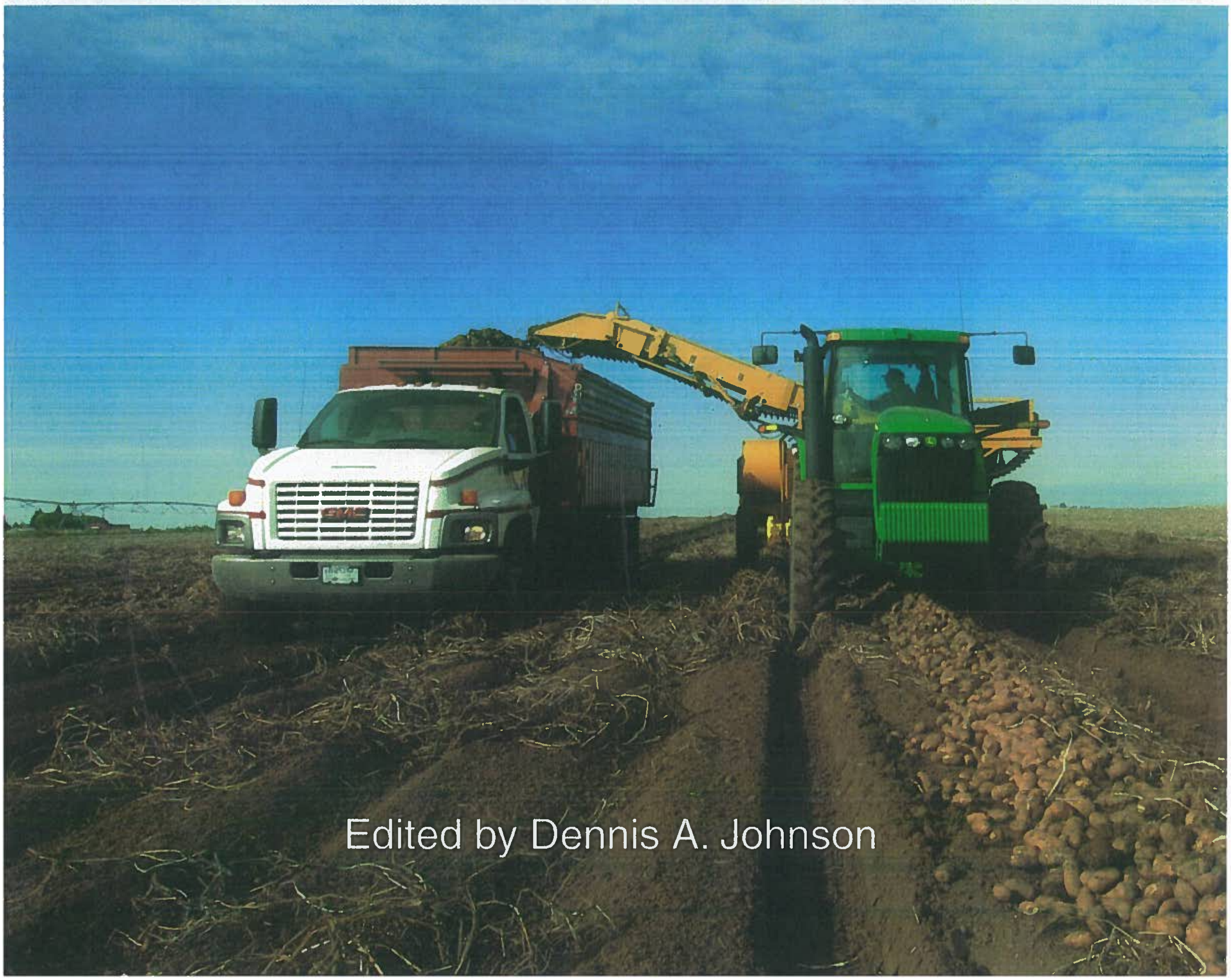
Plant Health Management Series

POTATO
Health Management

Second Edition



Edited by Dennis A. Johnson

N. Richard Knowles
Department of Horticulture and Landscape Architecture
Washington State University, Pullman

Edwin S. Plissey
Department of Plant, Soil and Environmental Sciences
University of Maine, Orono

Maintaining Tuber Health During Harvest, Storage, and Post-Storage Handling

After a healthy potato crop has been grown, the next challenge is to limit the loss of tuber quality during harvest, storage, and post-storage handling. Potato tubers are living organisms, and tuber quality only deteriorates after harvest and through storage and delivery to the processor or consumer. The objective, therefore, is to implement handling and storage practices that preserve tuber quality for as long as possible following harvest. Achieving this objective is even more difficult if quality has been compromised by various stresses (e.g., temperature, diseases, and insects) during production.

