminate the need for a prefabricated floor.

The refrigeration system is typically composed of a ceiling evaporator unit with a remote air-cooled condenser unit. The size of the refrigeration system will depend on the cooler size; insulation value of the floor, walls, and ceiling; surrounding air temperature; respiration heat of the produce stored in the cooler; and the temperature and maximum amount of produce entering the cooler per day (field heat). Humidity control is not usually included in a basic walk-in cooler package and would need to be supplied separately.

A basic walk-in cooler will have a swinging door that can range from 36 to 60 in. wide, while a drive-in cooler can have sliding or overhead doors up to 10 ft wide. Wider doors allow the use of a pallet jack or forklift to move large quantities of produce in pallet bins into the cooler with minimal labor. Multiple doors can aid in product rotation by allowing the oldest stock to be unloaded first (first in, first out). Doors in high traffic applications should be equipped with plastic strip curtains to reduce heat gain. Racking can be installed inside the cooler to organize produce, facilitate uniform cooling, and aid with product rotation.

PREFABRICATED COOLERS

Cooler walls, ceilings, and floors can be made from prefabricated insulated panels that latch together for easy installation (Figure 12). Insulated cooler panels consist of a core of polyurethane or polystyrene foam sandwiched between two

Figure 12. Prefabricated walk-in cooler. (Barr, Inc.)

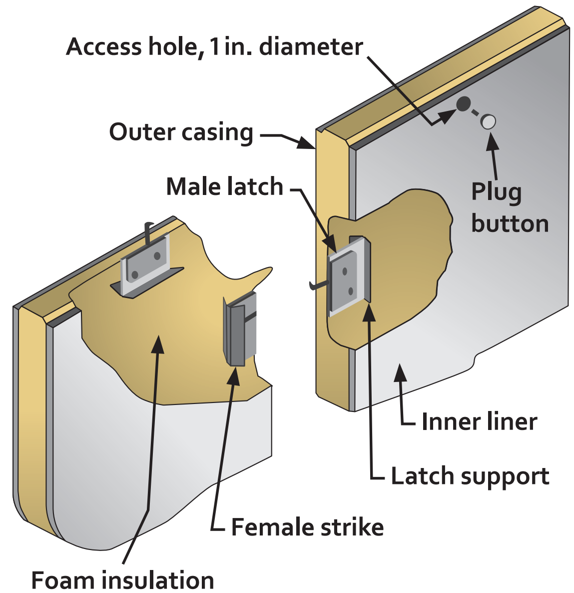


Figure 13. Prefabricated cooler panel latching mechanism. (Polar Bear® box)

sheets of steel, stainless steel, aluminum, or reinforced plastic. The tongue and groove edge of the wall panels and cam-lock mechanism are designed to seal panels together and prevent air leaks (Figure 13). The ceiling is attached to the walls with cam-locks or lag bolts depending on the manufacturer. A bead of caulk or FIP urethane is recommended in the wall and ceiling joints to ensure a seal and to prevent water and air infiltrating into the cooler through the seams. A small walk-in cooler can be assembled and ready to use in about an hour.

The wall and ceiling panels range from 2 to 12 in. thick and 42 to 48 in. wide. Wall height can range from approximately 7 ft for a small walk-in cooler to 40 ft for high-bay storage facilities. Walls are commonly 4 in. thick for an approximate R-value of 20. However, the 2007 Energy Policy Act requires a minimum R-value of 25 on all new coolers. A 5-in.-thick panel would be needed to meet the R-25 minimum value, but a 6-in., metal-clad washable panel is recommended and would have an R-value of about 30.

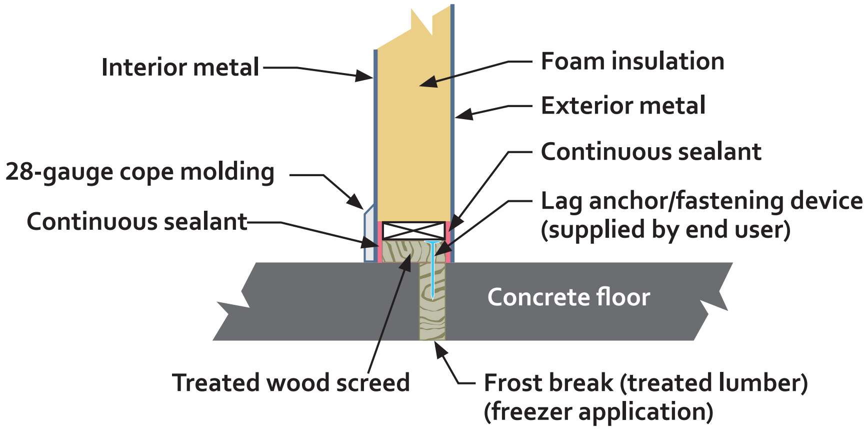


Figure 14. Wood screed with thermal break detail.

Cooler floors

Floors should be level, durable, light-colored, waterproof, and grease-resistant with a smooth or light-brushed finish that is easy to clean. Coolers that store food are required to have a washable interior surface. Concrete floors are typically used to meet this requirement. If the existing floor surface is not concrete, a prefabricated floor is required, or a concrete pad for the cooler must be poured.

Prefabricated cooler floors provide an insulated, cleanable floor surface to which the prefabricated wall panels latch. If prefabricated floors are set on top of an existing floor, a short ramp will be required to allow wheeled appliances into the cooler. The existing floor must be level, or the cooler will not assemble squarely and may have gaps between the walls and floor or ceiling. Alternatively, the existing floor can be dug out so that the prefabricated cooler floor sits level with the existing floor, and a ramp is not needed.

If pouring a concrete floor, the site for the floor should be well-drained with a gravel base at least 12 in. thick. Footing drains should be installed if the water table is high or the soil is poorly drained. A 10 mm plastic vapor barrier should be laid over the gravel base and covered with 1 in. (R-5) or 2 in. (R-10) of rigid foam board insulation.

The rigid foam board, typically extruded polystyrene, must be rated for the weight that the floor is expected to support, typically 15 psi for hand trucks or light vehicles and 25 or 40 psi for forklifts or tractors. Four to 5 in. of concrete (4 in. for hand trucks and 5 in. for forklifts) are poured over the foam board and reinforced with rebar, wire mesh, or fiber filler. Use a 3,000 psi-rated concrete for light loads (hand trucks) and 3,500 or 4,000 psi-rated concrete for floors with heavier loads such as fork trucks.

There should be a thermal break, such as a vertical piece of insulation or a piece of treated lumber, cast in the floor where the cooler wall will sit to prevent the formation of frost or condensation around the cooler perimeter during humid weather (Figure 14). Another option is to form a concrete curb or one course of 8 in. concrete blocks to support the cooler walls to prevent the lower wall edge from being wet with condensation or water from wet produce. When ordering the cooler, you must specify if the wall will be set on a curb to ensure that the door is the correct length.

Floor drains will facilitate easy cleanup after the storage season has ended and provide a drain for condensate from the refrigeration system. Piping for floor drains must be installed before the concrete is poured and usually will need to be routed to a sanitary sewer or septic tank (check local regulations). If a drain is not installed, some means of handling the condensation from the evaporator unit will be required to prevent ponding on the floor. Small coolers can use a single standard drain, while large coolers may require a slot or trench floor drain. Standard drains can be located in the center of the floor or in one corner, and slot or trench drains can be located along the walls or down the center of the floor. The floor needs to be sloped toward the drains at 1 to 2% grade or 1/8 to 1/4 in. per 10 ft, respectively.

If the walls are placed on a concrete pad, an angle iron frame or screed is anchored to the concrete pad to keep the walls in place. A steel or aluminum angle iron frame can be mounted on the inside or outside of the cooler wall, and the panels are fastened to it using bolts. If using a wooden or vinyl screed, it is fastened to the floor at the center-line of the wall. In the case of a wooden screed, the panels are set over the screed, which fits into a slot in the bottom of the panel (Figure 14). When using a vinyl screed, the panels fit into the U-shaped vinyl extrusion for a tight seal (Figure 15). Some manufacturers use an angle screed, where a piece of angled metal (steel or aluminum) is fastened to the floor with

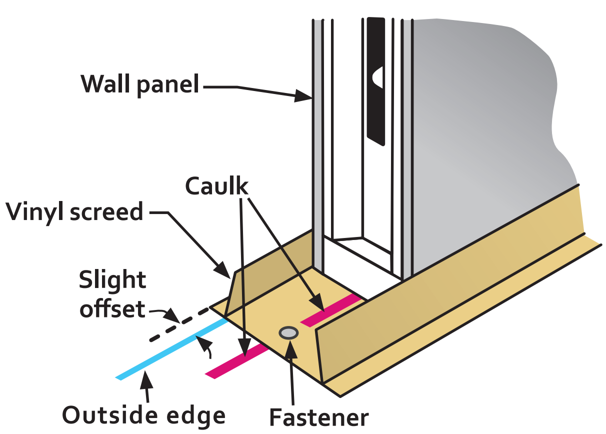


Figure 15. Vinyl screed detail. (Based on Imperial Brown® walk-in cooler installation manual illustration.)

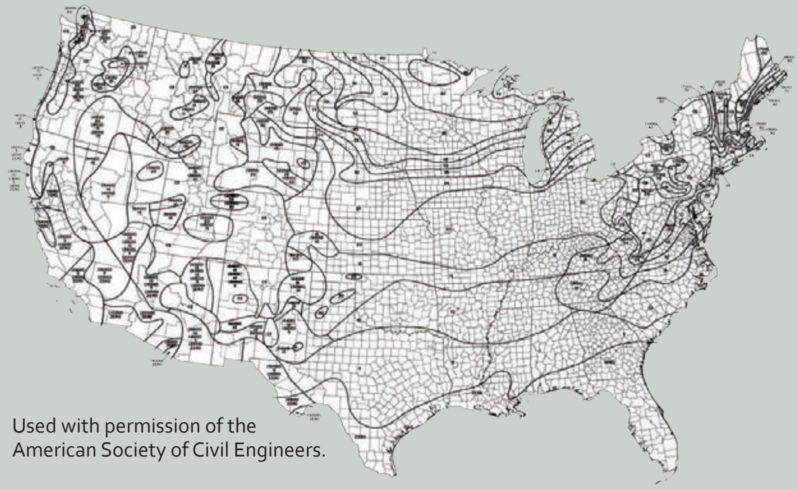
the vertical section at the centerline of the wall. The angle screed fits into a slot in the bottom of the wall panel. A bead of sealant should be placed under the screed before fastening it to the floor and on top of the screed before setting the wall in place. The floor must be level to allow the wall panels to fit together correctly. If the floor is not level, the screeds should be shimmed such that the wall panels sit on a level surface. Screeds are usually mitered at the corners.

Follow manufacturer's directions for installing the screeds. If a prefabricated floor is used, the floor must be set on a level surface. If shimming is necessary, the shim spacing must be no greater than 18 in. apart and extend the entire length of the floor.

Ceiling support

In general, a ceiling span of 10 ft can support a load of 75 pounds per square foot (psf), while a 12 or 14 ft span can only support a load of 30 psf. Therefore, cooler ceilings with spans greater than 14 to 16 ft will require additional support. They can be supported with an I-beam or C-channel on the inside or outside of the cooler or by using an external supporting structure such as a roof truss. External support is highly desirable, as an internal beam can affect air circulation, reduce space utilization efficiency, and deteriorate in the continuously damp environment. For external support, ceiling support brackets (supplied by the cooler manufacturer) are installed in the joints between ceiling panels. A cable or threaded rod is used to connect the ceiling brackets to a properly designed support beam directly above the brackets. Always use manufacturer's recommendations when determining ceiling load and ceiling support requirements.

Snow load must be considered for outdoor coolers, because cooler ceiling panels are not designed to structurally support much weight. A simple post-frame roof structure (pole barn) with a sloping roof can provide protection from the weather (winter snow load and summer heat gain) and can be used for ceiling support. If a roof is neither desired nor possible, additional support must be provided by a beam inside the cooler. A new cooler will come with instructions about ceiling support tailored for your location.



Used with permission of the American Society of Civil Engineers.

Figure 16. Snow load in the continental U.S.

(See Appendix B on page 83 for a larger version.)

To determine the design snow load for your location, consult the Snow Load Map shown in Figure 16 (a larger version is on page 83). If you are in a location subject to unusual snowfall, such as “lake effect” snow, consult local authorities. The information from the map may not precisely identify the snow load for your area.

For example, Madison, Wisconsin, located in the south central part of the state, has a design snow load of 30 psf. No additional support would be needed for an outdoor cooler with a ceiling span of 14 ft or less. If a cooler was installed outdoors in northern Wisconsin, Minnesota, Michigan, or northeastern North Dakota where snow loads are 60 psf, a support beam would be required for any cooler with a ceiling span greater than 10 ft, and multiple beams would be needed if the ceiling span was greater than 20 ft. If the cooler is sited adjacent to a taller building, snow drifting may add loading beyond the typical ground snow load, and additional ceiling support would be needed. (A discussion of snow load calculation is in the upcoming section on built-in-place coolers.)

Roofing membrane

Any cooler located outside should either be covered by a roof structure or an ethylene propylene diene monomer (EPDM) rubber roofing membrane (preferably white) to keep water and debris out of the seams. The rubber roofing membrane should cover the entire roof and extend down the sides past the seam between the ceiling and walls. The membrane should be fastened to the wall with screws and a termination bar that runs along the entire edge of the roof membrane. The membrane should be spot glued to the top of the cooler to keep it tight during windy conditions.

Some companies make tapered foam blocks that are placed on top of the cooler and then covered with the rubber membrane to add pitch, allowing the roof to shed water and prevent ponding. This also increases the insulation value of the roof, reducing heat loss and gain.

BUILT-IN-PLACE COOLERS

A freestanding walk-in cooler can be built using conventional wood framing techniques. The walls can be built from nominal 2x4, 2x6 or 2x8-in. lumber with studs placed 24 in. on center. The lumber dimension selected will depend on the type and amount of insulation to be used. For outdoor coolers, the walls should be anchored through the bottom or sole plate to a concrete slab with cast-in

L-bolts or an acceptable concrete anchor to prevent the cooler from being moved off its foundation by wind or being bumped by machinery. Alternatively, 2 or 3-in. angle iron secured to the concrete slab and the base of the wall can be used to anchor the cooler and provide a stronger attachment.

Types of insulation

Insulation can be installed in a wall or ceiling cavity, or it can be an integral component of a wall or ceiling. Insulation R-value requirements for a structure can refer to the "cavity insulation" value, which is the R-value provided by the insulation material itself, or the overall insulation value, which takes into account the R-value of the insulation, studs, doors, and fasteners in a building section. The 2007 Energy Policy Act requires a minimum cavity R-value of 25 for walk-in or drive-in coolers, but a minimum cavity R-value of 30 is recommended for any new coolers.

While there are many insulation products, not all are well-suited for insulating a cooler.

Fiberglass, blow-in fiberglass, cellulose, and open-cell foam (white bead board – expanded polystyrene) all will absorb moisture, attract rodents, and should not be used for insulating walls in cold storage facilities.

The enemy of insulation is moisture that usually infiltrates into the wall from the "warm" side and condenses inside the insulation when it cools to the dew point temperature of the humid air. A high-moisture environment must be maintained for high quality produce. Therefore, it is expected that the insulation used in cooler walls or ceilings will be exposed to moisture. If insulation absorbs moisture, the insulation value will be greatly reduced. For example, fiberglass or cellulose insulation will rapidly absorb moisture (in less than one year), and the insulation value can drop to near zero. Once wet in the wall cavity, these types of insulation are slow to dry.

Only closed-cell foam insulation should be used in cold storage facilities.

There are four types of closed-cell foam insulation used for refrigerated cooler walls and ceilings: extruded polystyrene, expanded polystyrene, polyurethane, and polyisocyanurate. The initial R-value of extruded polystyrene (XPS: pink, blue, green, or gray) is 5 per in., 4 per in. for expanded polystyrene (EPS: white), 6.25 per in. for polyurethane (yellow), and 6.8 per in. for polyisocyanurate (off-white or pale yellow). Unfortunately, water permeation into the foam insulation and off-gassing of the blowing agent will reduce the insulation properties from the initial R-values over the long term. Because of its high water permeability, expanded polystyrene (EPS: bead board) is not recommended for cooler wall panels.

As a rule of thumb, extruded polystyrene, polyurethane, and polyisocyanurate each have an approximate R-value of 5 per in. once installed, and 6 in. would be needed to meet the recommended R-value of 30. Extruded polystyrene has been shown to better retain its insulation value and be more resistant to water permeation than polyurethane over time, and foam-in-place polyurethane insulation will outperform polyurethane board. The long-term thermal resistance of polyisocyanurate is similar to that of polyurethane in dry locations – approximately an R-value of 5.5 per in. If the cooler is properly installed and the roof is covered (if located outdoors), moisture accumulation should not be an issue. If foam-in-place polyurethane or polyisocyanurate is used, it should be coated with a sealant to reduce water vapor migration.

Wall construction

Built-in-place cooler walls can be constructed and insulated several ways, and all methods begin with a stud wall. The bottom plate should be pressure-treated lumber, since it could be exposed to wet conditions. Anything above the bottom plate can be standard construction-grade lumber. It is recommended to wrap the bottom plate board with a piece of 4 or 6 mm polyethylene film to reduce the exposure to moisture. This can be done by laying a 24-in.-wide piece of polyethylene film under the bottom plate board before it is fastened to the floor and then wrapping the film up the sides before the inside and outside sheathing are attached.

In the first method, the width of the stud wall should equal the desired thickness of the insulation. Start by fastening an external covering to the outside of the stud wall and filling the wall cavity with foam-in-place insulation. Then, any excess foam extending beyond the stud wall is trimmed, and a coat of sealant is applied to protect the foam insulation from water vapor penetration. A washable covering, such as reinforced plastic, aluminum, or steel panels, is installed over the foam to meet sanitary codes and protect the foam.

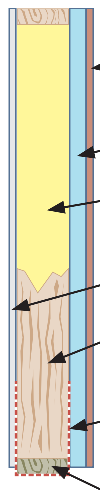


Figure 17. Wall section with foam between studs plus foam board on one side. (Sanford)

In the second method, foam boards are fastened to one or both sides of the stud wall, and the wall cavity is filled with foam-in-place insulation to the desired R-value (Figure 17).

The third method is to fasten rigid foam insulation boards to the stud wall to a thickness that achieves the desired insulation value with no insulation in the wall cavity. Foam boards can be installed on the inside and/or outside of the studs. Foam boards can be fastened to the studs with adhesive or by using screws or nails with washers on the heads. Foam board with a tongue-and-groove edge is best to provide a tight seal. All seams should be sealed with joint seaming tape to minimize air leakage that would lead to moisture migrating into the wall cavity. If multiple layers of rigid foam board are used, the seams of different layers should be staggered, and seams on the outer layer should be taped. The joints between the walls and ceiling and the walls and floor should be taped or caulked to prevent air or moisture from infiltrating into the wall cavity. Foam-in-place insulation costs more per board foot than foam board, but it may be more cost-effective when accounting for the labor to install the foam board.

Based on an R-value of 5 per in. for foam, a minimum of 5 in. of foam is needed to achieve the minimum R-value of 25. A 2x4 wall filled with 3.5 in. of foam will have a cavity R-value of about 17.5. To achieve the minimum recommended R-value of 25, 2 in. of foam board can be attached to the studs for a total insulation value of R-27.5 (Figure 17). The foam board can be placed all on one side or an inch on each side. A 2x6 wall will hold 5.5 in. of foam for an R-value of 27.5, and a 2x8 wall will contain 7.25 in. for an R-value of 36.

A cleanable, corrosion-resistant wall covering should be applied on the interior of the walls and ceiling to protect the foam from ignition sources and mechanical damage, to prevent infiltration by rodents, and to provide a cleanable interior surface. Typically, flat or corrugated reinforced plastic panels are used. Aluminum or steel panels are a more durable option if bumped with equipment, but these will corrode over time and need to be replaced sooner than plastic. The outside of the walls and roof of the cooler should be covered with one-half-inch plywood or OSB sheathing to protect the insulation from physical damage and, if located outdoors, some type of exterior siding for weather protection.

Ceiling construction

Ceiling joists can be placed 24 in. on center with spaces between joists filled with a minimum of 5 to 6 in. of foam-in-place insulation or foam board attached to the inside. If using foam-in-place insulation, attach the ceiling panels or a sheet of foam board, install any electrical wiring, and then fill the cavity with foam-in-place insulation from above. Cover the outside with plywood to protect the foam from sunlight, ignition sources, and rodents. A flat roof is typically covered with rubber roofing membrane material. Light colors are recommended for all roofs to reduce solar absorption and heating.

The size of ceiling joists will depend on ceiling load and span. Ceiling loads include the weight of the structure itself, anything permanently attached to the ceiling (dead load), and items temporarily stored on top or suspended from the ceiling (live load). In the case of outdoor coolers, the weight of forces of nature, such as snow and wind loads, must also be considered. If an outdoor cooler is attached to or near a taller building, snow drifting can add additional ceiling or roof load. A total design load (dead + live load) of 30 psf is the minimum recommended if no live loads will be placed on the roof.