This chapter presents optimal handling and storage practices for crops that are healthy at harvest. Some guidelines for handling and storage of "problem crops" will also be outlined. Maintaining tuber health through harvest, storage, and post-storage handling requires a thorough understanding of the crop history, to best predict its subsequent physiological behavior. Only then can effective management practices be developed for maintaining postharvest quality in relation to the condition of the crop prior to harvest and its end use as seed, processing, or fresh-market potatoes.

Tuber Quality

The holistic approach to maintaining tuber health during harvest, handling, and storage recognizes that preharvest factors (e.g., characteristics of the cultivar, growing conditions, agronomic practices, stress) and conditions during harvest and handling prior to storage affect the postharvest behavior of both seed and commercial potatoes (Fig. 10.1). Vine condition, soil and tuber temperature, and mechanical damage during harvesting can greatly affect crop quality and subsequent storability and thus must be considered in timing the harvest. In areas with a relatively short growing season, target yield and tuber size development are also important factors.

Decreases in tuber quality are evident at each stage of the supply chain from producer to consumer, and the causes of deterioration can be stage-specific. For example, mechanical injury during harvest and transport is a major cause of subsequent loss of quality. Bruising, improper curing, starch breakdown, sugar buildup, weight loss, decay, and sprouting affect quality during storage. Another cause of deterioration in wholesale and retail markets is greening of tubers exposed to light.

Economic returns for fresh-market potatoes are largely dictated by the tuber size profile, with premiums paid for specific size classes. In the market for premium clear- or foil-wrapped baking potatoes (Fig. 10.2), an absence of external defects is paramount. Regardless of the cultivar, blemish-free tubers with good skin set and good color command the highest market prices.

Processors require a constant supply of healthy, disease- and damage-free tubers of the proper size throughout the year. The ability to retain processing quality over a long storage period is thus desirable. While the preferred characteristics vary according to the type of processing (e.g., chips, fries, extruded by-products), a high ratio of processed product to raw product is desired, and this generally requires a high dry matter content. Low levels of reducing sugars (glucose and fructose) and a high starch content are essential in tubers used for chip and french fry processing. Processors often provide premiums to growers to encourage production and delivery of high-quality tubers.

For seed potatoes, a supply of disease-tested, unsprouted tubers of the correct size and physiological age that will produce vigorous, high-yielding plants in commercial production is of utmost importance.

From a postharvest perspective, the challenges are to preserve the characteristics that constitute quality in seed, fresh-market, and processing potatoes through proper management of handling and storage environments. To accomplish this, the process must begin before harvest and involve an integrated assessment of the impact of all facets of production on the health of a crop at harvest.

Preparing for Harvest

To attain the maximum postharvest quality and storability of the crop, decisions about the timing of the harvest should be based on consideration of several factors, including vine condition, crop maturity, target yield and grade, and soil and tuber temperatures. Killing vines at the end of the season

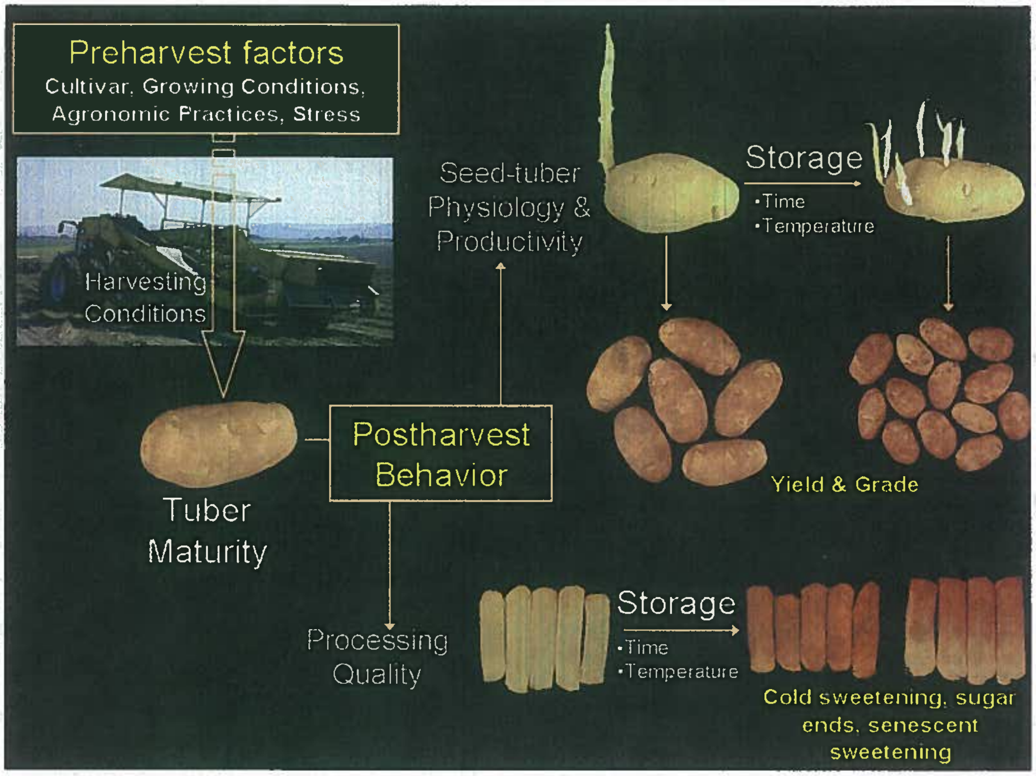


Fig. 10.1. Variables inherent in the production environment, together with conditions during harvest, affect tuber maturity, which subsequently affects the postharvest behavior and quality of seed and processing potatoes. A thorough understanding of crop history is needed in order to define the best management practices for maintaining postharvest quality.

Fig. 10.2. Minimizing mechanical injury during harvest and transport is critical to providing maximum yield of blemish-free tubers marketed as premium clear- or foil-wrapped microwavable and baking potatoes.

hastens skin set, reduces disease potential, and facilitates mechanical harvesting. In areas with long growing seasons, vines of many cultivars begin to senesce naturally as harvest approaches. In areas with shorter growing seasons or higher moisture and relative humidity during the maturation phase of tuber development (Growth Stage V), vine senescence will be delayed, and managing vine condition and tuber maturity may be more challenging.

Managing Crop Maturity

Proper management of a crop prior to harvest minimizes mechanical damage to tubers during harvesting and handling. In some areas, the crop is harvested while the vines are still green and the tubers are immature. These potatoes are usually shipped directly to a fresh or processing market where they are used immediately, before the full effects of harvest damage develop. The lack of skin set associated with harvesting tubers from green vines results in increased skinning during harvest, which leads to desiccation and loss of fresh weight in storage. Immature tubers also have higher rates of respiration, which leads to dry matter loss and heat production during transit and storage.

In the major production areas of the United States and Canada, most of the harvested crop is stored before marketing. To preserve quality and maximize storability, growers must produce mature tubers that resist mechanical damage during harvest and handling operations. A mature tuber is one that has been managed to achieve full physiological maturity, either naturally or artificially. Physiologically mature tubers contain high levels of total solids (i.e., they have a high specific gravity and a high starch content) and low levels of reducing sugars and sucrose (Fig. 10.3) and have good skin set. Sucrose and glucose can be monitored at the end of the growing season to estimate relative maturity, which will dictate temperature management early in the storage season. Potatoes with a sucrose content greater than 0.15% of tuber fresh weight (approximately 0.8% of tuber dry weight) at harvest are prone to premature increases in reducing sugars (glucose and fructose) during storage, which eventually causes off-color problems during processing.

The timing of the harvest operation is critical in management for healthy, damage-free tubers. Early-maturing cultivars, such as Russet Norkotah, Norland, and Shepody, are frequently ready for low-damage harvest with minimal preharvest treatment. However, in many northern production