Snow loads can be significant in northern areas. The flat roof load is equal to 10 psf plus the roof snow load. The design snow load of the roof can be calculated using the following equation:

$$P_f = 0.7 \times C_t \times I_s \times C_e \times P_g$$

Where P_f is the design snow load on a flat roof (psf), C_t is the thermal factor which is 1.2 for an unheated building, I_s is the Importance factor representing the risk of human life loss in the case of the building failure (which is 0.80 for agricultural buildings), C_e is the exposure factor, and P_g is the ground snow load (psf). The exposure factor is an indication of the amount of snow that will be blown off the roof or be added to the roof. A fully exposed roof is exposed on all sides with no wind breaks or nearby buildings; few coolers are likely to fall into this category. A sheltered roof is located near a wind break or other buildings that could increase the amount of snow that evenly accumulates on the roof. All other situations are considered partially exposed. The exposure factors are: Fully Exposed = 0.9, Sheltered = 1.2, and Partially Exposed = 1.0. The ground snow load can be determined from Figure 16 on page 23. Combining terms, the equation shortens to:

$$P_f = 0.7 \times C_e \times P_g$$

Roof load calculation example: An outdoor cooler 10 ft wide x 14 ft long will be built in southern Minnesota where the ground snow load is 40 psf. The cooler will be attached to an existing building of about the same height, resulting in no drifting onto the cooler roof. There are other nearby buildings and a shelterbelt of trees to the windward side of the farmstead. Based on this description, the cooler is sheltered and would have an exposure factor of 1.2. The design snow load would be 0.7 x 1.2 exposure factor x 40 psf ground snow load = 34 psf. The total design load would be 10 psf flat roof load + 34 psf design snow load = 44 psf.

Additional loads can occur from drifting snow. This is particularly an issue if the cooler is attached to a building with a higher roof. Contact your local building inspector, building contractor, or a structural engineer for assistance in determining the design drifting load. If coolers are located outdoors, a roof slope of one-quarter to one-half inch per foot of width is recommended to prevent ponding on the roof. Coolers in areas with high snow load may require a gabled roof to reduce the snow load. Wind clips or hurricane ties should be used to anchor ceiling joists or roof trusses securely to the walls.

Now that the roof load has been determined, Table 7 is used to determine ceiling joist sizing. If the lumber size indicates "Beam required," the span is too wide for the load to be supported by lumber up to a 2x12. This will require a supporting beam in the center of the ceiling to narrow the span.

Joist selection example: Continuing from the previous example, the total design load was 44 psf. Referring to Table 7, locate the row corresponding to a 10 ft ceiling span and a 50 psf ceiling load (always round up to the next larger load). The value in the right column indicates that 2x8 lumber will be needed for the ceiling joists.

If the cooler is outdoors, a truss rafter (beamed roof), rather than ceiling joists and a flat roof, can be used to enable the roof to shed rain and snow. Contact a truss rafter supplier to determine the proper size. A minimum of a 4/12 roof pitch would be recommended to aid in shedding snow. The roofing materials can consist of steel roofing or asphalt shingles. It is recommended that the gable ends be enclosed to prevent snow, rain, insects, and rodents from entering, but they need to be well-ventilated to reduce heat build-up under the roof. Natural airflow vents or a thermostatic-controlled power vent fan can be used to provide ventilation under the roof. If the gable ends are left open, a rubber membrane should be installed over the cooler to protect the insulation from moisture and to prevent water from ponding on the ceiling.

Table 7. Ceiling joist dimensional lumber size spaced 24 in. on center.

Span (ft)	Ceiling load (psf)	Lumber size (nominal inch)
8	30	2 x 6
10	30	2 x 6
12	30	2 x 6
14	30	2 x 6
8	50	2 x 6
10	50	2 x 8
12	50	2 x 10
14	50	2 x 12
8	70	2 x 8
10	70	2 x 10
12	70	2 x 12
14	70	Beam required
8	90	2 x 8
10	90	2 x 10
12	90	2 x 12
14	90	Beam required
8	110	2 x 10
10	110	2 x 12
12	110	Beam required
14	110	Beam required

Source: Southern Pine Span Tables, Southern Forest Products Association.

Electrical wiring

Wiring for a walk-in cooler must meet the requirements of the National Electric Code and any local electrical codes. All fixtures, outlets, and switches in walk-in and drive-in coolers must be rated for wet environments. Any outlets in or near the cooler must be protected by a ground fault circuit interrupter (GFCI). The type of wiring also needs to meet code for wet environments. In most municipalities, you will need a permit from the building inspector to change or add wiring to a building. When hiring an electrician, make sure they have experience with agricultural wiring requirements in Section 547 of the National Electric Code, as it differs from commercial or residential wiring.

Cooler lighting

Adequate lighting inside the cooler is important for safety and for visually monitoring the condition of the produce. A level of 10 foot-candles is the minimum recommendation. If any inspection of produce is performed in the cooler, a level of 50 foot-candles is recommended at 30 in. above the floor.

Typically, lighting is 1 to 2.5 W per square foot of floor space for linear fluorescent lamps at 15 and 50 foot-candles, respectively, and 0.5 to 1.5 W per square foot of floor space for LED (light emitting diode) lamps. LED lamps are recommended, because they provide good light quality and maintain light output at cold temperatures. If either LED, compact fluorescent (CFL), or halogen screw-in lamps are used, they must be housed in wet-rated fixtures such as a jelly jar (Figure 18). If LED or CFL lamps are to be used in a jelly jar, they must be rated for installation in an enclosure (see lamp packaging), or they will overheat and fail prematurely. Low-profile linear fluorescent fixtures can also be used. A T8 fluorescent lamp would be preferred over a T5 fluorescent lamp due to the greater light output of the T8 at low temperatures. All light fixtures, switches, and wall outlets install inside a cooler **must** be rated for wet environments as required by the National Electric Code.

Figure 18. LED wet-rated *jelly jar* style ceiling fixture. (Sanford)

Cost comparison: built-in-place vs. prefabricated coolers

To construct a built-in-place cooler 12 ft square and 8 ft tall using conventional stud framing techniques (not including the floor), construction materials will cost approximately $2,700, and the self-contained refrigeration unit will cost $2,900 to $3,750, for a total materials cost of $5,600 to $6,450. Labor is estimated to cost an additional $2,700, bringing the total cost of a built-in-place cooler to between $8,300 and $9,150.

New prefabricated panels for a cooler of the same size will cost approximately $5,100, and the integrated refrigeration unit adds $3,200, for a total materials cost of about $8,300. Owing to the rapid setup of prefabricated coolers, labor costs are negligible. A used prefabricated cooler with refrigeration costs approximately $5,500.

Table 8. Estimated cooler cost comparison.

12 x 12 ft and 8 ft tall	Materials/Unit	Refrigerator unit	Installation labor	TOTAL
Built-in-place cooler	$2,700	$2,900 - 3,750	$2,700	$8,300 - 9,150
Prefabricated cooler	$5,100	$3,200	(minimal)	$8,300

Scott A. Sanford

This example illustrates that the cost of materials and refrigeration for a built-in-place cooler are less than that of a prefabricated cooler of the same size, but the additional labor required to construct a built-in-place cooler makes their total costs comparable. Prefabricated coolers have the advantage of being quick to set up, tightly sealed, and easily expanded or moved if needs change. The prefabricated cooler will retain resale value, because it can also be easily disassembled and sold. A built-in-place cooler is not typically easy to disassemble and move.

CONVERSION OF AN EXISTING ROOM

In some instances, retrofitting part or all of an existing building may be more cost effective than constructing a new built-in-place or prefabricated cooler. A milk house in an unused dairy barn or the end of a building might easily be converted to a cooler. Several considerations must be made.

Any fiberglass or loose-fill insulation should be removed, as it will absorb moisture and fail to provide any insulating value. Over time, wet insulation will cause deterioration in the walls or ceiling and increase energy costs. Use only foam board or foam-in-place insulation in the wall and ceiling cavities (see the discussion of *Types of Insulation* on page 24). The final R-value of the insulation should be 25 to 30 (see the discussion of *Wall Construction* on page 24).

The inside surface should be a washable material that also protects the foam from ignition sources. Typically, reinforced flat or corrugated plastic sheets or metal panels are used.

Any electrical wiring should be updated to meet current electrical code requirements for wet environments, which normally requires replacing all switches, wall outlets, and light fixtures with wet-rated hardware.

Cooler doors should be fully insulated and have a full door seal. A good seal around the door and threshold is important to reduce air infiltration and to keep pests out. If using a standard passage door, foam board insulation can be added to the inside to increase the insulation value. There are companies that specialize in custom cooler doors with higher insulation values and robust hinges that can be installed in a built-in-place or retrofitted cooler. Another option is to purchase new or used cooler doors mounted in a prefabricated panel that can be install into the cooler wall. If the cooler door isn't well insulated, it will have higher heat loss and gain, and it will likely be the site of condensation.

"Any fiberglass or loose-fill insulation should be removed, as it will absorb moisture and fail to provide any insulating value."

The floor should be smooth with no cracks and sloped to a drain. If the current floor is physically sound but the surface is pitted, there are concrete coatings that can be applied in thin layers to recondition the floor. Concrete doesn't bond well to concrete without chemical or mechanical preparation first. Follow manufacturer's instruction for best results.

Environmental control

Accurately controlling temperature and humidity of the storage environment is essential to maintaining produce quality. Sub-optimal storage conditions can lead to unacceptably high spoilage or a greater amount of culling and trimming. Even under optimal environmental conditions, a crop entering storage in poor condition will have a short shelf-life and should be marketed sooner. Environmental control involves maintaining the required air temperature, relative humidity, and uniform air distribution in the storage room. Spoilage can occur if any one of these is not maintained within an acceptable range.

Figure 19. Ceiling-mounted evaporator units. (Sanford)

Ventilation systems

Ensuring uniform air circulation to all areas of the cooler is essential for removing respiration heat and maintaining a uniform product temperature. Generally, a minimum airflow rate of 10-15 cubic feet per minute (cfm) per ton of produce is required, but many crops will require higher airflow rates during curing or field heat removal periods.

In a typical cooler, the evaporator fan units are suspended just below the ceiling along one end with all the fans blowing in the same direction (Figure 19). In this arrangement, cold air moves across the ceiling, down the opposite wall, across the floor, through or around the stored produce, and then back up the wall behind the evaporators before being cooled and recirculated again (Figure 20).

Containers should not be stacked any higher than the evaporators so that airflow can reach the opposite wall. A space of 8 to 10 in. should be left between the end walls and the boxes of produce, and 4 to 6 in. between the sidewalls and the boxes of produce (Figures 20 and 21). When stacking pallet bins, the fork entry openings should be oriented in the direction of the airflow to promote

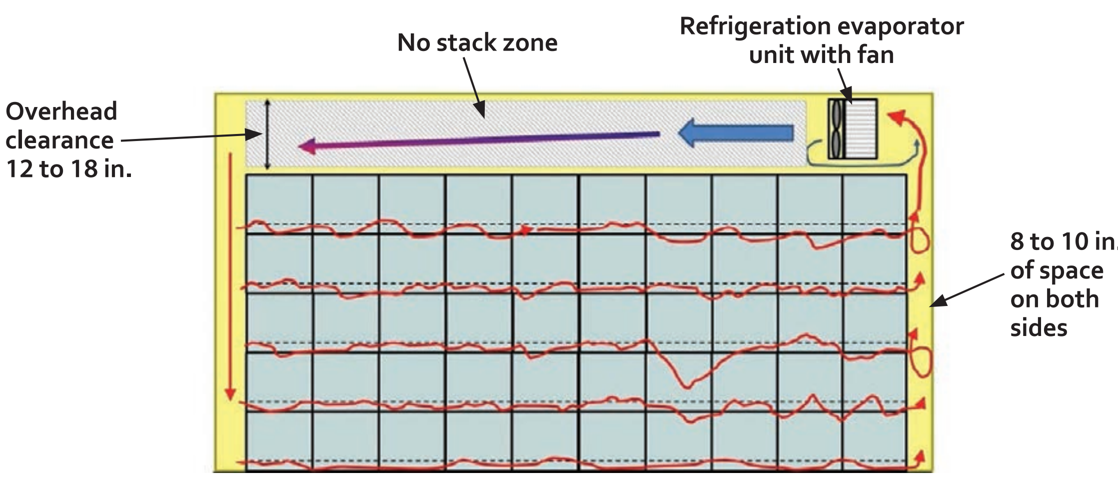


Figure 20. Cooler airflow. (Sanford)

as much air circulation around the bins as possible (Figure 21). The disadvantage of this arrangement is that positive airflow is not present to move air into the produce stored in the container. This means there is limited air exchange and removal of field heat if rooms are filled with warm-harvested produce all at once. Studies indicate clean product in pallet bins loaded as described in rooms with properly designed cooling equipment will remain at the desired uniform temperatures following removal of field heat.

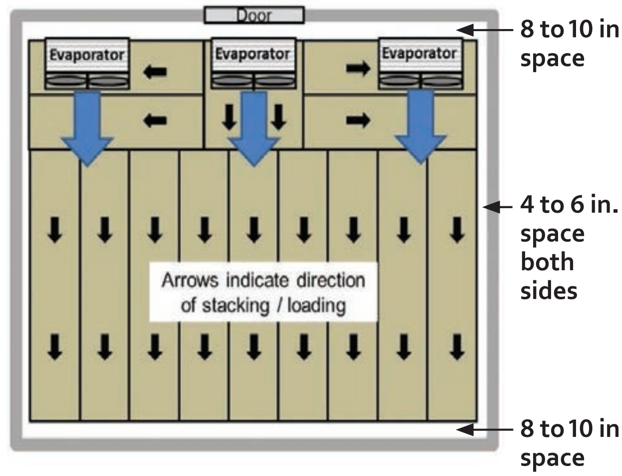


Figure 21. Stacking pattern for maximum cooling. (Sanford)

PLENUM WALL

A plenum wall can be used for faster cool-down of produce and to remove field heat – advantageous for summer and early fall produce (Figure 22). Plenum walls can also be used for more positive air circulation for long-term storage of sensitive crops. It is a little more expensive to build than a standard cooler, and the plenum area reduces the number of bins a cooler can hold.

The location of the evaporator changes with a plenum wall. It is mounted in the wall with the fans blowing into the plenum to force the air through the bins. The humidifier should also be located in the plenum. If the humidifier is located in the main produce space, all of the air entering the plenum will have been dehumidified before coming in contact with the produce. The produce needs to be stored in pallet bins with slotted bottoms and 2-way fork entry openings. A plenum wall has openings that align with the fork entry openings under the pallet bins. In all rows, there should be slots in the plenum wall for every other bin vertically as illustrated in Figure 22.

Pallet bins must be configured specifically for use with plenum walls. Bins should have 2-way fork entry openings, and the base of the bin parallel to the fork entry openings should have solid sidewalls. The floor of the bin should be meshed or slotted with 8 to 11% opening, and

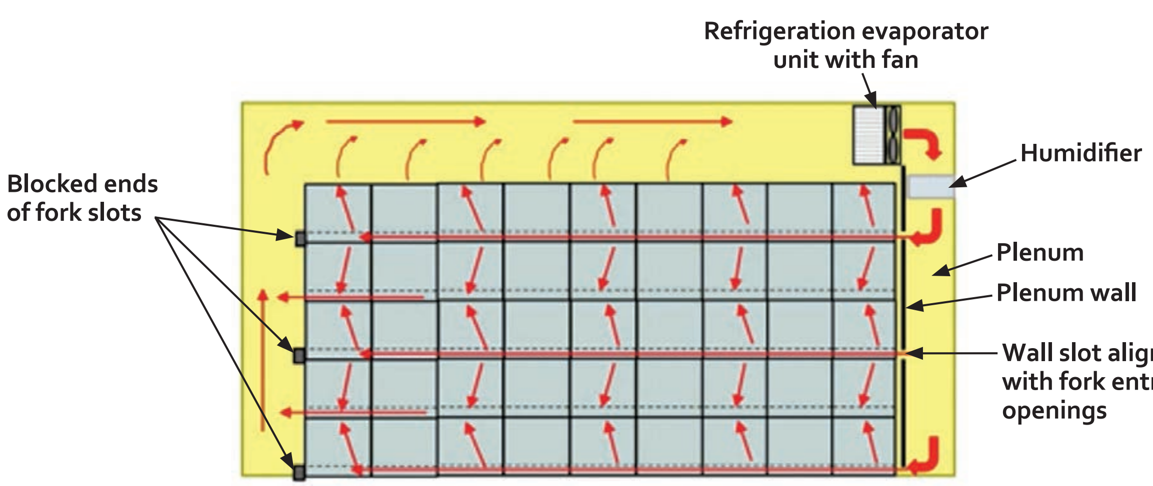


Figure 22. Storage room with plenum wall. (Sanford)

the bin height must match the wall openings (Figure 23).

The bins are stacked tightly against the plenum wall so that the fork entries are aligned with the wall slots and the fork entries align in each row to form an "air duct." At the opposite end, the fork entries in the rows that align with the wall slots are blocked, forcing the air through the produce in the bins above and below, while the fork entries in rows that do not align with the wall slots serve as the exhaust ducts back into the room.

Figure 23. Stacked pallet bins with 2-way fork entry. (Sanford)

BULK STORAGE AIR CIRCULATION

Crops suitable for bulk storage include potatoes, onions, beets, cabbage, parsnips, pumpkins (processing type), rutabagas, sweet potatoes, turnips, and winter squash. A pallet bin system may be a better choice than a bulk system from a labor standpoint if a grower does not have access to bulk handling equipment, such as self-unloading wagons or trucks, conveyors, pilers, and scoops. Bulk storage does not provide any advantages from a quality perspective. If crops are to be stored directly from the field without presorting or pregrading, pallet bins can be taken to the field and loaded directly to avoid extra handling.

Figure 24. Air distribution pipe with holes. (Sanford)

Figure 25. Potato storage with on-floor ventilation piping ready for new harvest. (Sanford)

If crops are piled in bulk storage, air must be forced through the crop for cooling, humidification, and removal of CO_2 and ethylene gas. A bulk storage room will have some type of air distribution system on or in the floor to allow air to enter at the bottom of the pile. There are two ways this is typically done. First, ducts (culvert pipe) with two rows of holes cut through the duct wall can be laid on the floor with the holes located near the floor (Figure 24). One end of the duct is connected to a plenum, and the other end is covered with a cap. Rows of ducts are typically laid 8 to 10 ft apart (center to center) as the storage area is filled (Figure 25). Spacing also depends on the size of the ventilation duct used.

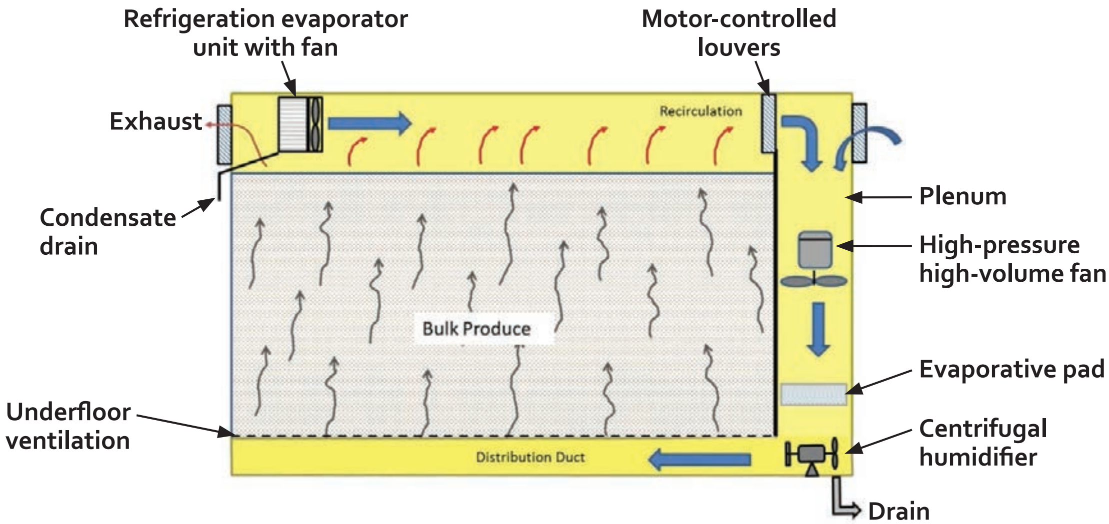


Figure 26. Bulk storage cross-section with underfloor ventilation. (Sanford)

Underfloor ventilation is a second option. Figure 26 shows a cross-sectional view of a bulk storage area with underfloor ventilation. In this storage room, ducts are formed in the concrete floor, and planks are laid in grooves over the ducts, leaving space between planks for air to circulate under the crop (Figure 27). The planks are level with the floor surface and do not interfere with equipment. The air will circulate through the plenum, where it is cooled, mixed with fresh air, and humidified before circulating up through the crop. Additional information on the design of a bulk storage facility can be found in the ASABE Standard EP475.1 entitled *Design and Management of Storage for Bulk, Fall-Crop Irish Potatoes*.

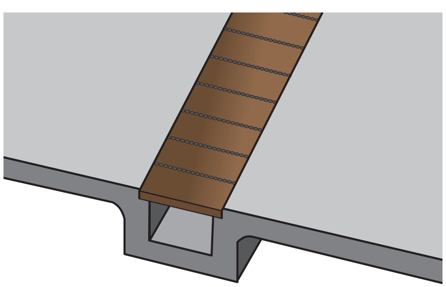


Figure 27. Underfloor ventilation duct. (Sanford)

The ventilation rate in a bulk storage facility should be just high enough to maintain a 1 to 1.5°F temperature difference between the bottom and the top of the pile. Over ventilation increases energy costs and often increases dehydration of the crop. Recommended ventilation rates for common storage crops can be found in the *Crop Profiles* section of this document.

Refrigeration systems

All refrigeration systems for walk-in coolers are not the same. The capacity, size of the evaporator heat exchanger, and controls all have an effect on the ability to control the temperature. Differences are discussed in this section. For a walk-in cooler, the refrigerator system will consist of an evaporator, a compressor, a condenser, and a control. The evaporator is located inside the cooler, typically suspended from the ceiling, and consists of a heat exchanger and fans. The refrigerant enters the evaporator's heat exchanger inside the cooler as a high pressure liquid, and the pressure is reduced through an expansion valve. At low pressure, the refrigerant vaporizes (boils) and absorbs heat from the air, lowering the air temperature inside the cooler. The vaporized refrigerant travels to the compressor which increases the pressure. At higher pressure, the vapor condenses back into a liquid form, and heat is dissipated into the air by the condenser – the heat exchanger outside of the refrigerated space. The liquid refrigerant then travels back to the expansion valve, and the cycle is repeated.

Fans in the evaporator and condenser circulate air over the heat exchangers and increase the rate of heat transfer between air and refrigerant. As air travels through the evaporator, it is chilled, and water vapor in the air condenses on the evaporator heat exchanger. This water must be piped to a drain or routed to a humidifier reservoir. Condensate should not be allowed to drip on produce or dumped on the floor without a place to drain.

Three arrangements of the compressor and condenser are possible: (1) both the compressor and condenser can be located on top or outside of the cooler, (2) the compressor can be located at the cooler with the condenser remotely located, or (3) both the compressor and the condenser can be located remotely. For a small cooler, the compressor and condenser are typically incorporated into a single unit.

The condenser should not be located in an enclosed area unless ventilation is adequate enough to remove heated air and replace it with cooler, ambient air during warm weather. The lower the air temperature surrounding the condenser, the lower the energy costs. If located outside, placing the condenser on a platform at least three feet above the ground or typical snow level, whichever is higher, is highly recommended. This reduces the amount of potential debris (leaves, dirt, snow, etc.) that can block or cover the condenser's heat exchanger. Blocking or obscuring the condenser results in reduced heat transfer rates and increases the energy required for cooling. If located next to a building, the condenser should be protected from water and snowfall from the building's roof. The best option is to enclose the refrigeration system in a machinery room for better security during the off-season and protection from the weather. However, the room must be vented to exhaust excess heat from the room during warm weather. Air movement through the condenser is critical for heat dissipation.

The condenser should be in a location that can be easily accessed for cleaning. Condensers and evaporators will have dirt and oil build-up on the heat exchanger, which reduces the rate of heat transfer. Cleaning once or twice per year is recommended.

Evaporator fans in a cooler typically run continuously to prevent air stratification in the cooler, increase heat transfer, and remove respiration gases. The fans can be a major component of the operating cost of a cooler. When purchasing new equipment, consider evaporator units with electronically commutated motors (ECM), because they are 30 to 35% more efficient than permanent split capacitor (PSC) or shaded-pole motors. They can reduce the energy costs to operate a small walk-in cooler by $15 to $90 per year.

The rejected heat from the refrigeration system can be used for space heating, or the heat can be captured in a refrigeration heat recovery unit to preheat water. This type of unit can recover up to 50% of the rejected heat in the form of warm water. The unit is installed in series with a water heater such that water drawn into the water heater first passes through the refrigeration heat recovery unit. Refrigeration heat recover units are most useful during warm months when the refrigeration and water needs are highest. However, the unit will not offset much heating costs during the fall, winter, and spring months when refrigeration requirements are typically lower.

REFRIGERATION CONTROLS

The basic controls for a refrigeration system regulate the temperature, but controls are also needed to defrost the evaporator. More advanced controls can regulate the refrigerant pressures and shut the system down if unsafe conditions occur. Controls for refrigeration are usually supplied by the refrigeration system installer and should be housed in an enclosure that meets the requirements of the surrounding environment, usually a wet or wash-down rated environment. A basic control has several adjustments including set point and differential temperatures. The set point is the temperature at which the control will turn on the refrigeration, and the differential is the degrees of temperature below the set point at which the control will turn off the refrigeration. Sometimes these are referred to as the cut-in point and the cut-out point, or refrigeration on and refrigeration off, respectively.

Refrigerator system controls are electromechanical or electronic. Electromechanical controls will have a knob or some type of screw adjustment to control the set-point temperature and a sensor that is filled with a fluid that expands and contracts as the temperature changes. The sensor can be mounted to the control enclosure, or it will have a 6 or 10 ft capillary tube (small tube attached to the sensor) that must be placed inside the cooler. The length of the capillary tube will restrict the placement of the attached control to within 6 to 10 feet of the cooler. Electromechanical controls are lower in cost and reliable but lack the resolution and differential adjustment necessary for controlling a storage room at near freezing.

Electronic control have an electronic sensor attached by a wire. They can be finely tuned, because the control can be set to a numerical value and have differential temperatures as small as 1°F, providing a greater temperature resolution than electromechanical controls. They also have other adjustments such as anti-short cycle delay to keep the system from frequently cycling on and off. Because the wire attaching the sensor to electronic controls can be of any length, the control itself can be installed further from the storage room at a convenient location. This also allows controls for multiple storage rooms to be located in one place for convenience.

"Produce often has a freeze point of just below 31˚F, so the margin for error is small."

The differential adjustment or the cut-out temperature is very important if storage rooms are to be kept at or near 32°F so as not to freeze the produce. Produce often has a freeze point of just below 31°F, so the margin for error is small. The temperature drop across the evaporator (difference in temperature between air that enters and exits the evaporator) is also important. If you purchase a refrigeration system configured for a walk-in grocery store or beer cooler, it likely has an evaporator with a high temperature drop, typically with air exiting at 7°F lower than the room temperature. Therefore, you are very apt to freeze something if the set point is below 36°F.

REFRIGERATION SIZING

The refrigeration capacity for a cooler must take into account: heat gain or loss by conduction through cooler walls, ceiling, and floor; infiltration heat gain or loss from air exchange through crack(s) in walls and from opening the door; removal of field heat (initial cooling of produce down to the cooler set-point temperature); removal of the heat of respiration; and equipment heat gain from lights, fans, forklifts, and people working inside the cooler.

Conduction heat gain or loss

Heat is gained when the surrounding air temperature is higher than the temperature inside the cooler, and heat is lost when the surrounding air temperature is lower than the cooler temperature. The conduction heat gain or loss per day by each component of the cooler enclosure (Q_{cond}) is calculated by multiplying the maximum expected temperature difference between the inside and outside of the cooler by the surface area (ft²) of the component (wall, ceiling, or floor) divided by its R-value and multiplying the total by 24 hours. The following equation can be used to calculate heat gain or loss for each individual component of the cooler enclosure.

$$Q_{Cond} = [A \times (T_o - T_i) \div R] \times 24 \text{ hours}$$

Q_{Cond} = Conduction heat gain or loss (Btu/day)

A = Area of walls, ceiling, or floor (ft²)

T_o = Outside temperature (°F)

T_i = Inside temperature (°F)

R = R-value of walls, ceilings, or floor (hr-ft² -°F/Btu)

The total conduction heat gain or loss of the cooler enclosure (Q_{TCond}) is the sum of conduction heat gain or loss of all components:

$$Q_{TCond} = Q_{Cond\ Walls} + Q_{Cond\ Ceiling} + Q_{Cond\ Floor}$$

Insulation value of a wall or ceiling made of multiple materials

How is the overall insulation value of a wall or ceiling determined if it is made of multiple materials (Figure 28)? The total R-value (R_T) of a building area with the same construction (wall, ceiling, floor) is the sum of all the R-values of each component as follows:

$$R_T = R_1 + R_2 + R_3 + \ldots R_n$$

The R-values for individual materials can be found on manufacturers' specification sheets or generic tables of building materials. The example wall section has sheet metal siding, 3½ in. of polystyrene foam insulation, covered by ⅜ in of CDX plywood. Individual R-values are as follows:

Metal siding: 0
Polystyrene foam (rated at R5 per inch): 3.5 in. x 5 = 17.5
Plywood: ⅜ in = 0.47
Inside and outside air film = 0.34

The total R-value of this wall section is:

$$R_T = 0 + 17.5 + 0.47 + 0.34 = 18.3$$

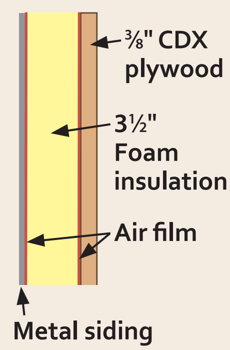


Figure 28. Example wall materials. (Sanford)

If there are different components or construction methods used in a wall or ceiling, the overall R-value (R_O) would weighted by the area (A) of each component compared to the total area as follows:

$$R_O = (A_1 \times R_1 + A_2 \times R_2 + A_3 \times R_3) \div (A_1 + A_2 + A_3)$$

Example. A cooler has a 35 ft² door with an R-value of 15 and a wall that has an R-value of 25 and an area of 165 ft² excluding the door. The overall R-value is as follows:

$$R_O = (35 \times 15 + 165 \times 25) \div (35 + 165) = 23.25$$

If the cooler is outside and exposed to the sun, an allowance should be made to compensate for the radiant heating of the outside surfaces of the cooler. This allowance in degrees is added to the temperature difference used to calculate the conduction heat gain. Allowances listed in Table 8 are affected by the surface color and the direction of exposure to the sun. Using Table 8, if a cooler has a flat roof with black rubber roofing (go to the first row for dark-colored surfaces and move to the last column for flat roof), we find an allowance of 20˚F. If the roof was covered with the recommend white roofing, the allowance would be only 9˚F. If the outside design temperature is 95˚F and a cooler temperature is 35˚F, the temperature differential would be 60˚F with an added allowance of 20˚F for the black roof for a total of 80˚F. This is used to calculate the conduction heat gains for the roof component.

Table 8. Outside design temperature correction for solar radiation (˚F).

Type of surface	East wall	South wall	West wall	Flat roof
Dark-colored surfaces: tar roofing, black paint	8	5	8	20
Medium-colored surface: unpainted wood; brick-red tile; dark cement; red, grey or green paint	6	4	6	15
Light-colored surfaces: white stone, light-colored cement, white paint	4	2	4	9

Source: Butler et al., 1956.

Air exchange

Infiltration heat loss is primarily due to the opening and closing of the cooler door and can be estimated using Table 9. Heavy use is defined as four or more openings per hour, average use is two to three openings per hour, and light use is one opening per hour or less. This should be the peak use that coincides with the hottest time of the day, typically mid-afternoon. The outside air that enters the cooler must be cooled to maintain the

Table 9. Average air changes per 24 hours for cooler temperatures above 32˚F

Volume (cubic feet, ft^3)	Light use	Normal use	Heavy use
200	26	44	88
300	21	35	70
400	18	30	60
500	16	26	52
600	14	23	46
800	12	20	40
1,000	10.5	17.5	35
1,500	8.5	14	28
2,000	7	12	24
3,000	6	9.5	19
4,000	5	8.2	16.5
5,000	4.5	7.2	14.5
6,000	4	6.5	13
8,000	3.3	5.5	11
10,000	3	4.9	10
15,000	2.4	3.9	8
20,000	2.1	3.5	7
25,000	1.8	3	6
30,000	1.6	2.7	5.5
40,000	1.4	2.3	5
50,000	1.2	2	4
75,000	1	1.6	3
100,000	0.8	1.4	3
150,000	0.7	1.2	2.5
200,000	0.7	1.1	2.2
300,000	0.6	1	2

Source: Butler et al., 1956.

cooler set-point temperature. Table 10 provides the Btu per cubic foot (Btu/ft^3) of air that must be removed to reduce the outside air temperature to the cooler set-point temperature. For refrigeration sizing, the outside air temperature should be based on the warmest expected temperature during the operational period of the cooler.

Table 10. Heat removed by refrigeration from air exchange.

Storage room temperature (˚F)	Btu/ft^3 of air							
	85˚F		90˚F		95˚F		100˚F	
	50%	60%	50%	60%	50%	60%	50%	60%
50	1.32	1.54	1.62	1.87	1.93	2.22	2.28	2.65
45	1.50	1.73	1.80	2.06	2.12	2.42	2.47	2.85
40	1.69	1.92	2.00	2.26	2.31	2.62	2.67	3.06
35	1.86	2.09	2.17	2.43	2.49	2.79	2.85	3.24
30	2.00	2.24	2.26	2.53	2.64	2.94	2.95	3.35

Source: Butler et al., 1956.

The infiltration loss (Q_{infl}) can be calculated from the formula:

$$Q_{infl} = \text{volume of cooler room (ft}^3) \times \text{air changes per 24 hr (Table 9)} \times \text{specific heat of the air (Btu/ft}^3\text{)(Table 10)}$$

Product load

Field heat is the energy that must be removed from the produce to cool it to the set-point temperature of the cooler. It is the largest component of the cooling requirement unless the produce is precooled to near the storage temperature before entering the cooler. The field heat is usually less for fall-harvested crops than for summer-harvested crops. The rate of field heat removal to maintain crop quality will vary depending on the recommended time to cool the produce. It can range from a few hours to a day. Slow field heat removal causes higher respiration rates, moisture loss, and shorter storage life of produce. The field heat load (Q_{FH}), or the rate at which field heat must be removed from produce, can be calculated by:

$$Q_{FH} = M \times C \times \Delta T$$

Q_{FH} = Field heat removal rate (Btu/24 hr)

M = Mass of produce (lb)

C = Specific heat of produce (Btu/lb/˚F)

ΔT = Temperature drop in 24 hours (˚F)

The specific heat (C) for most produce is about 0.9 Btu/lb/˚F. Specific heat for individual crops can be found in the *Crop Profiles* section.

Metabolic activity in the form of respiration will continue after the produce is harvested. Respiration is the oxidation of sugars that produce carbon dioxide, water, and heat. The rate of respiration is temperature dependent and slows as temperature decreases, which is one reason it is important to cool most produce rapidly. The respiration heat load (Q_{Resp}) is calculated with the following equation:

$$Q_{Resp} = M \times (K \div 2{,}000 \text{ lb})$$

Q_{Resp} = Respiration heat load (Btu/day)

M = Mass of produce (lb)

K = Rate of respiration heat production (Btu/day-ton)

The heat of respiration (K) for a particular crop can be found in the *Crop Profiles* section.

Supplemental loads

All energy expended inside a cooler will eventually end up as heat inside the cooler space, because energy cannot be destroyed only changed in form. Heat gain can be generated internally by fans, lights, forklifts, and people working in the cooler. Table 11 lists the heat gain from motors operating inside a cooler such as an evaporator fan, humidifier, or damper motors.

Use the following equation to calculate the internal heat gain (motor heat load, Q_{motor}) from motors:

$$Q_{Motor} = \text{motor Hp x heat gain factor (Table 11) x hours of operation}$$

For example, a ⅓ Hp evaporator motor that is operated continuously will have:

$$Q_{Motor} = 0.33 \text{ Hp x } 4{,}250 \text{ Btu/(Hp-hr) x } 24 \text{ hr/day} = 33{,}672 \text{ Btu/day}$$

The heat gain from electric lamps or heaters (Q_{Light}) is equal to the lamp or heater rating in watts (W) (including any ballast), multiplied by 3.41 Btu/(watt-hr) and hours of use.

$$Q_{Light} = \text{heater rating x } 3.41 \text{ Btu/(watt-hr) x hours of use}$$

For example, a fluorescent lamp that uses 64 W and is operated 6 hr/day will have:

$$Q_{Light} = 64 \text{ W x } 3.41 \text{ Btu/(watt-hr) x } 24 \text{ hr/day} = 5{,}236 \text{ Btu/day}$$

Even though the lights are used 6 hrs, the maximum of 24 hrs is used for refrigeration sizing.

People also give off heat that has to be removed by the refrigeration system. This pertains to people working in the cooler during peak cooling hours. The heat addition depends on the cooler temperature (see Table 12).

$$Q_{People} = \text{number of people x heat equivilent per person (Table 12) x 24 hrs}$$

For example, two people are sorting produce three hours per day in a cooler that is maintained at 40°F. From Table 12, the heat gain from the workers (Q_{People}) is 840 Btu/hr-person. The total heat gain from the workers is:

$$Q_{People} = 2 \text{ people x } 840 \text{ Btu/(hr-person) x } 24 \text{ hrs} = 40{,}320\text{/day}$$

Even though the workers were only in the cooler for 3 hours, maximum (24 hr) demand is used for refrigeration sizing.

Table 11. Heat gain from the work of motors located inside a cooler.

HP	Btu/(Hp-hr)
⅛ to ½	4,250
½ to 3	3,700
3 to 20	2,950

Source: Butler et al., 1956.

Table 12. Heat equivalent per person working in cold-storage room.

Temperature of cold-storage room	Heat equivalent (Btu/hr-person)
50	720
40	840
30	950
20	1,050
10	1,200

Source: Butler et al., 1956.

Total refrigeration capacity

The total refrigeration sizing (Q_{Ref}) is the sum of all the heat loads in units of Btu/day (even if the load was only for a short period of time): conduction heat gain, air exchange, product load, and supplemental loads. The total 24 hr load is then divided by either 16 hr or 18 hr of refrigeration operation to provide a safety factor.

$$Q_{Ref} = (Q_{TCond} + Q_{Infl} + Q_{FH} + Q_{Resp} + Q_{Motor} + Q_{Light} + Q_{People}) \div 16 \text{ hr}$$

REFRIGERATION EVAPORATOR SIZING

As high-humidity air in the cooler is cooled by the refrigeration system, water vapor condenses on the cold refrigerant coils, and the relative humidity of the air in the cooler is reduced. The degree of dehumidification will depend on the temperature difference between the air that enters and exits the evaporator (temperature drops). When the temperature difference across the evaporator is low, the amount of humidity removed from the air will also be low. Ideally, the temperature difference should be about 1°F to maintain 95% RH. This requires an evaporator with a coil designed for high humidity using a low temperature drop and a high airflow rate (1,500-1,900 cubic feet per minute/ton of refrigeration) compared to a typical walk-in grocery store or beer cooler. The evaporator will have more surface area and a higher cost than that of a beer cooler refrigeration system. If your refrigeration specialist does not understand the difference, you need to find one with experience in the vegetable or fruit industry.

Table 13. Minimum relative humidity levels[1] at various temperature differences between the set-point temperature and the evaporator coil temperature.

Temperature difference[2] across evaporator (°F)	Cooler set-point temperature (°F)		
	32	35	38
-1	95.8%	96.1%	96.1%
-2	91.2	92.3	92.4
-3	87.1	88.7	88.8
-4	83.0	84.7	85.3
-5	79.4	80.9	82.0
-10	62.7	64.1	65.3
-15	49.3	50.5	49.4

[1]Calculated from psychrometrics tables.

[2]Actual airstream temperatures between inlet and outlet. The temperature difference between the cooler and the evaporator coil will be approximately twice this value.

Source: Bartsch & Blanspied, 1990.

Table 13 shows the maximum relative humidity level that can be maintained based on the temperature difference across the evaporator and the cooler set-point temperature. An evaporator coil temperature only 2°F below the room temperature (air temperature drop of 1°F across the coil) will maintain a relative humidity of 95%. A coil temperature 4 to 5°F below room temperature (air temperature drop of 2 to 2.5°F) reduces the relative humidity to 90%. While 90% RH may seem high, it is too low for long-term storage of many crops. If a temperature of 32 to 35°F is needed, an electric defrost unit will be required to prevent ice from building up on the evaporator.

SMALL REFRIGERATION SYSTEMS

Room-sized air conditioning (AC) units can be used to cool small coolers with the addition of an external control to override the unit's control and achieve lower temperatures. A typical AC unit is normally operated in the 70 to 80°F range. For the proper storage of fruits and vegetables, the air temperature needs to be in the 32 to 50°F range with the most common set point near 38°F. A company call Store-it Cold sells an overriding control called a COOLbot™ which enables a room-sized AC unit to cool to as low as 35°F. This setup is has a low initial cost – a room-sized air conditioner and a COOLbot™ are cheaper than a conventional refrigeration system. In addition, the unit can be installed by the grower without the need to hire a refrigeration specialist. The biggest disadvantage is that a room-sized AC unit does not have the refrigeration capacity to rapidly remove field heat from much produce, because an air conditioner has less capacity (Btu/hr) at temperatures lower than its minimal design temperature (~75°F).

A report published by the New York State Energy Research and Development Authority indicated that room-sized AC units can be safely operated at lower temperatures than their intended use. Although the refrigeration cycle is 16 to 22% less efficient than that of a conventional walk-in cooler refrigeration system, the overall efficiency is slightly better, because the condenser and evaporator fans do not run continuously. The fan in a room-sized AC unit operates intermittently (only on when cooling), while the fan in a conventional refrigeration system runs continuously to provide air mixing.

If the fans of a conventional refrigeration system are operated intermittently, the room-sized AC unit will use 12-16% more energy, or an additional 100-500 kWh per season, to maintain the same conditions in a 100 to 250 ft^2 cooler. Intermittent fan operation can be a disadvantage, because a lack of air circulation can result in a lower rate of heat transfer from the stored crop as well as possible stratification of the air in the refrigerated space. A small basket fan running continuously could be used to circulate the air and prevent stratification, but this would result in a total energy consumption comparable to that of a standard refrigeration unit.