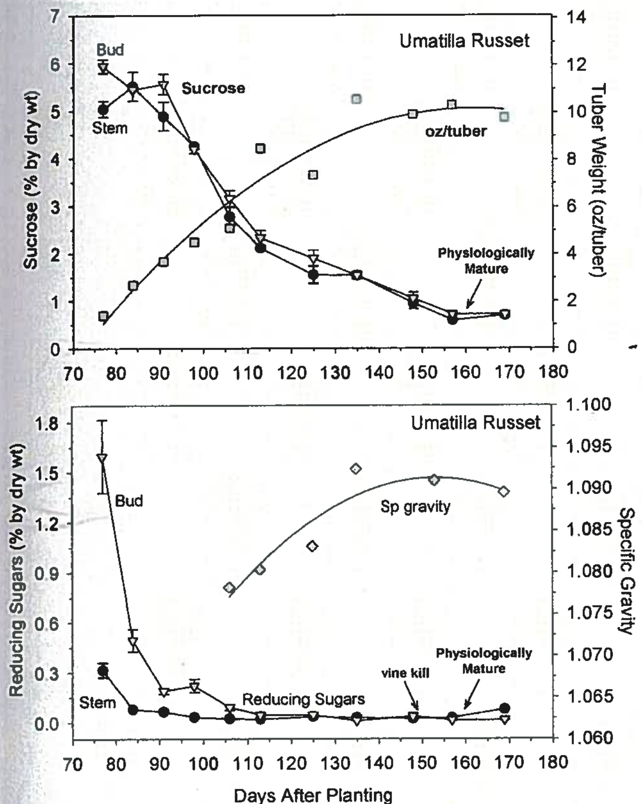


Fig. 10.3. A crop should be managed to produce physiologically mature tubers that contain high levels of total solids (i.e., have a high specific gravity) and low levels of sucrose and reducing sugars prior to harvest. Physiologically mature tubers with good skin set will maintain their processing quality the longest, under ideal storage conditions. Sucrose and glucose can be monitored to estimate tuber maturity. (Courtesy E. P. Driskill, Jr., and N. R. Knowles)

areas, damaging frost occurring before all fields are harvested often complicates planning for tuber maturity and a damage-free harvest, especially in crops of mid- or late-season cultivars. In these areas, early planting and early emergence are essential to allow time for crops to achieve full physiological maturity in a short growing season.

In most situations, careful management of fertility, irrigation, tillage, and vine killing is necessary to ensure the attainment of maturity. Nitrogen applied late in the season can delay maturity, reduce specific gravity, and raise the reducing sugar content. Nitrogen should be applied in amounts that do not exceed the crop's needs, and it should not be applied within 4–6 weeks of vine killing.

In irrigated production areas, the frequency and amount of irrigation should be reduced to achieve 70–75% available soil moisture during tuber maturation to encourage maturation and skin set. Excessively high soil moisture during maturation promotes pink rot, pink eye, and Pythium leak; it also causes enlargement of tuber lenticels, which often leads to increased bacterial soft rot in storage. Moreover, overly wet soil that remains caked on the surface of tubers will decrease the efficacy of chlorpropham (CIPC) and other sprout inhibitors applied later in storage. Soil and mud in the storage facility may clog vital air ducts and disrupt ventilation efficiency, leading to nonuniform movement of air through the bulk pile. Therefore, every effort should be made to ensure that potatoes going into storage are as clean as possible, and maintenance of ideal soil moisture conditions at harvest is the first step toward this goal. Where irrigation is available, excessively dry soil should be watered to prevent tuber dehydration, which increases the sensitivity of tubers to blackspot bruise during harvest (Chapter 23) and can lead to increased pressure bruising during storage. Soils with high clay content tend to form clods as they dry. Clods can be a significant source of bruising during harvest, and thus tillage and other field operations (e.g., irrigation) should be managed to minimize soil compaction and clod formation.

Vine Killing

Potato vines actively photosynthesize and translocate sucrose to developing tubers, where numerous carbohydrate interconversions take place. Vine killing halts this process, allowing soluble sugars to decline and solids (specific gravity) to stabilize in tubers during the maturation process prior to harvest (Fig. 10.3). It hastens maturity and facilitates periderm maturation and skin set (Box 10.1), thus minimizing certain kinds of mechanical injury during harvest and handling. A mature tuber with a well-set skin is considerably more resistant to injury during harvest, and infection by fungal and bacterial pathogens that enter tubers through wounds is minimized. For most cultivars, fully mature tubers can retain processing quality during prolonged storage.

Much loss due to disease in storage is directly attributable to failure to achieve proper vine kill and tuber maturation before harvest. Vine killing also kills weeds that might interfere with harvest, helps stop the spread of spores of the early and late blight pathogens from foliage to tubers at harvest (Chapter 21), and limits the late-season spread of viruses by aphids or mechanical means, which is of considerable importance in the production of seed potatoes.

Timely vine killing also improves the harvest operation by reducing the total vine mass moving through the harvester and by weakening the point where each tuber connects to its stolon. This allows easier separation of tubers from vines, thus reducing the loss of tubers from the harvester with the devining chains. Vine killing is also useful in controlling tuber size, where that is desirable.

The timing of vine killing is best determined by digging a few hills in several places across a field and examining tuber development. Glucose and sucrose monitoring should also be considered in assessing maturity status. In most production areas, vine killing is done by mechanical or chemical means (application of vine-desiccating compounds) or by a combination of these. Mechanical vine beaters can efficiently shred vines with minimal physical injury to tubers. Partial vine shredding or rolling of vines frequently enhances the efficacy of chemical desiccants. A drawback of very rapid vine killing is that it occasionally induces stem-end browning, a discoloration of the tuber vascular ring. This physiological disorder is usually more severe when chemical desiccants are applied at high temperatures when the soil is dry. Stem-end browning may reduce tuber grade sufficiently to affect the quality of french fries or chips.

Most potato cultivars require at least 10–14 days after application of a vine-killing treatment for tubers to mature sufficiently to resist bruising and skinning damage at harvest. During this period, the meristematic layer of cells, which

Box 10.1

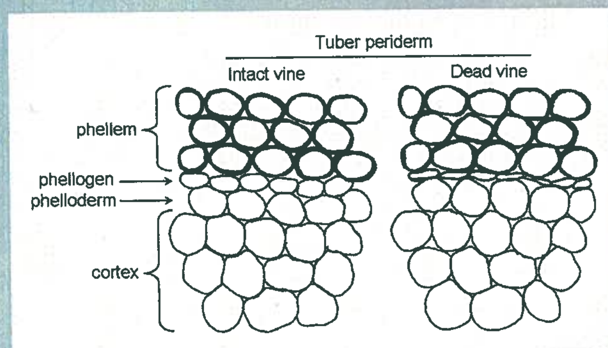
Skin Set

The periderm (skin) of a tuber is composed of phellem (cork) cells, a meristematic layer called the phellogen (cork cambium), and the phelloderm. During growth, the phellogen produces multiple layers of cells toward the outer side of the tuber, which differentiate into phellem cells. The phellem cells become coated with suberin, a waxy, fatty substance, which seals the periderm and prevents water loss from the tuber. The phellogen is thus responsible for producing the protective skin of the tuber.

Skin set occurs during tuber maturation and is important in minimizing the susceptibility of tubers to skinning injury during harvest and handling. Green vines indicate that the phellogen is still meristematically active, producing periderm as the tubers continue to develop. Skin set begins with the cessation of meristematic activity by the phellogen, which occurs naturally as vines senesce, but the process is hastened by vine killing. During skin set, structural changes strengthen the cell walls of the phellogen as it becomes inactive. This process constitutes the maturation of the periderm, rendering the tuber resistant to skinning. Damage incurred during harvest and handling exposes underlying cells of the cortex, which will form new phellogen and suberized wound periderm, thus sealing off the underlying tuber tissues in the process of wound healing.

The progress of periderm maturation and skin set can easily be checked by digging a sample of tubers and determining the ease with which the skins can be "slipped" by hand. If the skin (the outer layer of suberized phellem cells) slides easily on the phellogen layer when pressure is applied with a sideways motion of the thumb, the phellogen layer is still active, and harvest should be delayed. Inability to slip the skin by hand indicates that the phellogen is no longer active as a meristem, periderm maturation is complete, and the skin has set.

The process of skin set is usually completed within 10–14 days of vine death. Skin set greatly enhances the resistance of tubers to skinning during harvesting. This in turn reduces the susceptibility of tubers to desiccation and infection by various pathogens.



Organization of cells in the periderm (skin) of a potato tuber. During skin set, structural changes occur in the phellogen layer as the meristematic activity of this layer ceases under dead vines (right). (Drawing by G. N. M. Kumar)

produces the periderm (skin), becomes inactive, resulting in skin set. In fields where late blight or early blight is present, fungicide applications should be continued until all vines are dead. Cultivars that are susceptible to net necrosis, such as Russet Burbank, should also continue to receive insecticide applications to prevent late-season spread of *Potato leafroll virus* by aphids. Ideally, vines should be dead and dry before harvest begins. Delaying harvest more than 2 weeks after vines are completely dead is unwise, because tubers left in the ground are more likely to have increased levels of Rhizoctonia black scurf and silver scurf. Furthermore, some processing cultivars (e.g., Ranger Russet) will age and become overly mature if left too long under dead vines, especially in areas with relatively high temperatures at harvest, and this aging can lead to premature sweetening and loss of processing quality during storage. For seed crops, the accumulation of heat units by tubers left in the soil for a long period after vine killing contributes to aging, which can ultimately affect the productivity of the subsequent crop by altering the number of stems produced, tuber set, and tuber size.