Small, self-contained refrigeration systems for walk-in coolers are also available. They can be mounted in the wall or roof of a cooler and simply plugged in (Figure 29). These units are typically limited to ¼ HP (2,400 Btu/hr) to 2 HP (15,000 Btu/hr) and operate on 120 or 230 V electrical power depending on size. They are available in a side-mount or top-mount, and weather protected models are available for use outside. A side-mount unit will extend into the cooler which can be an obstruction, while a top-mount unit will be flush with the ceiling and will not act as an obstruction when filling the cooler. As with COOLbot™ units, these systems do not require a refrigeration technician for installation.

Self-contained refrigeration units have two main advantages over room-sized AC units with the COOLbot™ control. First, they are built for cold storage operating conditions and have specified cooling capacities published over a range of environmental conditions, so there is no guess work in choosing a capacity. Second, they have built-in, high-capacity circulating fans that can be programmed to continuously

"Intermittent fan operation can be a disadvantage, because a lack of air circulation can result in a lower rate of heat transfer from the stored crop as well as possible stratification of the air in the refrigerated space."

Figure 29. Side-mounted, self-contained refrigeration unit (evaporator and blower) shown from the outside (left) and inside (right) of the cooler. (Barr, Inc.)

Table 14. Typical refrigeration capacity for different sized coolers.

Cooler size (w x l x h) (ft)	Room volume (ft^3)	+32˚F Typical load[1] (Btu/hr)	+32˚F Heavy load[2] (Btu/hr)	+40˚F Typical load[1] (Btu/hr)	+40˚F Heavy load[2] (Btu/hr)
8 x 10 x 8	640	6,710	8,700	5,570	7,080
10 x 14 x 8	1,120	8,910	11,860	7,100	9,280
14 x 16 x 10	2,240	13,920	18,740	10,690	14,110
18 x 20 x 10	3,600	19,600	26,570	14,660	19,480
20 x 24 x 10	4,800	24,430	33,190	18,020	23,970
20 x 40 x 10	8,000	36,530	49,250	26,270	34,550

[1]Typical load assumes 2 lb of product per cubic foot (ft^3) of cooler volume entering per day at 50˚F and cooled to cooler set-point temperature in 24 hrs; 25% of volume with carrots for respiration load; 95˚F outside temperature; R-value of walls and ceiling are 25; uninsulated floor at 55˚F; average air exchange rate is less than 3 openings per hour; internal loads of 1 HP per 16,000 ft^3; lighting at 1 W/ft^2; 1 person load per 25,000 ft^3; 16 hr run time; plus a 10% safety factor.

[2]Heavy load assumes the same conditions as a typical load with twice the air exchange rate (4 openings per hr or more) and 3 lb of produce per ft^3 of cooler volume.

Adapted from Quick Load Calculations, Heatcraft Refrigeration Products, www.heatcraftrpd.com/PDF/MQuick Load Calculations.pdf

circulate the air, resulting in faster cool down of produce.

Electronic controls are a built-in component of refrigeration systems. When installed outdoors, a refrigeration system must be rated for outdoor use with an electrical system designed to withstand wet conditions. They are also design to run even in cold weather. These self-contained units do not necessarily have the low temperature drop across the evaporator as previously discussed.

Further information on refrigeration systems can be found in the *Additional Resources* section at the end of this document.

Table 14 has some estimated refrigeration capacities based on different cooler temperatures; maximum product loading rates per day; wall, ceiling, and floor insulation values; air exchange rates; internal loads; and run times. These are examples and do not reflect the full range of possible conditions.

Heater sizing

Coolers that are used during the winter and located outside, in an unheated building, or have exterior wall(s) exposed to the outdoors will need a heater inside the cooler in northern climates to keep the cooler air temperature from dropping below the critical storage temperature for the produce being stored.

The critical temperature might be the freezing point for crops stored near freezing or the chilling point for other crops. The heater needs to be sized to offset heat losses through the walls of the cooler and air exchange when the outside temperature is below the set-point temperature of the cooler. The heater size will be the sum of the conduction heat loss plus the air exchange heat loss minus the product respiration heat generation and the supplemental loads (lighting, motors, etc.) that would be operating during the coldest time of the day based on a minimum design temperature. A safety factor of 1.5 would be recommended (heat losses times 1.5). A fan needs to be running whenever a heater is operating to thoroughly mix the air and to prevent warm spots that could affect the product. An electric heater will be the lowest cost and allows accurate control.

Humidity control

Many growers lose income due to dehydration or spoilage losses, because they do not have the equipment to maintain the proper humidity and temperature. Vegetables are composed mostly of water and are usually sold by weight. If the crop dehydrates, income is lost. Water loss affects quality as well, and wilted but edible produce is difficult to sell.

A study by Van den Berg and Lentz (1977) looked at several crops stored at 32 to 34°F and two relative humidity levels of 90 to 95% RH and 98 to 100% RH. Table 15 shows moisture loss and weight loss due to decay and trimming for two storage seasons.

Results showed longer storage life and lower losses from trimming and decay at the higher humidity level for all vegetables tested. There was 81% less moisture loss and 38% less decay and trimming losses at 98 to 100% RH than at 90 to 95% RH. At the same storage temperature, moisture losses were 0 to 0.5% per month at 98 to 100% RH and 0.7 to 2.0% per month at the lower humidity level.

Table 15. Effect of relative humidity on crop losses.

Vegetable	Storage time (weeks)	Moisture loss (%/month)		Weight loss[1] (%)	
		Relative humidity			
		90 - 95%	98 - 100%	90 - 95%	98 - 100%
Brussels sprouts (individual)	11 - 12	3.4 - 5.2	0.3 - 0.4	40 - 100	20 - 30
Brussels sprouts (on stalks)	11 - 12	4.9 - 10.1	0.2 - 0.3	35 - 100	20 - 35
Cabbage	18	0.8 - 1.0	0.3 - 0.6	15 - 20	10 - 15
Cauliflower	5 - 6	3.0 - 3.9	0.6 - 1.4	15 - 30	20 - 30
Celery	11 - 12	2.2 - 3.1	0.4 - 0.5	70 - 75	45 - 65
Chinese cabbage	11 - 14	0.6 - 2.3	0 - 0.2	25 - 75	20 - 40
Leeks	9 - 11	2.8 - 3.0	0 - 0.8	25 - 30	20 - 30

[1]**Losses due to decay and trimming.**

Results averaged over two storage seasons. Source: Van den Berg and Lentz, 1977.

Table 16 shows the effect of temperature and humidity on storage life for common storage crops. Some crops, such as rutabagas, have a low transpiration (water loss) coefficient, so there is little difference in storage life due to either temperature or humidity. However, high relative humidity can aid in maintaining quality of some crops, such as carrots, despite being stored at higher than recommended temperatures. A 3 to 4% moisture loss in leaf vegetables becomes noticeable, as outside leaves wilt and must be trimmed to make the crop marketable. Softening or wilting is visibly noticeable with a total moisture loss of only 5 to 6% for root crops or cabbage, while 8% moisture loss makes them unsalable. When temperatures are too high for crops like cabbage, high relative humidity does not extend storage life. Physiological changes in cabbage are driven primarily by temperature, so deterioration is dominated more by physiology than decay or moisture loss. In addition, crops that are stored in bulk piles, such as potatoes, can have pressure bruising or indentations due to moisture loss, especially in produce near the bottom of the pile.

Table 16. Effects of temperature and relative humidity on storage life of common storage crops.

Crop	Storage temperature (˚F)	Relative humidity (%)	Storage life (weeks)	Limiting factors
Brussels sprouts	32 - 34	90 - 95	6 - 8	Wilting, decay, yellowing
		98 - 100	10 - 12	Decay
Cabbage	32 - 34	90 - 95	14 - 22	Wilting, decay, yellowing
		98 - 100	18 - 26	Decay, yellowing
	38 - 40	90 - 95	10 - 14	Wilting, decay, yellowing
		98 - 100	12 - 16	Decay, internal growth, rooting
	44 - 46	90 - 95	8 - 12	Internal growth, rooting
		98 - 100	8 - 12	Internal growth, rooting
Carrots	32 - 34	90 - 95	15 - 30	Decay, softening
		98 - 100	30 - 40	Decay, rooting, sprouting
	38 - 40	90 - 95	15 - 30	Decay, softening
		98 - 100	20 - 40	Decay, rooting, sprouting
	44 - 46	98 - 100	20 - 40	Decay, rooting, sprouting
Parsnips	32 - 34	90 - 95	20 - 30	Decay, shriveling
		98 - 100	35	Decay
	38 - 40	90 - 95	15 - 25	Decay, shriveling
		98 - 100	35	Decay
Rutabagas	32 - 34	90 - 95	35	Decay, softening, sprouting
		98 - 100	35	Decay, sprouting
	38 - 40	90 - 95	35	Decay, softening, sprouting
		98 - 100	35	Decay, sprouting

Source: Van den Berg and Lentz, 1978.

METHODS FOR ADDING HUMIDITY

There are three methods for adding humidity to the air inside a cooler to maintain the desired relative humidity: centrifugal humidifiers, misters, and evaporative pads. Centrifugal humidifiers, or atomizers, use centrifugal force to atomize water into fine droplets that evaporate into the air. They feed water onto a spinning disk which propels the water through orifices or slots to break the water into very small droplets. They are used extensively in large storage facilities.

Figure 30. Small-capacity centrifugal humidifier. (Sanford)

Small centrifugal humidifiers are available with capacities starting at 0.4 to 2 gallons of water per hour (gph) and a starting cost of about $300 (Figure 30). Some of the units have fixed humidification rates. Commercial-capacity centrifugal humidifiers have adjustable capacities of up to 24 to 36 gph and a starting cost of about $1,700 (Figure 31).

The humidifier should be adjusted so that the mist it produces can barely be seen and does not wet surfaces in the cooler. Ideally, the humidifier should run about 80% of the time. If the humidifier creates a dense fog in the cooler, the volume of water entering the humidifier should be reduced.

Figure 31. Commercial-capacity centrifugal humidifier. (Sanford)

Misters are a second method to add humidity to the air. Misters use a high pressure pump and a small nozzle to produce finely atomized droplets of water that rapidly evaporate. The mister nozzles can be located throughout the cooler for more uniform distribution. One disadvantage of misters is that they require more maintenance than centrifugal humidifiers, because the very small orifices in the nozzles clog easily. Water quality has a large effect on the amount of maintenance necessary for misters. Atomizers and misters can be used in walk-in coolers.

The third method is an evaporative cooling pad. This method forces air through a medium that is saturated with water. As the air travels through the medium, it picks up water vapor and cools. Evaporative pad coolers are typically used in bulk storage facilities where they can be easily incorporated into the airflow stream. Atomizers or misters are often used in conjunction with an evaporative pad for high humidity requirements (greater than 90% RH).

The amount of humidity needed will vary with the volume of planned air exchange, the volume of air exchanged from the cooler doors being opened and closed, infiltration from leaks, and the ambient air conditions. Some rough rules of thumb for sizing are: 1 gph for every 1,000 cubic feet per minute (cfm) of airflow for a bulk storage facility, or 1 gph for every 1,500 cubic feet of cooler volume. (Personal communication, E. Evans, Gellert Co., 2014.) Humidification capacity will also vary by crop. For example, a capacity of about 0.01 gph per ton is recommended for potatoes.

HUMIDIFIER CONTROLS

Humidifiers can be controlled manually, with a time clock with a cycle timer, or, preferably, with a humidistat. If a time clock or cycle timer is used, the humidifier can be set to operate for a given number of minutes per half hour to maintain humidity levels. A cycle timer can be adjusted to smaller time intervals, 8 minutes of operation per 10-min interval, for example.
On the other hand, the time clock can be adjusted to operate the humidifier more during the day when the cooler door is more likely to be opened

and closed. A cycle timer can also be used in series with a time clock to provide the benefits of both. Both will need to be manually adjusted for seasonal changes in ambient conditions. Some cooler environmental control systems are set to run the humidifier whenever the refrigeration system runs, since the refrigeration system will dehumidify the air. The amount of dehumidification will vary depending on the size of the refrigeration evaporator unit. See the *Refrigeration Systems* section for further information about refrigeration evaporator sizing.

The disadvantage of a time clock or cycle timer is the lack of feedback regarding the current humidity level. A humidistat is the best alternative for maintaining the correct humidity level and protecting the quality of the produce. Humidistats must have the correct range to maintain optimal conditions for the produce. Many humidistats have an upper range of 80 or 90% RH which is not high enough for storage crops requiring humidity levels greater than 90%. To accurately maintain the 95% RH level required for many crops, a humidistat must have a range up to 99% RH.

Humidity controls are less accurate as the room humidity gets closer to the high end of their range. The accuracy specification value, which is given in a plus or minus (+/-) range, represents how close the humidity measurement is to the true humidity value. A low value indicates that the control will maintain the humidity level closer to the desired value. Cost typically increases with the accuracy of the humidistat. An accuracy of +/- 3 or 4% should provide acceptable control at a reasonable cost. Resolution is another term that will appear in a humidistat product specifications. Resolution indicates the smallest change of a measured humidity value that the humidistat can control or display. Resolution is usually less important, though a minimum of at least 1% is desirable. Some humidistats have a resolution of 0.1%.

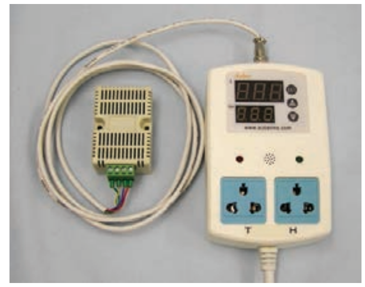


Figure 32. Humidistat with remote sensor. (Sanford)

A device with a remote sensor (Figure 32) is best, because it allows the control to be mounted outside the cooler in a dryer environment. The sensor is located inside the cooler in an optimal location, preferably 5 to 10 fan diameters from the evaporator fans in the path of airflow. Many humidistats are not designed for the humid environment of a cooler and may have a shortened life. The starting cost for a humidistat that meets the above requirements is approximately $140.

Some humidity controls are combined with a temperature control and are designed to prevent condensation in electronic devices. If these controls are used, the temperature must be set low to prevent the control from activating, as they are designed to turn on a heater if the temperature drops to prevent condensation from forming. The temperature control could be used to operate a heater for ensuring the temperature in the cooler does not drop below the critical temperature for the produce being stored.

ALTERNATIVES TO A HUMIDIFIER

Crops stored less than 60 days and/or those that have low ethylene production can be successfully stored in bins lined with perforated plastic bags to create a high humidity microclimate and reduce water loss. The bags should not be tightly sealed. The ends of the bags can be folded loosely over the top of the produce to allow some air exchange. This method reduces water loss but also reduces the rate of heat exchange and respiration gas exchange due to a lack of airflow around the crop. If bagging is used, the produce should be within 1°F of the storage temperature before bagging. Excess moisture should be absorbed or controlled by using burlap and holes in the bottom of the bag, for example. This is a greater issue if the crop is washed and not dried before being placed in bins or bags. Some condensation may occur at the top of the bag, which can cause root development on produce such as carrots.

HUMIDIFICATION ISSUES

Humidification of a refrigerated cooler with an improperly sized evaporator unit is a marginal proposition. If a cold room operates at an undesirably low RH, the issue is likely due to the design of the evaporator coil and refrigerant expansion valve setting. As shown previously, the coil surface temperature must be within 2°F of the desired cooler set-point temperature to maintain a RH above 90% (see Table 13 on page 40).

Obtaining this close temperature difference in a small cooler made of off-the-shelf, plug-and-play hardware is not easy. Often, these units do not have adjustable expansion valves, and typically the evaporator surface area is small compared to the required amount of heat transfer area needed to achieve a 2°F temperature difference.

Used equipment, grocery store beer and soda coolers, and even reefer body refrigeration units are not typically designed to produce storage environments with high relative humidity. These units will maintain temperature after the product is cooled down, but they will not provide adequate relative humidity for longer-term storage. Humidification of such a cooler will produce little if any real improvements; the added humidity will add to the cooling load by freezing on the coil with little overall humidity benefit to the product.

Ethylene

During respiration, crops will produce ethylene, a naturally occurring gaseous hormone that can increase the rate of ripening and spoilage. Ethylene production decreases as storage temperature decreases. Some crops produce higher amounts of ethylene than others, and some are more sensitive to ethylene than others. Ethylene exposure stimulates increased synthesis of ethylene in some crops. Ethylene increases the rate of ripening, formation of adventitious roots, and respiration rate. In addition, ethylene can also increase phenylpropanoid metabolism which can affect fruit pigmentation and disease resistance.

> **"Crops that produce large amounts of ethylene should not be stored in the same cooler with ethylene-sensitive crops."**

Crops that produce large amounts of ethylene should not be stored in the same cooler with ethylene-sensitive crops. Apples and pears are examples of high producers of ethylene. Most root crops are not sensitive to ethylene. Cabbage, brussels sprouts, and broccoli are very low ethylene producers but are highly sensitive to ethylene exposure. Late-season storage cabbage should not be stored in a cold room that has been used for early season apples, because the residual ethylene from the apples will damage the cabbage. Table 17 lists the relative ethylene production and sensitivity of common storage crops. For more information about ethylene production and sensitivity of storage crops, see the *Additional Resources* and *Crop Profiles* sections.

Table 17. Ethylene and odor production and sensitivity of common storage crops.

Crop	Ethelyne production	Ethelyne sensitivity	Produces or is sensitive to odor
Apples	Very high	High	✔
Beets	Very low	Low	
Brussels sprouts	Very low	High	✔
Cabbage	Very low	High	✔
Carrots	Very low	Low	✔
Celeriac	Very low	Medium	
Garlic	Very low	Low	✔
Horseradish	Very low	Low	
Jerusalem artichoke	Very low	Low	
Leeks	Very low	Medium	
Onions (pungent)	Very low	Low	✔
Onions (sweet)	Very low	Low	✔
Parsnips	Very low	Low	
Pears	Very high	High	✔
Potatoes, late crop	Very low	Medium	✔
Radish	Very low	Low	
Rutabagas	Very low	Low	
Shallots	Very low	Low	✔
Turnips	Very low		
Sweet potatoes	Very low	Low	
Winter squash (acorn, buttercup, butternut, Hubbard) and pumpkins	Low	Low	

Adapted from Thompson, 2004 and Wilson, 1999.

Table 18. Storage avoidance recommendations for odor-sensitive crops.

Vegetable	Should not be stored with
Apples	Cabbage, carrots, celery, dairy products, eggs, meat, onions, potatoes
Carrots	Celery
Onions (dry)	Apples, celery, pears
Pears	Cabbage, carrots, celery, onions, potatoes
Potatoes	Apples, pears

Adapted from Kitinoja, 1999 and Wilson, 1999.

Odor sensitivity

Some crops will readily absorb odors emitted by other crops. Onions and garlic are prime examples of crops that emit strong odors that can be absorbed by other crops, such as apples. Crops that emit strong odors are often sensitive to absorbing odors as well. Table 17 lists crops that produce or are sensitive to odors. Table 18 lists some common fruits and vegetables that should not be stored together. It is recommended that apples, onions, nuts, and potatoes each be stored separately.

Controlled atmosphere storage

Some crops can be stored longer or will maintain better quality if the atmosphere, or mixture of gases in the cooler, is modified and controlled. This technique is call controlled atmosphere (CA) storage. CA storage employs refrigeration in addition to reducing the amount of oxygen and increasing the amount of carbon dioxide from ambient levels. An elevated level of carbon dioxide (1-3%) reduces respiration rates. In the Midwest, apples, pears, cabbage, and onions are the main storage crops that can benefit from CA storage while in long-term storage.

The most researched crop stored in CA is apples. Apples can be kept in CA storage for 4 to 12 months, depending on the variety, versus 2 to 4 months in refrigerated ambient-air storage. Typically, CA storage can double the storage life and marketing period of apples. The recommended percentage of oxygen ranges between 1% to 4%, and 1% to 5% for carbon dioxide depending on the apple variety. See the *Crop Profiles* section on apples for CA storage recommendations by variety.

Unless apples, pears, or cabbage are being stored, most fresh market growers will not benefit economically from CA storage due to the crops grown or the relatively short length of storage. For more information, see the *Additional Resources* section on CA storage.

Energy efficiency

Energy efficiency is easiest to incorporate when deciding to purchase a cooler. One of the greatest determinants of walk-in cooler energy use is the insulation level of the walls and ceiling. A greater level of insulation (R-value of 30 recommended) for the walls and ceiling will reduce the amount of energy needed to maintain the temperature of the cooler.

Efficiency measures

Energy use can be reduced further by a number of efficiency measures aimed at minimizing air exchange and reducing internal loads, including:

- Install an automatic door closer to reduce air infiltration.
- Install strip curtains – overlapping, vertical strips of clear, flexible plastic that cover the door opening – to reduce air infiltration when the door needs to be open during loading or unloading. A variation of this is plastic swinging doors. However, swinging doors can be disabled by employees, which negates the potential energy savings.
- Avoid propping cooler doors open for an extended period of time.
- Install LED lights in the cooler. LED lights produce less heat per unit of light than other lamp types, which will reduce refrigeration run time.
- Install electronically commutated motors (ECM) for evaporator and condenser fans, as they use less energy than shaded-pole or permanent split capacitor motors.