Preharvest Storage Sanitation and Inspection

A clean storage facility is essential for preserving the health and quality of stored potatoes after harvest. Before harvest begins, the walls, plenum areas, air ducts, and floors of the storage should be thoroughly cleaned and sanitized (Chapter 7). After the storage is cleaned, all operating systems should be inspected carefully and repaired as needed (Box 10.2). The insulation, vapor barrier, fan and humidifier components, ductwork, sensory and regulatory components, and doors must all be functional and coordinated to ensure maintenance of the proper environment for long-term storage.

Preharvest Equipment Inspection

Mechanical damage to tubers is cumulative throughout the harvest and handling operations (Fig. 10.4). All harvest and handling equipment should be inspected before harvest to ensure that it is mechanically ready to perform the harvest with a minimum of damage to the crop. Significant bruise damage to more than 3–4% of the crop is excessive. Bruise damage can be considerably reduced by identifying problem areas and making "low-bruise" modifications to harvest equipment (Box 10.3). All harvesters, windrowers, bulk trucks, bin pilers, and other equipment used during harvest should be tested and serviced to ensure proper operation during periods of peak use. Worn and damaged parts should be replaced. Equipment should be regularly examined

Box 10.2

A Checklist for Preharvest Storage Inspection

Insulation

The insulation in potato storages should be inspected to be sure that it is intact in ceilings, walls, and doors. Adequate insulation must be installed in each component to avoid condensation and heat loss. The greater the expected difference between inside and outside temperatures during the storage season, the more insulation is needed. For most potato storages in northern areas, a minimum of R-30 in walls and R-40 in ceilings is recommended. Condensation on walls and ceilings and excessive heat loss along perimeter walls are often major factors leading to the breakdown of tubers in storage. These conditions are favorable for the development of bacterial soft rot and other damage that lowers processing quality and can result in rejection of entire lots.

Vapor Barrier

The vapor barrier serves two purposes: it maintains the high relative humidity needed to prevent water loss and shriveling of stored tubers, and it prevents water vapor from penetrating the insulation and thereby decreasing its ability to insulate. To be effective, it must be continuous over all interior storage walls. The preharvest inspection should include a thorough examination of the vapor barrier. The vapor barrier can be an integral component of the insulation. In modern storages, the insulation is specifically formulated and applied to create a textured surface that prevents condensation (Fig. 10.9E).

Fans and Humidifiers

Fans and humidifiers exchange air and add water vapor to the storage environment. Both functions are critical to the maintenance of tuber health in storage. Stored tubers require frequent air exchange through the pile to remove the undesirable products of respiration—carbon dioxide, heat, and excess water vapor. Fans should provide uniform temperature and even distribution of water vapor throughout the storage. The fans and humidifiers should be sized to deliver maximum output in the most difficult storage situations. Fan capacity is rated in cubic feet of air per minute (cfm). At least 1 cfm should be provided for each 100 pounds of stored potatoes. The relative humidity cell decks should be inspected and cleaned of mineral deposits. A recent development in fan motor control is the variable-frequency drive (VFD), by which the speed of ventilation fans can be adjusted according to the return air temperature, whenever outside air is available. VFDs prevent overventilation and can provide substantial energy savings, and they can cause less tuber shrinkage and prevent condensation more effectively than conventional fan control systems.

Before filling the storage, be certain that all bearings are properly lubricated and drive belts are in good repair. After the storage is filled, a smoke bomb may be used to check for proper air distribution through the storage pile. In storages equipped with only perimeter air distribution, a careful inspection must be made to ensure that the airflow is uniform throughout the facility and that it is removing excess condensation from the walls and ceilings. Consult with local advisors to determine procedures for optimal fan operation in specific storage facilities.

Duct System

The duct system includes a plenum chamber, which usually houses the fan and humidifier, and ducts, which distribute air uniformly to all storage areas. Ducts usually consist of galvanized culverts, wooden sections, or concrete troughs in the floor covered with boards. In newer designs (Fig. 10.9C) the air outlets are built into the concrete floor (Fig. 10.9D). Plugged or broken ducts interfere with airflow, and the quality of tubers may be affected in places where airflow through the pile is obstructed. During the preharvest inspection, make sure that all ducts are in good repair and are properly sized in relation to fan capacity, to provide uniform air distribution.

Doors

Storage doors must function as walls when the storage is in operation and thus must be equipped with adequate insulation and vapor barrier to maintain the desired environmental conditions in storage. Doors must seal tightly when closed, to avoid excessive heat loss during winter and to avoid heat gain from the outside air during warm periods. Because of their heavy use, doors are the storage component most often in need of maintenance and repair. The preharvest inspection is not complete until all doors have been repaired and function properly.

Sensors and Control Panels

In automated storages, the control panel and environmental sensors are critical to successful storage management (Fig. 10.9B). Improper installation, malfunction, or sensor failure can allow unfavorable environmental conditions to develop quickly, leading to subsequent damage to tuber health. All thermocouple wires should be inspected for proper placement and function. Be certain that automated controls function properly and that all storage systems are well integrated. Determine that dampers and damper motors function properly on demand from the control panel to maintain the storage environment within allowable tolerances.

Box 10.3

Equipment Modifications for a Low-Bruise Harvest

Considerable research has been done to identify the parts of harvest and handling equipment where the most bruise damage to tubers occurs during the harvest operation. The modifications described here can be made to existing equipment to reduce bruising. When new equipment is purchased, it is wise to look for these features as part of the original design.

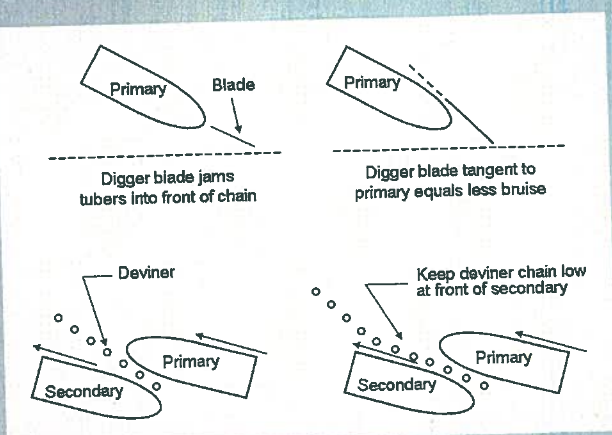
Harvester

The harvester is the major source of mechanical damage to tubers (Fig. 10.4). Several modifications can be made that together reduce damage to tubers as they flow through the machine.

The digging blade on the harvester should be matched to the soil texture and be positioned so that the flow of soil and tubers is delivered up onto the digger chain, rather than bumping into the front of it (see the figure below). Hinged metal plates can be installed at the back of the digger blade to bridge the gap and rise from the blade to the primary conveyor.

With hooked chain on the primary conveyor, all links in the chain should be down links if bruise damage there is mainly due to pinching of tubers. However, if bruise damage on the primary conveyor results mainly from an inability to separate soil from tubers without excessive shaking or rollback (mostly a problem with round tubers), a configuration with one straight link and three or four down links provides positive tuber movement and increased soil separation. Ideally, all hooked chain on the harvester should be replaced with belted chain, which virtually eliminates pinching of tubers.

Other improvements that should be considered are hydraulically activated shakers on the primary bed, to improve operator control of soil separation, and full-width belted primary chain, particularly if a windrower is used with the harvester. When potatoes that have been windrowed into the furrow between rows are being picked up by the harvester, considerable damage to tubers is inflicted by the lag hooks of the twin-bed harvester chain. A full-span belted primary chain with an accompanying full-span lifting blade delivers windrowed potatoes onto the harvester with a minimum of bruising. Belting or rubberized deflectors should be installed along the sides of the conveyors to deflect tubers away from the gap between these areas and the edge of the conveyor.



Position of the digger blade and deviner chain in relation to the primary and secondary conveyors for reduced tuber damage. (Adapted from G. M. Hyde, R. E. Thornton, and R. E. Hermanson, 1983, Reducing potato harvesting bruise, Extension Bulletin 1080, Cooperative Extension, College of Agriculture and Home Economics, Washington State University)

On harvesters with an overriding deviner chain, the deviner should operate in conjunction with the secondary conveyor. The deviner is frequently a major source of tuber damage on both harvesters and windrowers. If the first one or two sets of deviner chain rollers are removed, the chain runs flat on the secondary conveyor for the first few inches following the drop from the primary conveyor (see the figure below). Before this is done, the secondary conveyor speed and the deviner chain speed must be measured and adjusted so that they are the same. This rather inexpensive modification can result in a significant reduction in bruise damage on many harvesters.