Prompt completion of routine maintenance will also improve energy efficiency, such as:

- Regularly clean the evaporator and condenser heat exchangers.
- Replace worn, cracked, or weathered door seals.
- Turn off lights in the cooler when not needed.
- Set the defrost frequency at minimum requirements. Defrosting is needed to ensure unrestricted airflow through the evaporator. Keep in mind that the added heat from defrosting will need to be removed by the refrigeration unit.

Material handling

Material handling is an important consideration when planning a farm or storage facility. Growers move large volumes of materials to and from their fields. A well-planned system can reduce handling which reduces labor and other costs in turn. Consider the different handling requirements of each crop to minimize bruising and other quality issues. Some crops like potatoes, carrots, and onions can be handled and stored in bulk (Figure 33). This reduces labor and handling, especially if the crops can be moved into and out of storage using conveyors. Crops like apples and pears, which are prone to bruising, are typically stored in bins. The size of bins can vary from small totes to pallet bins. Selection of a particular bin size may be affected by the size of the individual vegetables or fruits, how easily the crop can be bruised or damaged, the depth the crop can be piled, type of material handling equipment, size of the cold storage facility, and the type of air handling system in the cooler. The volume of the crop will also influence decisions about container type and size, storage facility size, and handling machinery to minimize labor costs.

Bulk piles

Many root or fall-harvested crops can be stored in bulk piles. Potatoes, carrots, onions, beets, parsnips, rutabagas, sweet potatoes, turnips, pie pumpkins, and winter squash can be piled.

Typically, bulk piles are only justified if there is a large volume of the crop and transport of the crop into and out of storage can be mechanized. Belt conveyors (Figure 33) are most often used to load and unload crops in bulk storage. When loading, it is important to avoid bruising and surface abrasions that can lead to storage issues such as spoilage. Therefore, the height of the conveyor must be easy to adjust so that the crop is not dropped more than 12 in.

Figure 33. Loading potatoes into a bulk storage facility using a conveyor. (Sanford)

The height of the pile varies with crop from 6 to 15 ft. Maximum pile depths are listed in the *Crop Profiles* section at the end of this document. Bulk storage facilities for piling should have on-floor or underfloor ventilation to provide even airflow through the pile to remove respiration heat and ethylene and to keep the crop hydrated. The ventilation system should allow the ducts running on or under the floor to be closed individually. This will ensure that air is forced up through the crop rather than bypassing the crop through the path of least resistance when the bulk storage facility is not full. The section on *Ventilation Systems* offers additional information about planning airflow systems for bulk storage.

When using bulk piles, humidity control is essential to prevent or reduce pressure bruising. Pressure bruising occurs when the crop loses water and is no longer turgid enough to support the weight of crop above, resulting in an indentation and/or bruising.

Storage containers

Pallet bins can be used for all root crops and cabbage. Pallet bins are a good alternative to bulk storage for handling large quantities of produce with reduced labor compared to loading and unloading bulk storage by hand. Tote bins or baskets are useful for small quantities of produce or produce that is easily bruised or damaged.

TOTE BINS AND BASKETS

Tote bins can be made of wood, metal, or plastic. Plastic totes are preferred, because they are lightweight, durable, non-corrosive, easy to clean and sanitize, and do not absorb moisture (Figure 34). Any boxes and bins used to hold crops must be made of an FDA-compliant material for food contact. The bottom of the bin should have a minimum of 10% opening for air circulation. The interior surface should be smooth for easy cleaning and to reduce crop damage. Depending on the type of ventilation requirements, bin sides may also need to have openings for air circulation. See the section on *Ventilation Systems* for additional information about planning crop storage airflow systems.

Bins should be stackable without a lid and allow nesting for efficient storage of empty bins. Bin sizes will vary depending on the type of crop and personal preference. For ease of handling, bins should be sized to efficiently use space on a pallet or shelf. Square or rectangular containers use space more efficiently than round ones. Small bins, totes, or baskets should also have handles or handholds. The weight of a full bin and how it will be handled should be taken into consideration when determining bin size.

Figure 34. A bin and basket for handling produce. (Sanford)

Figure 35. Wooden pallet bin with a slotted bottom. (Sanford)

PALLET BINS

Pallet bins can be purchased or built depending on the desired bin materials and size. Pallet bins can be made of wood, plastic, metal, or wire mesh. Wooden bins can be built in any size desired and can usually be repaired if damaged (Figure 35). However, wooden bins are not easily sanitized, and they can decay if left outdoors for extended periods.

Plastic bins have the advantage of being easily washed and sanitized, though they must be made of an FDA approved material for food contact. If damaged, some plastic bins can be repaired by the manufacturer. Plastic pallet bins are only available in select sizes. Some typical sizes are: 48 x 48, 48 x 45, 48 x 40, and 32 x 30 in., with heights ranging from 16 to 50 in. The size of bins will affect the number of bins that may fit in a cooler, the type and size of racking, and the capacity of a lift needed to move them.

The weight of the produce placed in a bin must be less than or equal to the rated capacity of the bin. The weight capacity of pallet bins range from 600 to 2,000 lbs. Stackable pallet bins may have reduced capacity when stacked. Some bins can be stacked only with the use of a lid or cover, which impedes air movement through the crop. All bins will have a maximum stacking height that can be found in the manufacturer's specifications. The loaded weight of a pallet bin will impact the required capacity of material handling equipment.

Pallet bins should have fork-entry openings to allow transport by forklift or pallet jack to aid in material handling and reduce labor. Fork entry can be 2-way entry from opposite sides (Figure 36) or 4-way entry from all sides (Figure 37). If using the fork entry area as an air duct, as discussed in the *Ventilation Systems* section, 2-way entry should be used.

The sides and bottoms of bins can be solid, mesh, or slotted. Mesh or slotted bins are preferred (Figure 38), because these openings will increase air movement through produce and the rate of cooling. A study of 12 cold storage facilities on farms measured faster cooling of leeks and spinach in open-sided crates, with rates of 2.1˚F/hr and 0.7˚F/hr, respectively, versus 0.4˚F/hr in closed cardboard boxes.

Some pallet bins are designed to collapse to minimize the space required for storage when not in use (center photo). Rectangular bins can be nested to reduce storage space, where one bin is placed on its side inside of another bin and a third bin is placed upside down over the top. Square bins cannot be nested.

Figure 36. Plastic pallet bin with 2-way fork entry. (Sanford)

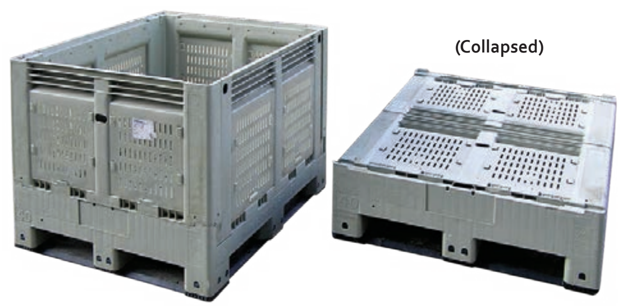


Figure 37. Plastic knock-down pallet bin with 4-way fork entry. (Sanford)

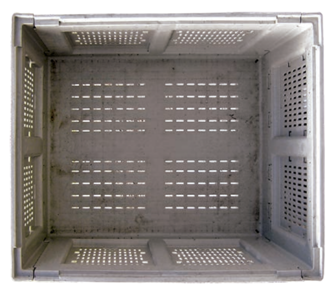


Figure 38. Plastic pallet bin with bottom and side ventilation. (Sanford)

CALCULATING STORAGE CONTAINER REQUIREMENTS

When planning a storage facility, it will be helpful to estimate the number of storage containers needed using the crop's typical yield, the interior volume of the intended storage container, and the bulk density of the crop. Typical yield and bulk density of common winter storage crops can be found in the *Crop Profiles* section. The total yield can be estimated by multiplying the linear length of the rows by the typical yield per row length or multiplying the area planted by the typical yield per area planted. For example, if a producer grows a 750 ft row of beets and expects a yield of 10 lb/ft, the expected total yield would be 750 ft x 10 lb/ft = 7,500 lb of beets. If a producer grows one quarter (0.25) acre of beets and expects a yield of 15 tons/acre, the expected total yield is 0.25 acres x 15 tons/acre x 2,000 lb/ton = 7,500 lb of beets.

The internal volume of a container ($V_{container}$) can be measured or found on product specification sheets from the manufacturer. Beets are typically stored in bulk or pallet bins. For this example, the size of the pallet bin is 48 x 40 x 31 in. with internal dimensions of 45 x 37 x 26 in. Multiplying the internal dimensions together (length x width x height), the internal volume of the pallet bin is 43,290 cubic inches ($in.^3$). Note, if the desired storage container is circular, the calculation of the internal volume of the container is the radius (half of the diameter) squared x π (which is equal to 3.14) x height. If the container is smaller at the bottom than the top, calculate the average radius to determine the internal volume.

To convert the internal volume from cubic inches to cubic feet, we divide by the conversion factor of 1,728 $in.^3/ft^3$. Using the example, the pallet bin has an internal volume of 43,290 $in.^3 \div 1{,}728\ in.^3/ft^3 = 25 ft^3$. Bulk densities are typically measured in pounds per cubic foot (lb/ft^3). Beets have a bulk density of 40 to 44 lb/ft^3. When bulk densities are reported as a range, use the smaller number (lower density) to generate a conservative estimate.

To estimate the total storage volume (V_T) needed for the entire crop, the crop yield is divided by the bulk density as follows:

$$V_T = \text{Yield} \div \text{Bulk Density } (lb/ft^3)$$

For the example, 7,500 lb of beets $\div$ 40 lb/ft^3 bulk density = 187.5 ft^3.

To estimate the number of containers needed to store the whole crop, the container volume is divided by the total storage volume required:

$$\text{Number of Containers} = V_T \div V_{Container}$$

For the example, 187.5 ft^3/25 ft^3 per container = 7.5 bins. Round up to 8.

If the bulk density of a crop is not reported elsewhere, it can be easily determined using a container of a known volume, a weight scale, and enough produce to fill the container. Using a container close to the desired size will provide a more accurate estimate. First, determine the weight of the empty container and record the value. Next fill the container with produce until it is approximately level with the measured volume, and weigh the filled container. Heaping produce will result in an inaccurate calculation. Now, subtract the weight of the empty container from the weight of the container when it is filled with produce to get the net weight of the produce. For more accuracy, fill and weigh the container several times, and use the average of the results. To determine the bulk density of the produce, divide the weight of the produce by the volume of the container in units of square feet.

For example, a tote basket has internal dimensions of 22.5 x 14.5 x 8 in. (2,581 $in.^3$) and holds 63.5 lb of beets. The volume of the tote basket is 2,581 $in.^3 \div 1{,}728\ in.^3/ft^3 = 1.5\ ft^3$. The bulk density of the beets is 63.5 lb of beets $\div$ 1.5 ft^3 = 42.3 lb/ft^3. Typical range is 40-44 lb/ft^3.

Material Transport

There are a number of devices that can aid in material handling, including 2-wheel dollies (hand trucks), wheel carts, pallet jacks and fork-lifts. Most of these options require a hard, relatively smooth floor (no bumps) to work properly. A 2-wheel dolly can be useful for moving stacks of tote bins around the packing shed, while a wheel cart or flat-rack wheel barrow might be used for moving small quantities of bins from the field to the packing shed (Figure 39).

Figure 39. Flat-rack wheel barrow with tote bins. (Sanford)

PALLET JACK

Figure 40. Pallet jack. (Sanford)

A pallet jack is a necessity for moving pallets of produce in and out of storage and around the packing shed on most farms (Figure 40). The cost of a pallet jack is generally $300 to $600 depending on features and weight capacity. Lifting capacities range from 2,000 to 8,000 lb. Pallet jacks cannot be used to stack pallet bins, but some have lift features that can raise the pallet up to 30 in. to reduce bending when accessing produce in a bin. Raising and lowering can be accomplished manually by pumping a handle or peddle, while battery-powered pallet jacks can lift the pallet and may be self-propelled, only requiring the operator to provide steering.

PALLET STACKER

A pallet stacker can be used to move and stack pallet bins or place pallets on racks (Figure 41). They are limited to 600 to 4,000 pounds of lifting capacity and can lift items 5 to 12 ft. Pallet stackers have the advantage of being able to maneuver in tight spaces, so they are useful for placing pallets on racks from a narrow aisle. They require a reasonably level, flat, hard surface floor with minimal discontinuity (bumps) to work safely.

Figure 41. Battery-powered pallet stacker. (Crown Equipment Corp.)

Manual stackers require the operator to rock a lever back and forth to pump oil into a hydraulic cylinder for lifting items. Battery-powered units have hydraulic pump driven by a DC motor that actuates at the touch of a button. Some battery-powered units are self-propelled, where the operator walks with the stacker and provides steering. Some models have frame extensions that extend forward and straddle the item being lifted for counter-balancing a load. Because counter-balanced weighted stackers have no forward frame extension, pallet bins can be stacked tightly together. However, these stackers have lower lifting capacities. Manual pallet stackers start at about $1,300, while battery-powered units cost $4,000 or more depending on lifting capacity and height.

For a small grower, it may be possible to stack pallet bins outside the cooler with a tractor or skid-steer loader with forks and use a pallet jack to move the stacked bins into the cooler. The pallet jack must have enough capacity to lift a stack of bins, a hard surface must be present on which to roll the pallet jack, and the cooler door must be high enough to allow a stack of bins to pass through.

A gasoline- or diesel-powered device should never be used in an enclosed area due to the potential for carbon monoxide poisoning from the exhaust.

Figure 42. Battery-powered forklift with solid rubber tires. (Sanford)

FORKLIFT

A forklift, also called a lift or fork truck, can lift heavier loads than a pallet stacker and is usually battery- or propane-powered for indoor use (Figure 42). A forklift is longer than a pallet stacker, so a wider aisle is needed to place pallets on racking. It is ideal for loading storage rooms where racking is not used.

Should you buy new or used? In general, if the forklift will be used more than 4 hr/day, new equipment is recommended, because maintenance costs of used equipment can easily exceed the investment savings.

Battery or propane? The cost of a battery-powered forklift is usually more than the cost of a propane-fueled unit, although the operating cost of a battery-powered unit is less. A typical battery charge is enough for 5 to 6 hr of operation and may require up to 16 hr for a full charge. Operating costs (fuel, oil, batteries, maintenance, etc.) may range from $1/hr for a small electric forklift to $20/hr or more for a large internal combustion forklift. A propane-fueled forklift typically costs 15 to 25% more to own and operate than an electric model.

The type of tires on a forklift is important. If the forklift will only be used on level, concrete surfaces, a small hard-wheeled unit will work. However, if the forklift will be used on uneven ground, on ramps, or outdoors, a unit with all-terrain pneumatic tires is recommended.

The cost for a new 5,000-lb capacity forklift will be from $20,000 to $25,000. Previously owned units typically will cost half as much depending on age and condition.

Gasoline- or diesel-powered forklifts or skid-steer loaders should not be used in enclosed areas.

A skid-steer loader with forks can be useful for transporting or moving pallet containers in the field or from field to packing shed, but these units should not be used inside due to the potential for carbon monoxide poisoning from exhaust fumes. See the *Additional Resources* section for more information about forklifts.

Forklift training

According to federal OSHA regulations, any employee who will be using a forklift or a skid-steer loader with a fork attachment must be trained and authorized by the employer to operate the equipment. Skid-steer loaders are not covered by the same standard as forklifts unless they are used with a fork attachment. If used with a fork attachment, a skid-steer loader is considered a “rough terrain forklift,” and training is required. Training must be specific to the equipment being used, in the workers native language, involve a written test, and require demonstration of proper use. The OSHA website (www.osha.gov) has information on training requirements for forklifts (“power industrial trucks”) and training materials. Training the operators of any power equipment on a farm should be considered a “Best Practice” for protecting valued employees and reducing accidents. There are a number of online sources for training materials, and local forklift dealers may also offer training programs. For more information and assistance, contact a state university cooperative extension safety specialist or an OSHA office.

LOADING DOCK

A loading dock is a time-saving investment, because it reduces the time needed to load and unload trucks. The loading dock area can be an open platform, flush to a building, inside a building, or under a roof. An open platform dock (Figure 43A) is the least expensive option, because no roof or walls are required. However, workers are subject to the weather when loading. Flush loading docks (Figure 43B) are the most common option and enable loading and unloading without being affected by weather conditions if dock seals are used. If you are considering building a garage to store a truck, you might consider a completely covered dock (Figure 43C).

The height of the platform is an important consideration, as vehicle bed height can range from 30 to 62 in. depending on the type of truck or trailer. If multiple vehicles of different heights will be used, it may be advantageous to install multiple loading platforms or a dock leveler.

The grade at the loading dock where the vehicle sits should be near level (+/- 2% grade) whenever

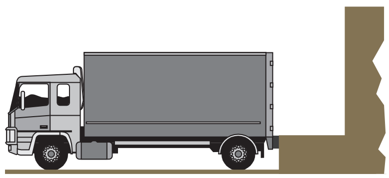


Figure 43A. Open loading dock.

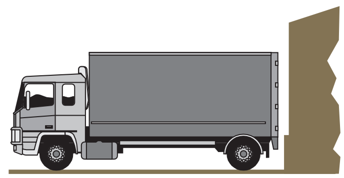


Figure 43B. Flush loading dock.

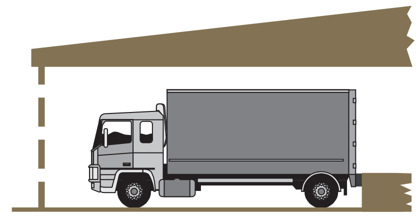


Figure 43C. Covered loading dock. (all Sanford)

possible, especially if using manual equipment such as a pallet jack to move materials into and out of the vehicle. Grades of more than a few percent can lead to a loss of traction and slipping if surfaces become wet and cause equipment to hang at the transition between the dock and body of the vehicle. A grade of no greater than 10% is recommended if using electric-powered handling equipment and no greater than 15% if using gas- or diesel-powered equipment.

The difference in height and the gap between the loading platform and the truck or trailer body can be accommodated with a dock plate, a dock board, or a dock leveler.

Figure 44. Dock plate. (Sanford)

A dock plate is a metal plate that bridges the gap between the truck and the dock for hand-operated pallet jacks (Figure 44). They are available in widths from 30 to 72 in. with weights from 50 to 236 lb. Dock plate capacities vary with plate thickness as well as the width and length of the span. Capacities generally range from 1,400 to 6,000 lb.

A dock board performs the same function as a dock plate and is used for loading with powered forklifts with capacities of 10,000 lb and more. Dock boards must be manually positioned for each use, which may require a lifting device to assist with moving it due to the weight of the board. Steel dock boards weigh between 210 and 600 lb depending on the size, while lighter aluminum dock boards weigh 120 to 230 lb.

A dock leveler is a spring-loaded or hydraulically operated platform that can be raised or lowered to create a smooth transition between the dock and the vehicle for loading equipment (Figure 45). A dock leveler is recommended for high-traffic loading docks where many trucks are loaded per day. Because these devices are built into the loading platform, they must be considered in the planning stages when building a loading dock. See the *Additional Resources* section for more information.

Figure 45. Dock leveler. (Sanford)

Adequate space must be provided in the loading dock area for equipment to maneuver easily and to collect or "stage" the materials that will be loaded into trucks. A staging area allows an order to be assembled and checked before it is loaded on a truck. Some warehouses paint a to-scale outline of a truck body on the floor of the staging area, so an order can be accurately sized for the truck transporting it.

Food safety issues

The greatest concern of food safety experts is Listeria bacteria which can grow at temperatures from 39°F (the typical temperature of a cooler) to 99°F. Listeria is found in soils, uncooked meats, and fresh fruits and vegetables. It can also be carried by animals.

Avoiding pathogens

There are some important considerations to keep produce pathogen-free and limit producer liability:

- Do not store diseased or compromised produce.
- Do not store any meat products in a cooler with produce.
- Clean and disinfect the cooler before the start of the summer and winter storage seasons.
- All surfaces in the cooler must be light-colored and smooth so dirt can be easily seen and removed.
- Floors must be washable and in good condition without cracks. Wood or soil floors are not typically allowed.
- Produce should be protected from condensation falling from the refrigeration system. Condensate should be collected and piped to a drain or a reservoir for the humidifier.
- Produce should never be placed directly on the floor.
- Temperatures in the cooler should be checked and logged daily. Use thermometers that are not part of the control system to monitor the cooler temperature. Thermometers should be calibrated at least once per year.
- All containers used for harvesting or storing produce should be inspected, repaired, cleaned, and disinfected before each use.
- Harvest tools that directly contact the produce, such as knives and shears, should be cleaned and disinfected daily.
- Keep pets out of produce fields, the packing shed, and the cooler.
- Avoid items in fields that could be used as perches for birds whenever possible.
- Do not store pesticides in the cold storage area or packing shed.
- All doors, door seals, and walls should be in good repair to exclude rodents.
- Do not pile produce waste near the packing shed to avoid attracting rodents.
- Have a rodent control program to keep rodent populations at a minimum.
- Toilet facilities and hand washing stations need to be available where employees are working.

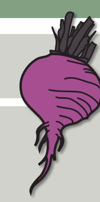
On-farm coolers may or may not require licensing and inspection depending on state regulations. However, if the food is processed in any way (cut or otherwise prepared for use), the cooler must be licensed and inspected. Check with your state food safety office for requirements. For more food safety information, see the *Additional Resources* section.

Case studies of select crops

The following case studies provide a summary from different growers about how they produce, store, and market different winter storage crops, including carrots, potatoes, beets, cabbage, onions, garlic, and winter squash.

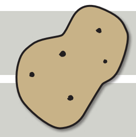
(Prices listed in all case studies are at the time of publication.)

BEET CASE STUDY: Dave Van Eeckhout, Hog's Back Farm (Organic)



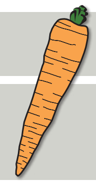
Varieties	**Red Ace is preferred for bunching and storage.**
Planting location and dates	Western Wisconsin. Early July for Late September or October harvest.
Production tips to ensure best storage quality	Good thinning practices ensure adequately sized beets for storage.
Harvest	Harvest timing can be critical for beets. A warm September can size them up to an unmarketable size in a couple of weeks if there's good moisture. Monitor their progress diligently. The middle row of our 3-row beds is harvested by hand for late season bunched beets so that it's out of the way when we're harvesting the storage beets using our Scott-Viner® harvester that requires 30 in. between rows.
Storage	The clean beets are stored in harvest totes with lids. Ours hold about 50 lb per tote, and they have holes drilled in the bottom for drainage. This type of box generally keeps the humidity level quite high, since they are boxed when wet. They are held at a storage temperature of 33 to 36°F. Beets are the easiest crop to maintain in excellent condition.
Cleaning and packing	Beets are washed at or close to harvest. The harvester doesn't cut the tops as cleanly as it does carrots, so we do a final trim of the top and tail with pruners as we're feeding them into the brush washer.
Marketing	Distributed mostly to CSA members and remaining 10 to 15% of harvest to wholesale and restaurant accounts.
Pricing	$1.40 per lb to restaurant accounts.
Labor considerations	Having good labor or good management during the thinning can make the difference between a great crop and a good crop. Washing is slower due to trimming but can be done with a crew of two or three people.
Economic assessment	The wholesale market seems limited. There are some fairly large growers out there, and people just don't consume that many of them. Our restaurant accounts can go through 30 to 50 lb per week each, so they can be nice to have if you're already making a delivery. Unusual varieties like gold, white, and chioggia can add to sales, but the demand is less for these non-red beets.

POTATO CASE STUDY: Mike Noltnerwyss , Crossroads Community Farm (Organic)



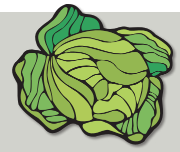
Varieties	**Yukon Gold, Kennebec, Russets, Red Pontiac and French Fingerling.**
Planting location and dates	Southern Wisconsin. Between May 1st and May 20.
Production tips to ensure best storage quality	We prefer larger-sized potatoes for storage, because it means less handling per unit of weight. To help achieve this, we plant with 12 in. spacing in each row and ensure that we have 100 lb of nitrogen available per acre. Ample hilling is very important for increasing size and yield while reducing the amount of potatoes that turn green. Because disease organisms gain entry through wounds caused during harvest and handling, avoid damage to tubers.
Harvest	After vines are killed by either naturally dying back or mowing, we wait about two weeks for skins to set and for late blight symptoms or other rots to appear on any infected tubers, so they can be discarded before storage. We use a potato harvester or an under cutter that lifts tubers to the surface for collection by hand.
Storage	Potatoes are first held unwashed in plastic pallet bins and stored in the bottom of our barn to cure. We cover them to keep them in the dark. They can store this way into December. For winter storage, we wash the majority and store them clean in a walk-in cooler, where they hold at 35°F. We leave some unwashed in anticipation of holding them until the first spring farmers' markets. They are stored in pallet bins covered with plastic to maintain moisture. The insulation of the cooler paired with the heat of respiration from the veggies in the cooler is usually enough to keep the cooler from freezing. If the temperature drops below 33°F, we can add heat by either turning on lights, turning on fans (which will circulate air to warm up the perimeter of the cooler that is closer to freezing), or using small space heaters. In our experience, potatoes are one of the easiest crops to store long-term.
Cleaning and packing	Investing in a brush washer was the best thing we've ever done for post-harvest efficiency. Potatoes get picked out of the pallet bins by hand, placed into black crates, and then dumped onto the washer conveyor. We have a round table where we sort out diseased, green, or scabby culls from the rest of the washed potatoes.
Marketing	Most of our crop goes to our winter CSA customers. We are able to sell a small amount to restaurants throughout the winter, and we sell them at the farmers' market in the spring if we haven't already sold out of the crop before then.
Pricing	We sell potatoes for $1.13 per lb to restaurant customers, $1.50 per lb at the farmers' market and closer to $2 per lb in late winter and spring. Sometimes, we run a special for 5-lb bags for $6 at the market.
Labor considerations	Of all the vegetables we grow, potatoes require the least amount of labor per dollar of sales. Granted, a lot of equipment is necessary to get to this point in potato production. Weed control is almost entirely handled mechanically with a tine weeder and buffalo cultivator. As a heavy, bulky crop, it is also important to have an efficient means to move them around, such as pallet bins.
Economic assessment	Potatoes are a commodity crop, and it can be hard to get a good price. Unusual varieties are perhaps a better fit for a smaller farm, but be careful to choose varieties that yield well. Also, developing a market may take time. Fortunately, potatoes are very popular. Unless weed control, hilling, and harvest are mechanized, it is very difficult for potatoes to be profitable.

CARROT CASE STUDY: Steve Pincus, Tipi Produce (Organic)



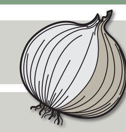
Varieties	**Bolero, Nectar (trialing Necoras and Miami).**
Planting location and dates	Southern Wisconsin. Late June for September or October harvest; early July for late October or November harvest.
Production tips to ensure best storage quality	To ensure best storage quality, don't over-irrigate in October. Barely enough moisture is best, and this will keep the field drier for easier harvest and post-harvest handling. Carrots get sweeter with colder weather, so keep them in the ground as long as you dare. Yields increase substantially from mid-October into early November.
Harvest	Cold weather slows root metabolism for longer storage, but don't get caught by rain or snow. At Tipi Produce, a 5-person crew harvests using a 1955 Scott-Viner one-row harvester. They work relatively slowly to avoid breaking the brittle roots but still harvest and stack 15,000 lb per day.
Storage	Tipi Produce stores carrots unwashed in 18-bushel bins holding 700 lb of saleable roots. Bins are covered with large plastic bags and held at 30 to 34˚F. Refrigeration is needed for initial cooling. Roots are alive and respiring, so it is important to get them down to 40˚F as quickly as possible. During winter, storage areas need heat to keep the roots from freezing, although the carrots themselves help by producing heat from respiration. Carrots should be stored at close to 100% humidity. The plastic bag covers and storing the carrots unwashed have provided good results, but a humidifier can be used to ensure adequate moisture levels.
Cleaning and packing	At Tipi Produce, bins are upended, dumping carrots onto a cement floor. Then, they are shoveled onto a chain-link conveyer that sifts out some of the soil cling to the carrots. The conveyer drops the carrots into a tank of water to soften clinging soil. Then, the roots are washed in a barrel washer. A quick final spray removes remaining soil, and the carrots are graded and bagged on a stainless steel table.
Marketing	Tipi Produce sells to wholesale customers through the winter and into April and also distributes carrots to CSA customers for winter CSA boxes.
Pricing	Tipi has 4 saleable grades. About two-thirds of Tipi's sales are in 5-lb bags. ***#1 grade:*** Bulk store sales and restaurants for $1 per lb. ***Bagging grade:*** Sold to stores in 5-lb bags for $4.80. ***Consumer juice grade:*** Broken pieces and other flawed carrots sold to stores in 25-lb bags for $14. ***Juice bar grade:*** Larger, rougher roots sold in bulk for $0.75 to $0.80 per lb.
Labor considerations	Carrots help keep our best employees working, engaged, and ready for greenhouse planting and other early spring work.
Economic assessment	Carrots have been a winner for us, but you need to invest in a proper harvester, storage coolers, bins, material handling equipment, washer, and a heated workroom. The downside is that you will not get as much winter downtime.

CABBAGE CASE STUDY: Steve Pincus, Tipi Produce (Organic)



Varieties	*Green:* Storage #4 for long-term storage; most any type for short-term storage. *Red:* Super Red 80, Red Dynasty, Cairo. *Savoy:* Famosa and Clarissa. *Napa:* Emiko.
Planting location and dates	Southern Wisconsin. Transplant #4 in early to mid-July, reds and savoy in mid-July, napa in early to mid-August.
Production tips to ensure best storage quality	Select disease-resistant varieties. Also, consider doing a hot water treatment on your seed to reduce seed-borne diseases, such as black rot. Prevent severe insect damage and bruising during harvest and post-harvest handling to reduce storage diseases. Producing a healthy crop also helps. We want lots of decaying organic matter in the ground where we plant cabbage; cabbage will use a lot of nitrogen. We will use a heavy compost application pre-plant and a mid-season side dressing of high-nitrogen compost or soy meal. Cabbage also does great following a legume cover crop.
Harvest	Late October to early November. Be careful of cold temperatures and freezing. If there is freezing damage, leave heads in the field to heal if possible. Don't harvest while frozen! Leave some wrapper leaves and a longer stem butt to allow for a final trim before selling.
Storage	Bins work well, but for years we just piled cabbage into a cooler with a raised and insulated floor. Long-term storage conditions should be 32 to 34°F with high humidity but no free moisture.
Cleaning and packing	We trim and box in a storage room – a cold damp job.
Marketing	Some for CSA, but mostly wholesale to stores. Stores want 2 to 4-lb heads. We save larger heads for restaurants.
Pricing (delivered to store)	Green: $0.55 per lb Red: $0.75 per lb Savoy: $0.75 per lb Napa: $0.75 per lb
Labor considerations	Easily harvested with a quick trim at sales time.
Economic assessment	No special equipment is needed to grow, harvest, store, trim, and sell, and we see moderate returns per acre. However, cabbage has a low value per pound and per cubic foot of storage space, but it is a good addition to root crop sales.

ONIONS CASE STUDY: Janaki Fisher-Merritt, Food Farm (Organic)



Varieties	**Yellow-Copra, Clear Dawn, New York Early.**
Planting location and dates	Duluth, Minnesota. Start seeds in the greenhouse the first week of March. Plugs are used in order to transplant in late April.
Production tips to ensure best storage quality	Manage thrips populations to prevent premature death and opening up of onion leaves for diseases to enter. We don't knock tops over like some people do to promote sealing of the bulbs. We find this tends to invite disease and does not work as well as up-rooting them.
Harvest	Pull in early September and cure on the ground for about 2 weeks. We then top them in the field and collect them in buckets which are carefully emptied onto benches in the greenhouse covered by a shade cloth. Dryness and air circulation are important.
Storage	We store cured onions on bread racks. Each rack holds 60 lb, and they are stacked 10 racks high on caster frames. The onions are stored between 34 and 45°F with low humidity in the farm's modern, temperature-controlled root cellar.
Cleaning and packing	Clean, sort, and pack by hand.
Marketing	Mainly for CSA. Any surplus is sold wholesale to retails stores.
Pricing	$1.10 per lb wholesale to restaurants.
Labor considerations	Onions are generally a very labor-intensive crop. The early planting dates mean that there isn't much time for stale bedding, and the plants are in the ground for a long time. So, this means lots of cultivations and hand weeding. The crop must also be handled numerous times in the harvesting/curing/storage process, and it takes up fall greenhouse space.
Economic assessment	We don't feel that onions are very profitable for us even though there is a high demand for them in our area. But, our CSA members really like them in their winter share boxes.

GARLIC CASE STUDY: Mike Noltnerwyss, Crossroads Community Farm (Organic)

Varieties	**Georgian Crystal has been the most successful. In the past we've grown Chesnok Red, German Extra Hardy, and Killarney Red, but these varieties haven't yielded or stored as well as Georgian Crystal.**
Planting location and dates	Central Wisconsin. Mid- to late October.
Production tips to ensure best storage quality	Be careful of bruising and dry as quickly as possible. We cure most of the crop on wire racks in our greenhouse for 2 to 3 weeks.
Harvest	Harvest in early to mid-July. Softneck is usually a week earlier than hardneck. We undercut the crop with a plastic mulch lifter, then pull by hand, rub soil off the roots, and put in black bulb crates to be hauled into the greenhouse. We put a shade cloth on to keep some of the sun off. We leave garlic in the greenhouse to dry until the onions are ready to come in, usually 3 weeks at least. Extra ventilation and air-flow may be necessary for adequate curing conditions. If we run out of room in the greenhouse, bundles of 50 are hung in the rafters of a pole barn.
Storage	We store in waxed boxes, although crates would be ideal. Garlic stays at ambient room temperature through summer and fall. In summer, we store in the top floor of the barn, which is drier than the bottom. Once cold weather hits, we move it to the bottom floor to prevent it from freezing.
Cleaning and packing	The most labor-intensive part of garlic is clipping the roots and cleaning. It takes us about an hour to clip roots and clean 30 lb of garlic – usually around 300 bulbs. We like the garlic to be very dry when we are cleaning it so that the outside wrapper falls off with the slide of your thumb. We usually clean garlic in the afternoon for this reason and sometimes put it in the greenhouse for a couple hours on a sunny day before we clean it.
Marketing	Primarily to restaurants and distributed to CSA members. Far less is sold at farmers' markets than expected. We typically sell out by December, so we hope to increase production to sell through the winter months.
Pricing	$6 per lb wholesale to restaurants, and $2 each or 3 for $5 for large bulbs at farmers' markets.
Labor considerations	Post-harvest garlic keeps employees busy in inclement weather. As far as labor in the field for garlic production, we typically don't have too much of a problem getting the weeding and harvesting done with our regular-sized crew. The timing of harvest (mid-July) is at a pretty good time of year when there isn't too much demand from other crops.
Economic assessment	At $10 per hour for labor, we invest $3,000 in labor for a crop potentially worth $15,000. We like to be at or below 30% of gross sales with our labor cost to justify a crop. The economics of garlic are really about getting large bulbs. If bulbs are large, it just takes so much less time in terms of post-harvest labor per pound.

WINTER SQUASH CASE STUDY: Dave Van Eeckhout, Hog's Back Farm (Organic)

Varieties	*Acorn:* Sweet Reba Bush. *Butternut:* Waltham. *Buttercup:* Bonbon. *Red Kabocha:* Sunshine. *Others:* Sugar Dumpling, Delicata, and Pie Pumpkins.
Planting location and dates	Western Wisconsin. Greenhouse seeding begins May 15 and transplanting into black plastic mulch during the second week of June.
Production tips to ensure best storage quality	We install row cover immediately after transplanting to protect against cucumber beetle feeding on young transplants. Row covers are left on until female blossoms start about the second week of July. They need to be removed for cultivation once or twice. The combination of plastic mulch and row cover guarantees maturity of the longer season squashes in a cool year and limits insect damage, which can lead to disease issues and poor fruit quality.
Harvest	Mid- to late September for CSA. The main crop is harvested when temperatures get close to frost with some warm days left. Ideally, squash is clipped from the plant and left to cure in the sun for several days if temperatures are mild. Field-cured squash is loaded into pallet-sized boxes on 3-point forks. Great care is taken to avoid puncturing the skin with the stems of other squash, especially butternut. Stems are cut to a half-inch, and all squash are oriented the same direction if possible. All handling is done with gloves to avoid fingernail damage.
Storage	We store squash in a dry walk-in cooler with a temperature of 40 to 50°F. A space heater is used during colder weather to maintain these conditions.
Cleaning and packing	Most of our squash is stored dirty and washed-to-order. This saves the step of having to cull out rotting produce twice. Since the soil has had a chance to dry on by this point, we use a pre-soak to loosen soil, followed by putting them through the brush washer. A hard-to-clean patch may need to be held down on the first brushes to get it clean.
Marketing	Most go to CSA shares, 5% to restaurant accounts, and 15% to a distributor.
Pricing	$0.65 per lb to restaurants and $0.57 per lb to distributor ($0.52 per lb after the cost of a new waxed box).
Labor considerations	Washing is the most time-consuming step for squash. If we had the time, we'd wash it all after curing, which I think would help with storage. Palletizing and organizing, so that it's lifted as few times as possible, is also important.
Economic assessment	Wholesale only when there is CSA surplus. Bug pressure can dramatically sway yields from one year to the next. In a good year, like 2009, yields of 30,000 lb per acre are possible.

Crop profiles

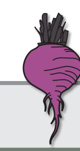
For links to reference resources for each crop, visit: fyi.uwex.edu/cropstorage/resources

This section summarizes information on the long-term storage requirements of individual crops from three main sources: (1) the USDA-Agricultural Research Service Agricultural Handbook No. 66, *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks* (Gross et al., 2004), (2) Postharvest Fresh, a consulting company at Sydney University in Sydney, Australia, and (3) the North Central IPM (Integrated Pest Management) Center sponsored by the USDA National Institute of Food and Agriculture.

These sources provide much more information than is presented here. Information available for each crop includes yield; bulk density; harvesting and handling considerations, such as harvesting methods and pre-cooling requirements; storage conditions, including controlled atmosphere considerations; respiration rates; chilling sensitivity; ethylene production and sensitivity; physiological disorders and post-harvest diseases of concern. Some of the yield data included is from state university extension publications.

VEGETABLES:

Beets



YIELD:

8-10 lb/10 ft of row or 30,000-40,000 lb/acre in Wisconsin

15 lb/10 ft of row in Kansas

7-11 lb/10 ft of row or 16,000-24,000 lb/acre or 24 ft row in New York

100 lb/100 ft row or 14,000 lb/acre in Maine

BULK DENSITY: 40-44 lb/ft^3

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
880-1,320	2,200-2,400	3,520-4,400	5,280-8,360	11,000-15,400

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Bunched beets	32	98-100	10 to 14 days
Topped beets	34-36	98	8 to 10 months
Freezing point	30.4		

HARVEST: Beets for long-term storage should be harvested in late fall, topped about ½ in. above the crown, and cooled to less than 41°F within 24 hour after harvest and before being placed in storage. Bunched beets with greens should be cooled to 39°F within 4 to 6 hours of harvest using hydro-cooling, forced air cooling, or icing. Large roots will store better than small ones. Diseased or damaged roots should be discarded before storage.

HANDLING: Topped beets are typically stored in tote bins or pallet boxes on small-scale farms, but they can be stored in piles 10-14 ft deep. Beets should not be washed until packaging for market.

VENTILATION: 40-60 cfm per ton of beets

STORAGE COMPATIBILITY: Beets produce very little ethylene and are not sensitive to ethylene exposure.

CONTROLLED ATMOSPHERE STORAGE: There is no advantage to CA storage of beets. In fact, elevated CO_2 levels weaken tissue and increase susceptibility to rot; research has found increased decay at CO_2 levels greater than 5%.

ADDITIONAL CONSIDERATIONS: At temperatures less than 34°F, an increase in black spot and rot can occur. Good air circulation is also imperative to reduce black spot, mold, and rot issues.

Brussels sprouts

YIELD:

80-100 sprouts or 2-2.5 lb/plant in California

7,000 lb/acre in North Carolina

16-20 lb/10 ft of row with 15 in. between plants or 6,000 lbs/acre in Wisconsin

11-14 lb/10 ft of row with 21 in. between plants in Missouri and Indiana

10-18 lb/10 ft of row in Arkansas

8,000-12,000 lb/acre in Michigan

BULK DENSITY: 25 lb/ft$_3$

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
4,400-13,200	9,680-21,120	27,720-36,960	28,160-59,840	37,840-83,600

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Individual sprouts	32	95-100	3 to 5 weeks
	41	95-100	2 to 3 weeks
	50	95-100	10 days
Freezing point	30.6	Low chilling sensitivity	

HARVEST: Pre-cooling effectively removes field heat from Brussels sprouts before storage. Vacuum-cooling, hydro-cooling, icing, and forced-air cooling can all be used. The coding method used will depend on the way sprouts are stored – packed or in bulk.

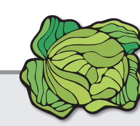
HANDLING: Brussels sprouts are typically stored in bulk in tote bins, though they can be stored on the stem to increase storage length or packaged in a vented polyethylene bag to reduce water loss (preferred).

STORAGE COMPATIBILITY: Brussels sprouts produce very little ethylene. However, they are very sensitive to ethylene exposure, which causes the leaves to yellow and abscess.

CONTROLLED ATMOSPHERE STORAGE: CA storage can inhibit yellowing and discoloration of the cut end, although it may only lengthen storage by about 1 week.

ADDITIONAL CONSIDERATIONS: Brussels sprouts can be affected by bacterial rots, leaf spot, and grey mold in storage.

Cabbages



YIELD:

10,000 lb/acre for fresh market cabbage, or 44,000 lb/acre for kraut cabbage in Wisconsin.

50,000-80,000 lb/acre in Michigan

15 lb/10 ft of row in Kansas

60 heads/150 lb/100 ft row or 31,500 lb/acre in Maine

BULK DENSITY: 27-31 lb/ft^3

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
880-1,320	1,980-2,640	3,740-4,180	4,400-7,040	6,160-10,780

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Cabbage heads-early harvest	32	98-100	3 to 6 weeks
Cabbage heads-late harvest	32	98-100	3 to 6 months
Freezing point	30.4-30.5	Low chilling sensitivity	

HARVEST: Cabbage for winter storage is generally harvested in October and November. If harvested during warm weather, cabbage should be pre-cooled soon after harvest to reduce wilting. Do not use hydro-cooling or ice to remove field heat from cabbage going into long-term storage due to the potential for disease transmission via the water. If harvested under cool conditions, cabbage can be placed directly into storage. Generally, early maturing cabbage tends to have shorter storage life than late maturing varieties. Firm cabbage heads store best.

HANDLING: Cabbage heads can be stored in bins (recommended for fresh market) or bulk piles with a stacking depth less than 9.8 ft. Cabbage will typically store up to 6 months depending on crop quality and storage conditions. All loose leaves should be removed to ensure good air circulation around the heads. Light in the storage room can reduce physiological disorders that cause yellowing and weight loss of the heads. Cabbage can be stored for about 8 weeks in a bin lined with polyethylene and a 1/4-in. hole/ft^2 for respiration if humidity control is not available.

(continued on next page)

Cabbages – continued

VENTILATION: 40-60 cfm per ton of cabbage

STORAGE COMPATIBILITY: Cabbage produces very little ethylene at temperatures up to 77°F. However, exposure to ethylene increases respiration and accelerates senescence. Quality declines with yellowing of leaves, wilting, and abscission. These issues have been observed as particularly problematic in air-cooled rather than CA storage. Storing cabbage in CA rooms where apples have been stored presents a risk of damage from residual ethylene or from ethylene emitted by applies stored in adjacent rooms of the facility.

CONTROLLED ATMOSPHERE STORAGE: Storing cabbage in a CA environment can reduce shrinkage loss due to trimming, retard senescence, reduce loss of flavor and color, and inhibit root growth. The recommended level of O_2 ranges from 1 to 5% and 0 to 8% for CO_2. For most varieties, 1-3% O_2 and 4-6% CO_2 are recommended. For white cabbage, 5% O_2 and 2.5-5% CO_2 are recommended. High levels of CO_2 (>8-10%) can cause injury that may not be apparent for 1 to 6 months after exposure. Damage can occur as off-flavors and off-odors, bronzing of outer leaves, and internal discoloration.

ADDITIONAL CONSIDERATIONS: High humidity is critical to reduce decay and trimming losses. Only 3 to 6 wrapper leaves should be left on each head to ensure good air circulation. Air circulation needs to maintain uniform temperatures and relative humidity around all bins and cabbage heads. Temperatures above 34°F may promote senescence-related storage losses, especially if held long term (6 months).

Carrots

YIELD:

10-20 lb/10 ft of row or 20,000-30,000 lb/acre (fresh market); 60,000-80,000 lb/acre (processing) in Michigan

40,000-60,000 lb/acre in Wisconsin

100 lb/100 ft row or 30,000 lb/acre (Johnny's Select Seeds)

BULK DENSITY: 34 lb/ft^3 for baby whole carrots

26 lb/ft^3 for field run carrots

HARVEST AND HANDLING: Carrots should be washed, topped, and hydro-cooled to less than 41°F before being placed into storage. Carrots can be stored in bins or bulk piles with a stacking depth less than 14 ft.

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
2,200-4,400	2,860-5,720	4,400-9,240	5,720-11,880	10,120-20,900

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Ideal conditions	32-34	98-100	7 to 9 months
	32-41	90-95	5 to 6 months
Freezing point	29.8	No chilling sensitivity	

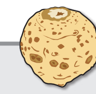
VENTILATION: 40-60 cfm per ton of carrots

STORAGE COMPATIBILITY: Carrots produce very little ethylene and should not be stored with ethylene-producing crops. Exposure to ethylene causes the production of isocoumarin, which imparts a bitter flavor.

CONTROLLED ATMOSPHERE STORAGE: CA storage does not extend storage life compared to cooled storage with high RH.

ADDITIONAL CONSIDERATIONS: High RH is paramount to maintain crispness. The freeze point of carrots is 30°F. If proper humidification equipment is not available, storing carrots in a plastic bag can be a substitute to maintain high RH around the carrots.

Celeriac (celery root)



YIELD:

60 lbs/100 ft of row in Kansas

8,000-16,000 lb/acre in Michigan

14,000 lb/acre in New York

BULK DENSITY: 22-25 lb/ft^3

HARVEST AND HANDLING: Pre-cooling is recommended for long-term storage to retain the best quality.

VENTILATION: (no special considerations)

STORAGE COMPATIBILITY: Ethylene production rates are low, but this crop is slightly sensitive to exposure.

CONTROLLED ATMOSPHERE STORAGE:
Not recommended

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
1,100-1,760	2,420-3,300	3,960-6,160	7,040-8,360	9,020-10,780

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Ideal	32-36	95-98	6 to 8 months
	38	95-98	3 months
Freezing point	30.6	No chilling sensitivity	

ADDITIONAL CONSIDERATIONS: Storage life decreases as temperature rises above 38°F. Shriveling and loss of moisture are the main causes of unmarketable produce.

Garlic

YIELD:

40 lb/100 ft of row in Kansas

6,000-16,000 lb/acre with an average of 12,000 lb/acre in North Carolina

8,000-10,000 lb/acre in Minnesota

3,000-5,000 lb/acre in Wisconsin (organic production)

BULK DENSITY: 26-30 lb/ft^3

HARVEST: Garlic is a member of the onion family and is generally harvested once the bulb has matured, which occurs after the tops have fallen and dried. Garlic can be dug by hand or with a modified potato digger.

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
880-2,640	1,760-5,280	2,640-7,920	3,080-6,600	3,080-5,720

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Cured bulbs	68-86	less than 75	1 to 2 months
	45-50	less than 75	3 to 4 months
	32-35	60-70	5-9 months
Freezing point	30.5	No chilling sensitivity	

HANDLING: Garlic bulbs must be cured before storage. Generally, garlic can be cured for one to two days laying on the soil in the field. The bulbs need to be kept out of direct sunlight to prevent sun scalding, and they should not be field-cured if temperatures are over 90°F. Bulbs can also be cured in a well-ventilated greenhouse or building to protect them from the weather. Then, the tops and roots are trimmed, and the garlic is bagged or placed in bins for a final indoor curing period of 2 to 4 weeks. Ideally, bulbs are cured at 60-80°F until the outer leaf sheaths around the bulb and the stem tissues of the bulb are dry.

Garlic is typically stored in bins or mesh bags and should be well-ventilated to keep the product dry.

VENTILATION: 1 cfm per ft^3 of garlic

STORAGE COMPATIBILITY: Garlic should be stored separately, because the odor is easily transferred to other products.

CONTROLLED ATMOSPHERE STORAGE: High CO_2 levels retard sprout development and decay at storage temperatures of 32-41°F. Low O_2 alone does not slow sprout development.

ADDITIONAL CONSIDERATIONS: Inadequate curing or high moisture in storage can lead to mold growth and rooting.

Horseradishes

YIELD:

2.3-4.6 lb/10 ft of row in Illinois

3,000-12,000 lb/acre in Virginia

7,000-8,000 lb/acre with 15 to 24 in. between plants and 30 to 36 in. between rows in Oregon

4,000-8,000 lb/acre with 18 in. between plants and 30 in. between rows in Illinois

6,000-10,000 lb/acre in Michigan

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
1,760	3,080	5,500	7,040	8,800

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Horseradish	30-32	90-98	8 to 12 months
Freezing point	28.7	Low chilling sensitivity	

BULK DENSITY: 40 lb/ft^3

HARVEST: Horseradish is very sensitive to wilting and loses its pungency quickly at high temperatures. Therefore, it must be pre-cooled immediately after harvest to 38-40°F and 90-98% RH.

HANDLING: Store horseradish in perforate polyethylene bags or lined bins to keep relative humidity high.

VENTILATION: (no special considerations)

STORAGE COMPATIBILITY: Horseradish produces very little ethylene and is not sensitive to ethylene exposure.

CONTROLLED ATMOSPHERE STORAGE: No benefit

ADDITIONAL CONSIDERATIONS: Horseradish is highly susceptible to water loss, especially smaller roots, which results in limp texture. This crop is best harvested in late fall during cold weather due to high physiological activity of roots at warmer temperatures.

Jerusalem artichokes (sunchoke/girasole)

YIELD:

Mammoth French White, 10,000 lb/acre in Minnesota

Columbia, 20,000 lb/acre in Minnesota

10,000-14,000 lb/acre in North Carolina

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
2,200	2,640	4,180	–	10,890

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Undamaged tubers	32-34	90-95	6 to 12 months
Freezing point	28	They can withstand freezing down to 23°F with little damage. Temperatures of 14°F or below will result in rapid deterioration. Freeze damage will vary with cultivar, temperature, and crop quality.	

BULK DENSITY: (unavailable)

HARVEST AND HANDLING: Jerusalem artichokes have thin, dedicate skin. If damaged, they can experience extensive water loss and last only a few weeks in storage. Careful harvest is essential. Some varieties are more prone to storage losses than others.

Jerusalem artichokes can also be left in the ground and dug as needed in areas where the soils cool but freezing of the ground is uncommon. A layer of straw over the tubers can also help prolong field storage.

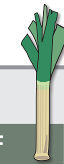
VENTILATION: (no special considerations)

STORAGE COMPATIBILITY: Jerusalem artichokes are not sensitive to ethylene exposure.

CONTROLLED ATMOSPHERE STORAGE: No benefit

SPECIAL CONSIDERATIONS: Storage losses vary by cultivar. Shriveling due to water loss is the main reason for unmarketable produce.

Leeks



YIELD: 150 stalks/100 ft row or 32,550 stalks/acre in Maine

10 lb/10 ft of row in Wisconsin

BULK DENSITY: 25 lb/ft^3

HARVEST: Leeks should be promptly cooled with hydro-cooling, crushed ice or vacuum-cooling to 32°F to retain quality.

HANDLING: High moisture levels are critical to prevent wilting. If humidity control is not available, leeks may be best stored in sealed polyethylene bags. Storing without packaging or in a perforated polyethylene bag reduces storage length. If storing in a bin, a liner is recommended to retain moisture.

VENTILATION: (no special considerations)

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
2,200-4,400	4,400-6,380	11,000-15,400	16,500-25,740	24,200

Temperature, humidity, and storage length

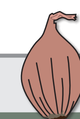
	Temperature (°F)	Relative Humidity (%)	Storage Length
Sealed in bags	32	95-100	2 to 3 months
No packaging or perforated bag	32	less than 95	5 to 6 weeks
High temperature	greater than 50	less than 95	12 days
Freezing point	30.7	Low chilling sensitivity	

STORAGE COMPATIBILITY: Leeks produce very low levels of ethylene but are moderately sensitive to ethylene, which can cause softening and increase the rate of decay.

CONTROLLED ATMOSPHERE STORAGE: CA storage can extend storage length to 4 to 5 months but with some loss of quality.

ADDITIONAL CONSIDERATIONS: An elongated and curved bottom is an indication of prolonged storage. Leeks held in polyethylene lined bins or bags will elongated at less than 1% per week under crushed ice, at 3% per week without ice, and at 13% per week at 40°F. Leaves will also turn yellow at warmer temperatures.

Onions



YIELD:

10 lb/10 ft of row in Kansas

31,500 lb/acre in Wisconsin

100 lb/100 ft row or 38,500 lb/acre in Maine

BULK DENSITY: 38-41 lb/ft^3

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
660	1,100	1,540	1,540	1,760

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Sweet	32	65-75	1 to 3 months
Pungent	32	65-75	6 to 9 months
Freezing point	30.6		

HARVEST AND HANDLING: Onions must be dried and cured before storage. Typically, they are dried in the field or in a shed for 2 weeks before moving to storage. For storage, they can be piled on the floor up to 12 ft high (depth varies by variety) or stored in pallet bins. Once in storage, curing should continue with forced-air ventilation at 75-110°F and 50-80% RH using outside or heated air until necks are tight. Curing temperatures of 75-90°F and 75-80% RH develop the best skin color. Rapid cooling to storage temperature after curing inhibits sprouting and rooting of bulbs but increase refrigeration requirements. Gradually cooling the onion bulbs 1-2°F per day will reduce the chance of condensation on the bulbs and reduce the refrigeration capacity required. Condensation on bulbs can lead to rot and color changes of the dry skin.

VENTILATION: 30-80 cfm per ton of onion for curing (2-5 cfm per ft^3 of onions); 20-25 cfm per ton of onion for storage
Or 2 cfm per ft^3 for immature or inadequately field-cured bulbs; 1 cfm per ft^3 for fully mature bulbs

STORAGE COMPATIBILITY: Onions should not be stored with other crops.

CONTROLLED ATMOSPHERE STORAGE: A low O_2 atmosphere reduces respiration and extends storage life, while elevated CO_2 reduces sprouting and root growth. An atmosphere of 3% O_2 and 5-7% CO_2 seems to work best to extend storage and inhibit sprouting.

ADDITIONAL CONSIDERATIONS: Inadequate curing can shorten storage life. Onions will lose 3 to 5% of their weight during curing. The dew point temperature of the outside air entering storage should be 2°F or more above the temperature of the onions to prevent condensation on the onions. Onions must be treated with a sprout inhibitor if storing more than 4 months. If stored at 28-30°F onions should be thawed at 41°F for 1 to 2 weeks before removal from storage, because rapid thawing will damage bulbs.

Parsnips

YIELD: 10-12 lb/10 ft of row or 20,000 lb/acre in Wisconsin
75 lb/100 ft row or 12,600 lb/acre in Maine

BULK DENSITY: 34 lb/ft^3

HARVEST AND HANDLING: Parsnips are handled and stored similarly to carrots. They should be cooled rapidly to 40°F or less immediately after harvest. Parsnips can be stored in bins or bulk with stacking depth less than 12 ft.

VENTILATION: 40-60 cfm per ton of parsnips

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
1,760-3,520	1,760-3,960	4,180-5,500	6,600-9,460	–

Temperature, humidity, and storage length

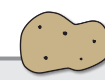
	Temperature (°F)	Relative Humidity (%)	Storage Length
Roots	32-34	98	4 to 6 months
Freezing point	30.4	No chilling sensitivity	

STORAGE COMPATIBILITY: Parsnips produce very little ethylene. They are sensitive to ethylene and may acquire a bitter flavor if exposed. Parsnips may be stored with other root crops.

CONTROLLED ATMOSPHERE STORAGE: No benefit

ADDITIONAL CONSIDERATIONS: Parsnips should be held at 32-34°F for 2 weeks to attain sweetness before marketing. Waxing can reduce water loss.

Potatoes



YIELD:

100 lb/100 ft of row in Kansas
20,000-40,000 lb/acre in Ohio
37,000 lb/acre in Wisconsin
28,700 lb/acre in Missouri
36,000 lb/acre in Minnesota
31,000 lb/acre Michigan

BULK DENSITY: 42 lb/ft^3 Total cwt of bulk stored potatoes = (pile length x pile width x pile height) ÷ 2.3

HARVEST: Potatoes need to be cured for about 2 weeks after harvest to allow healing of the cuts and scrapes that occurred during harvest, to stimulate suberization, and to reduce respiration. Optimal curing conditions are between 50 and 65°F (most commonly 55°F) and 95% RH. Temperatures lower than 50°F and greater than 75°F or with a relative humidity less than 80% will delay curing. Typically, air temperature during curing is controlled by bringing in outside air as conditions permit (nights) or using refrigeration. After curing, the tuber temperature can be reduced by 1 to 3°F per day until the desired temperature is reached. Cooling too rapidly can cause rot, such as black spot.

Respiration heat production at different temperatures (Btu/ton-day) **when mature** (cured)

32°F	41°F	50°F	59°F	68°F
–	1,320-3,960	2,860-4,180	2,420-4,840	3,080-6,380

Temperature, humidity, and storage length (The temperature ranges vary depending on the end product – mainly to prevent the starch from converting to sugars that darken when fried.)

	Temperature (°F)	Relative Humidity (%)	Storage Length
Seed potatoes	40	95	1 to 2 months
Fresh market	45-50	95	3 to 4 months
French fries	50-59	95	5 to 8 months
Chipping	59-68, 41-50 for newer varieties	95	–
Freezing point	30.9	Internal browning can occur at 34-35°F, and sugar levels can increase when stored below 45°F.	

HANDLING: In commercial facilities, potatoes are stored in bulk in piles 12-16 ft high. The potatoes are moved into and out of the storage facility by conveyor belt. Pallet bins, totes, or crates can also be used but need to have slotted or perforated bases and sides to allow ventilation. The length of storage will depend on product quality entering storage, variety, use of sprout inhibitors, and the air distribution and environmental control systems of the storage facility.

VENTILATION: 20-30 cfm per ton of potatoes during curing. 10-20 cfm per ton of potatoes after cooling to storage temperature (can be intermittent). Air circulation is important for temperature and humidity control. Flow rate is dependent upon the outside air temperature and the rate of cooling needed. Generally, systems are designed for 20 cfm. A variable speed drive can be used to reduce the fan speed, airflow rate, and energy use once the potatoes are cooled to the holding temperature.

STORAGE COMPATIBILITY: Potatoes naturally produce low levels of ethylene, but ethylene production increases if they are cut, bruised, or wounded. Sprouting can be induced after 2-3 months if ethylene levels are high. Potatoes can impart an "earthy" odor to apples and pears if held together in a storage room with low air exchange.

CONTROLLED ATMOSPHERE STORAGE: No benefit

ADDITIONAL CONSIDERATIONS: Regardless of air temperature, RH levels should be maintained above 95% to minimize water loss and pressure bruising – blackened tissue and impressions in potatoes from the weight of the potatoes directly above.

Pumpkins (pie type)

YIELD:
15,000-18,000 lb/acre in Ohio
20 lb/10 ft of row in Wisconsin
30,000-50,000 lb/acre in Michigan
5,500 fruits/acre in Iowa
1,500-3,000 pumpkins/acre or 24,000-60,000 lb/acre in Illinois
300 lb/100 ft row or 40,000 lb/acre in Maine

Respiration heat production for pumpkins is very similar to winter squash shown below (Btu/ton-day)

54°F	77°F
54°F - 19,360-24,200	77°F - 13,420-26,62

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Cured fruits	50-55	50-70	2 to 3 months
Freezing point	30.5	Chilling injury can occur at less than 50°F.	

BULK DENSITY: 37 lb/ft^3

HARVEST: Avoid injury and wounds during and post-harvest, wash off field debris, and dip pumpkins in a 10% bleach solution to reduce storage rot. Washing without bleach or an approved fungicide is not recommended. Curing pumpkins for 7-10 days at 80-85°F and 80-85% RH will allow scratches to heal before cooling to holding temperature. Pumpkins do not store as well as winter squash.

HANDLING: Pumpkins should be mature and stored in bins, baskets, on racks, or in bulk piles less than 12 ft high. The fruit surface should be kept dry with good air circulation.

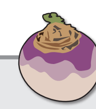
VENTILATION: 30-40 cfm per ton of pumpkins

STORAGE COMPATIBILITY: Pumpkins produce very little ethylene unless wounded, but they are sensitive to ethylene exposure. They should not be stored with crops that produce large amounts of ethylene, such as apples.

CONTROLLED ATMOSPHERE STORAGE: Though CA storage is not typically used, storing in 3% O_2 and 5% CO_2 at 50˚F reduced the amount fruit that was no longer marketable after 2-3 months in storage.

ADDITIONAL CONSIDERATIONS: Alternaria rot can develop after removal from storage if chilling injury has occurred. Fungal and bacteria rots are the leading cause of storage losses. Most fruits are infected in the field before or during harvest. Crop rotation and growing on crop residue such as straw to reduce soil contact can help prevent rots.

Rutabagas



YIELD:
30,000-40,000 lb/acre with 4 to 8 in. between plants and 30 in. between rows in Michigan
8-12 lb/10 ft of row
150 lb/100 ft row or 40,000 lb/acre in Maine

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
880-1,320	1,760-2,640	2,090-4,180	4,400-6,820	7,480-8,800

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Rutabagas	32	98-100	4 to 6 months
Freezing point	30	No chilling sensitivity	

BULK DENSITY: 37-45 lb/ft^3

HARVEST: Rutabagas should be cooled to 32°F as quickly as possible (within 3-4 hours of harvest) to reduce moisture loss and discoloration, especially if soil or air temperatures are greater than 77°F. Slow cooling can cause brown surface discoloration called "storage burn." Pre-cooling can be done with room-cooling, forced-air cooling, hydro-cooling, or icing.

HANDLING: Waxing is a common practice to enhance appearance and reduce moisture loss. Waxed roots can be marketed immediately or stored for 1-2 months. Roots for long-term storage should not be waxed, as it impedes respiration and will not look aesthetically pleasing coming out of storage. They can be stored in bulk piles up to 6 ft high or in bulk bins. Leaves should be removed before storage but keep tap and side roots intact. Trim just before marketing.

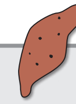
VENTILATION RATE: 30-50 cfm per ton of rutabagas

STORAGE COMPATIBILITY: Rutabagas produce very little ethylene and are not affected by ethylene exposure. They impart strong odors that can be transferred to other produce stored in the same area.

CONTROLLED ATMOSPHERE STORAGE: No benefit

ADDITIONAL CONSIDERATIONS: If the temperature is allowed to increase or humidity to decrease, weight loss can be substantial. When stored for 6 months, shrinkage can be 6% if held at 36°F and 95% RH and 11% if held at 41°F and 90% RH. Waxing can reduce water loss, but it can reduce O_2 exchange and result in internal breakdown if the coating is too thick.

Sweet Potatoes



YIELD:

10 lb/10 ft of row in Kansas

2 lb/10 ft of row in Wisconsin

10,000-20,000 lb/acre in New Jersey

13,000 lb/acre in Iowa

19,000 lb/acre in Virginia

20,000 lb/acre or 2 lb/hill in Missouri

BULK DENSITY: 40-44 lb/ft^3

HARVEST: Tubers are cured at 82-86°F and 90-97% RH for 4-7 days. A ventilation rate of 36 cfm per ton of sweet potatoes is required during curing to remove CO_2 and supply O_2. Wound healing takes place during the curing period to reduce moisture loss and decay.

HANDLING: Sweet potatoes can be stored in pallet boxes or bulk piles less than 17 ft high.

Ventilation: 36 cfm per ton of sweet potatoes

Respiration heat production at different temperatures (Btu/ton-day)

	50°F	59°F	77°F
Cured	3,080	4,400-5,280	–
Non-cured	–	6,600	11,880-15,400

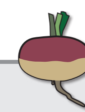
Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Cured roots	55-59	85-90	12 months
	greater than 66	greater than 90	2 to 3 months
Freezing point	29.7	Chilling Injury: Storage below 54°F will result in chilling injury. Symptoms of chilling injury include root shriveling, surface pitting, abnormal wound periderm formation, fungal decay, internal tissue browning, and hardcore formation.	

STORAGE COMPATIBILITY: Sweet potatoes are susceptible to ethylene exposure, but this is a minor concern under normal storage conditions.

CONTROLLED ATMOSPHERE STORAGE: No benefit

Turnips



YIELD:

8-12 lb/10 ft of row

20,000-30,000 lb/acre with 2 to 3 in. between plants and 14 to 18 in. between rows

5-10 lb/10 ft of row in Kansas

30,000-40,000 lb/acre in Wisconsin

50 lb/100 ft row or 40,000 lb/acre in Maine

BULK DENSITY: 37-43 lb/ft^3

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
1,320-1,980	2,200	2,860-4,180	4,620-5,280	5,280-5,500

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Turnips	32	90-95	4 to 5 months
Freezing point	30.1	No chilling sensitivity	

HARVEST AND HANDLING: Turnips can be pre-cooled in water at harvest, but the temperature differential should not be greater than 50°F to prevent cracking. The tops should be removed at harvest, and the roots should be stored in slatted bins or crates.

VENTILATION RATE: 30-50 cfm per ton of turnips

STORAGE COMPATIBILITY: Turnips produce very little ethylene.

CONTROLLED ATMOSPHERE STORAGE: There is no known use of CA storage for turnips.

ADDITIONAL CONSIDERATIONS: Waxing roots can slightly delay weight loss and intensify the purple color of the root.

Winter squash

YIELD:

1 lb/ft of row in Kansas

2 lb/ft of row in Wisconsin

24,000-40,000 lb/acre in Michigan

30,000 lb/acre in Iowa

200 lb/100 ft row or 40,000 lb/acre in Maine

BULK DENSITY: 37 lb/ft^3

HARVEST: Avoid injury and wounds during and post-harvest, wash off field debris, and dip squash in a 10% bleach solution to reduce storage rot. Curing squash for 7-10 days at 80-85°F and 80-85% RH will allow scratches to heal before cooling to storage temperature. The surface of the squash should be kept dry with good air circulation.

Respiration heat production (Btu/ton-day)

54°F	77°F
54°F - 19,360-24,200 (buttercup)	77°F - 13,420-26,620 (butternut)

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Acorn-type	50-55	50-70	5 to 8 weeks
Butternut	50-55	50-70	2 to 3 months
Turban and Buttercup	50-55	50-70	3 months
Hubbard	50-55	50-70	6 months
Freezing point	30.5	Chilling injury occurs at temperatures less than 50°F.	

HANDLING: Squash can be stored in bulk with a pile height of less than 12 ft. Store in bins or crates typically used for winter squash sold at fresh market. There are variations in storage longevity among varieties.

VENTILATION: 30-40 cfm per ton of winter squash

STORAGE COMPATIBILITY: Only compatible with pumpkins due to temperature requirements.

CONTROLLED ATMOSPHERE STORAGE: Controlled atmosphere storage can be used, but controlling relative humidity is critical. Results vary depending on variety.

ADDITIONAL CONSIDERATIONS: Fungal and bacteria rots are the main cause of storage losses. Alternaria rot can develop after removal from storage if chilling injury has occurred. Most fruits are infected in the field before or during harvest. Crop rotation and growing on crop residue such as straw to reduce soil contact can help prevent rots.

FRUITS:
Apples

YIELD:

16,300 lb/acre in Illinois

13,700 lb/acre in Indiana

11,000 lb/acre in Iowa

24,950 lb/acre in Michigan

8,600 lb/acre in Minnesota

14,105 lb/acre in Missouri

14,880 lb/acre in Ohio

11,770 lb/acre in Wisconsin

BULK DENSITY: 30-38 lb/ft^3

HARVEST AND HANDLING: Apples should be cooled rapidly to 32°F to maintain firmness. Rapid cooling can be achieved with room cooling, forced-air cooling, or hydro-cooling. Forced-air and hydrocooling can rapidly reduce fruit temperatures but are not as widely used as room cooling. Room cooling is slow and inefficient, because loading rates are typically higher than the refrigeration capacity. Using multiple cooling rooms to remove field heat can increase cooling rates. Apples are stored in pallet boxes with slatted bottoms and sides.

Idea storage conditions vary by variety as shown in the table, and some varieties are particularly sensitive, such as Empire, MacIntosh, and Macoun.

VENTILATION: (no special considerations)

STORAGE COMPATIBILITY: Apples should not be stored with other crops, because they are ethylene producers and absorb odors.

CONTROLLED ATMOSPHERE STORAGE: When in ambient air storage, apples will store from 2-4 months at 30.2-39.2°F and 90-95% RH, depending on variety. When stored in a controlled atmosphere environment, the standard atmosphere for apples is 2-3% of both CO_2 and O_2. See Table.

Respiration heat production at different temperatures (Btu/ton-day) for summer apples

32°F	41°F	50°F	59°F	68°F
660-1,320	1,100-2,420	3,080-4,400	3,960-6,820	4,400-9,020

Respiration heat production at different temperatures (Btu/ton-day) for fall apples

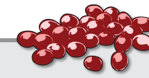
32°F	41°F	50°F	59°F	68°F
440-880	1,100-1,540	1,540-2,200	1,980-4,400	3,300-5,500

Recommendations for controlled atmosphere storage of New York apple varieties*

	CO_2 (%)	O_2 (%)	Temperature (°F)	Notes
Cortland	2-3 first month then 5, or 2-3	2-3	32-36	
Delicious	2	2	32	
Empire	2-3	2-3	35-36	If not treated with DPA (diphenylamine), use 1.5-2% CO_2 for first 30 days.
Fuji	2-3	2	32	
Gala	2-3	2	32	Loss of flavor can occur if stored longer than 4 months.
Golden Delicious	2-3	2	32	Shriveling of skin can be an issue.
Idared	2-3	2	34	
Jonagold	2-3	2-3	32	
Jonamac	2-3 first month then 5, or 2-3	2-3	36	Loss of flavor can occur if stored beyond December.
Law Rome	2-3	2	32	
Macoun	5	2-3	36	
McIntosh	2-3 first month then 5	2-3	36-38	
Marshall McIntosh	2-3 first month then 5	4-4.5	36	
Mutsu	2-3	2	32	
Spartan	2-3	2-3	32	
Stayman	2-5	2-3	32	

*Watkins, 1997.

Cranberries



YIELD:

23,300 lb/acre in Wisconsin

15,400 lb/acre in Massachusetts

BULK DENSITY: 40 lb/ft^3

HARVEST AND HANDLING: Cranberries are stored in pallet bins. The red color of cranberries can be increased by holding the fruit at 45 to 50°F for up to 2 weeks before reducing to the long-term storage temperature.

VENTILATION: (no special considerations)

Respiration heat production at different temperatures (Btu/ton-day)

32°F	41°F	50°F	59°F	68°F
880	880-1,100	1,760	–	2,420-3,960

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Pallet bins	36-40	90-95	2 to 4 months
Freezing point	29.5-30.4	Holding crop between 30.5 and 33°F for longer than 2 weeks can cause chilling damage.	

STORAGE COMPATIBILITY: Cranberries have a low ethylene production rate. Exposure to low levels of ethylene (10 µL/L) will accelerate maturity and the development of red coloring. Therefore, airflow and exchange are important to maintain the fruit in long-term storage.

CONTROLLED ATMOSPHERE STORAGE: There is no known use of CA storage of cranberries, but some research suggests that an environment of 21% O_2 and 30% CO_2 would be optimal. CA storage has not been shown to lengthen storage life.

ADDITIONAL CONSIDERATIONS: At higher relative humidity (>82%), weight loss is reduced, but decay from fungal diseases increases. Poorly colored fruit can be held at 45-50°F for 1 to 2 weeks to allow coloring to develop before reducing storage temperatures to 36-40°F.

Pears

YIELD:

16,400 lb/acre in New York

9,200 lb/acre in Michigan

BULK DENSITY: 38 lb/ft^3

HARVEST: For long-term storage, pears are picked before maturity based on Magness-Taylor flesh firmness values: Bartlett 19.5 lb; D'Anjou 15-15.25 lb; Bosc 15 lb. Fruit firmness at harvest will affect storage life. It is important to reduce field heat as quickly as possible to the storage temperature. The core temperature should be cooled to near holding temperature within 4 days after harvest. Delays in cooling will shorten storage life.

Respiration heat production at different temperatures (Btu/ton-day) **for d'Anjou pears**

28°F	30°F	32°F	34°F	50°F	70°F
500	515	735	865	1,430	1,540

Temperature, humidity, and storage length

	Temperature (°F)	Relative Humidity (%)	Storage Length
Bartlett	30 (all varieties)	90-95	120 days
	34	90-95	70 days
	36	90-95	40 days
Freezing point	29	No chilling sensitivity.	

HANDLING: Pears can be stored in bulk bins or packed in cartons to reduce scuffing. If packaged in cartons, airflow around each carton will be important to ensure airflow around fruit.

VENTILATION: (no special considerations)

CONTROLLED ATMOSPHERE STORAGE: CA storage is used to keep pears for long-term storage. Typically, two CA protocols are used. In the first protocol, pears are stored in 2%-2.5% O_2 and less than 0.8% CO_2. In the second protocol, the level of CO_2 is elevated to 11-12% for 10-14 days at 30°F followed by regular CA conditions described in the first protocol or ambient air storage. The second protocol can extend storage life by 40% over conventional air storage, from 5 months to 7 months. Storage temperatures of 37-50°F cause dry texture and inferior flavor in some varieties.

Additional Resources

Visit fyi.uwex.edu/cropstorage for links to the resources in this section.

ACTIVE HEAT TRANSFER SYSTEMS

Midwest Plan Service. 1990. Ch. 5: *Earth tube heat exchangers,* In *Heating, Cooling, and Tempering Air for Livestock Housing.* MWPS-34. Ames, IA: Midwest Plan Service.

BUILDING PLANS

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Glossary

From the National Agricultural Statistics Service

Bulk density. The weight of a product for a given volume. A higher value indicates a denser product or more weight for a given volume. Example: 40 pounds per cubic foot (40 lb/ft^3).

Dew point. The temperature at which the air is holding the maximum amount of water vapor, or 100% relative humidity.

Ethylene propylene diene monomer rubber (EPDM) rubber. A synthetic rubber that has excellent weathering properties.

Freeze point. The temperature at which the first ice crystal appears. It is generally lower in vegetables and fruits than the freezing point of pure water due to soluble solids in the water contained in plant tissue.

Relative humidity (RH). The ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at the same temperature.

Roof truss. A structural component of a building that supports the weight of a roofing system (lumber and roof covering). Trusses are built of lumber or steel and are nailed, glued, bolted, or screwed together to form a frame that is attached to the side walls of a building.

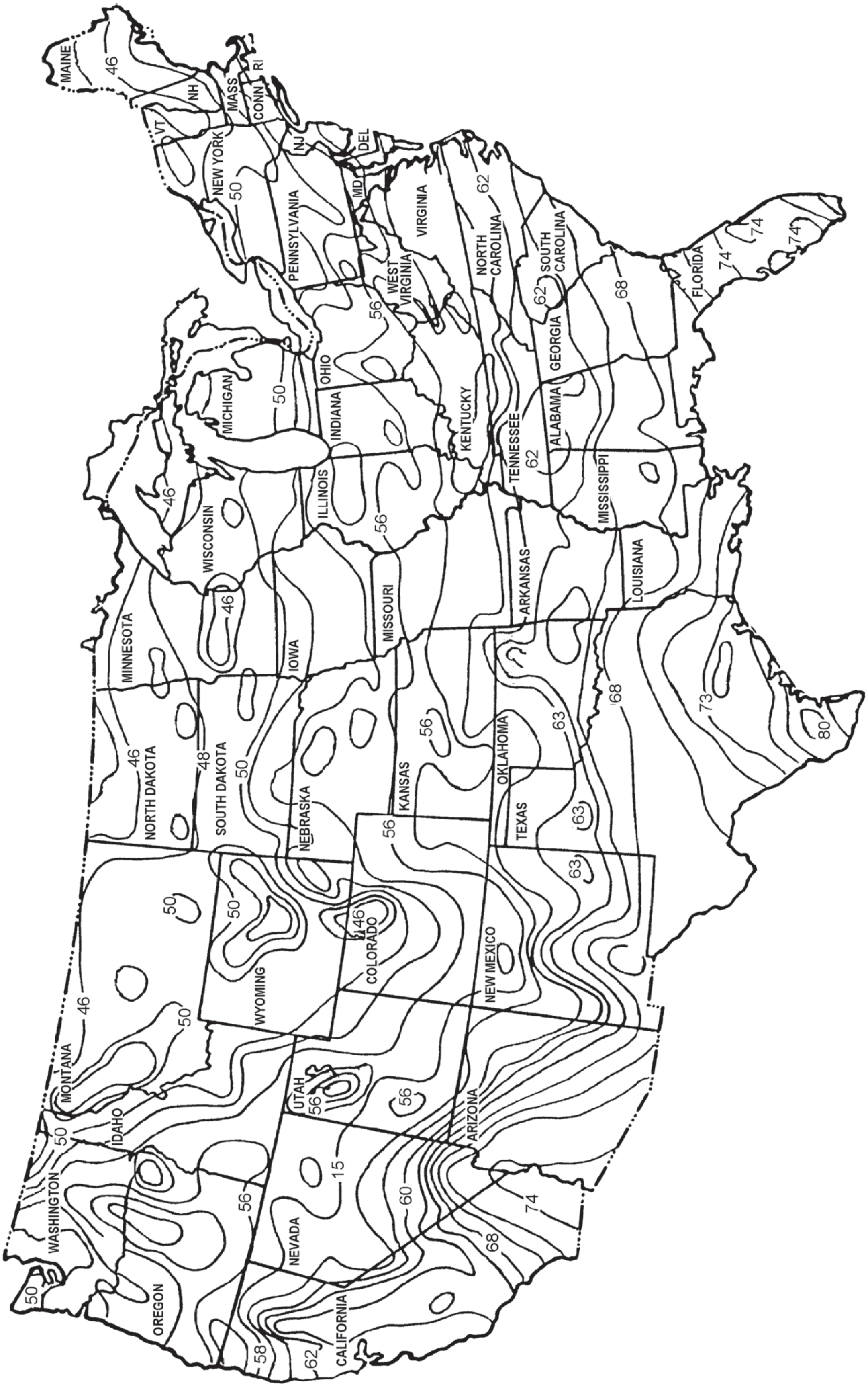
R-value. The measure of a material's resistance to heat transfer through the material with units of (ft^2-hr-°F)/Btu, energy transferred through a material per unit area, per unit of time, per degree of temperature difference between the hot and cold side of a material. A higher value indicates more resistance to heat flow or higher insulation value. R-value equals the inverse of U-value ($R = 1 \div U$).

Screed. A wood strip or u-shaped vinyl channel that is fastened to a floor to provide a retainer to which prefabricated cooler walls are fastened. Screeds keep the walls in place and provide a seal from air or water movement into or out of the cooler.

U-value. The conductive heat flow rate through a material per unit area, per unit of time, per degree of temperature difference between the hot and cold side of a material. The units are Btu/(ft^2-hr-°F). A lower value indicates less heat flow due to a greater insulation value or resistance to conduct heat. U-value is the inverse of the R-value ($U = 1 \div R$).

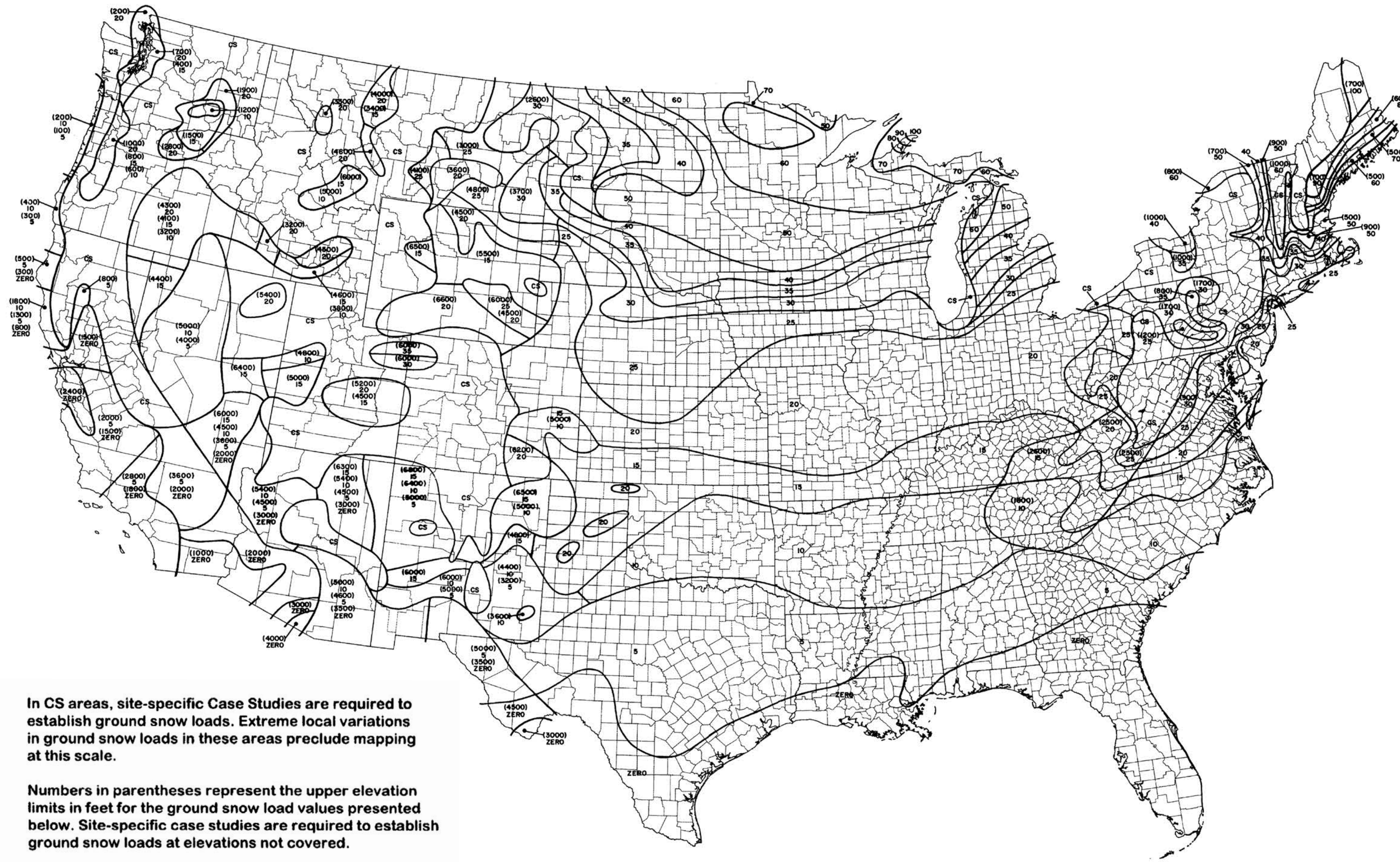
Vapor barrier. A thin layer of material that has low permeability to water vapor. They are used in building construction to prevent water vapor from entering the wall and damaging the building components. Polyethylene films, foil sheeting, and closed-cell foam insulation boards are examples of materials commonly used in vapor barriers.

Appendix A: Ground temperatures in the continental U.S.



Used with permission of the National Ground Water Association.

Appendix B. Ground snow load map of the continental U.S. (lb/ft^2)



In CS areas, site-specific Case Studies are required to establish ground snow loads. Extreme local variations in ground snow loads in these areas preclude mapping at this scale.

Numbers in parentheses represent the upper elevation limits in feet for the ground snow load values presented below. Site-specific case studies are required to establish ground snow loads at elevations not covered.

To convert lb/sq ft to kN/m^2, multiply by 0.0479.

To convert feet to meters, multiply by 0.3048.

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On-Farm Cold Storage

of Fall-Harvested Fruit and Vegetable Crops

PLANNING – DESIGN – OPERATION

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Visit **fyi.uwex.edu/cropstorage** for more information and links to additional resources.

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