The drop from one conveyor system to another can be a major source of bruise damage, and it is important to minimize the height of the drop. The drop from the secondary chain to the rear cross-conveyor is the largest on most harvesters. The 90° change in direction of the potato flow, in addition to the drop, increases the potential for damage at this point. The best padded chains available should be installed on the rear cross-conveyor to help reduce bruise damage. In addition, the upper end of the secondary conveyor should be modified by installation of a dogleg drive sprocket, which can decrease this drop to 6 inches or less. This modification is most easily achieved if belted chain is used on the secondary bed.

Modifications at both ends of the rear cross-elevator may significantly reduce bruise damage. A split secondary conveyor can be used, with the inside of the secondary extended over the rear cross-conveyor; the extension should be about one-third of the width of the rear cross. Similarly, the rear cross-conveyor can be extended over the side elevator, just enough to avoid damage at the inside corner, where the end of the rear cross meets the inside of the side elevator conveyor. Additional padding and chain edge deflectors can also be installed in the side elevator conveyor to reduce bruising.

Bruising due to rollback is a serious problem on the side elevator, because the angle of flow is rather steep. Rollback can be reduced by operating the conveyor at a speed that allows it to remain full of material. If this cannot be done, rollback can be reduced by installing a plastisol flight link every eight lengths of the side elevator chain. The plastisol material is stiffer at the wing ends of the flight and thus reduces rollback along the elevator edges. Another way to reduce rollback is to install a hugger belt on the side elevator conveyor.

The drop from the side elevator to the front cross-conveyor is also a key site for bruising, especially if many stones are present. This drop should be minimized as much as possible (see the figure below). Deflector belting is essential on the sorting table, to cover hooked or belted chain edges, where bruise damage often occurs. Exposed chain edges at the sorting table are also a safety hazard, as harvest personnel might catch their fingers there.

All areas of potato flow on the harvester should be examined carefully, and padding devices should be installed wherever possible to reduce tuber buffeting, which causes mechanical damage.

Harvester Chain Speed Calibration

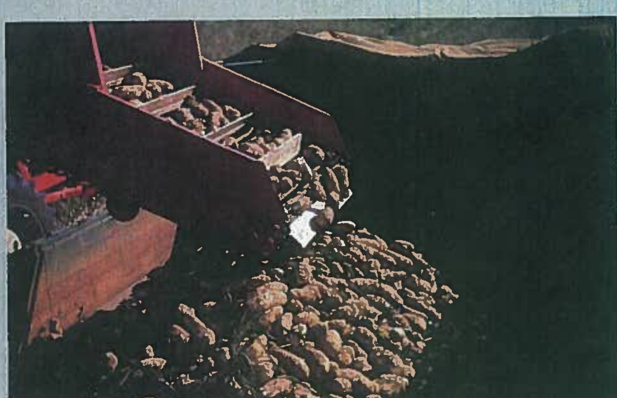
An important low-bruise principle is that all conveyors on the harvester should be filled to capacity at all times during operation, to prevent bouncing, buffeting, and rollback of tubers. To accomplish this, the conveyor speed and forward ground speed must be coordinated, so that the volume of material handled on each conveyor is equal to its capacity.

The conveyor speed can be calculated from the chain's length and the number of revolutions per unit of time. First, measure the circumference of the conveyor with a flexible tape. Next, mark the chain with spray paint, and then time it as it makes one full revolution. The conveyor speed (in feet per second) is equal to the chain length (in feet) divided by the time taken for one revolution (in seconds). To express the speed in miles per hour, multiply the number of feet per second by 0.68. The desired speed of various harvester conveyors in relation to ground speed has been established for most areas and can be obtained from local advisors. Adjustments to conveyor speed should be based on these recommendations.

Details of harvester modifications and conveyor adjustment to minimize bruising have been outlined in several bulletins and in four videos prepared by the National Potato Anti-Bruise Committee of the Potato Association of America in cooperation with the University of Idaho and Washington State University (see Sources of Additional Information at the back of this book). Local advisors should be consulted to obtain these and other sources of information.

Bulk Trucks

There is considerable potential for damage to tubers during handling between the harvest operation and the warehouse (Fig. 10.4). Bulk truck bodies should be inspected, and any rough areas that could cause injury during handling should be repaired or padded to protect the crop. Unloading conveyors should be repaired or modified to minimize damage during unloading. Bulk trucks should be equipped with tarps or mechanical covers to protect potatoes from wind, rain, or sunburn during transit. A self-tarping mechanism should be installed to avoid the need for walking on the potatoes when the truck is being covered (see the figure below).

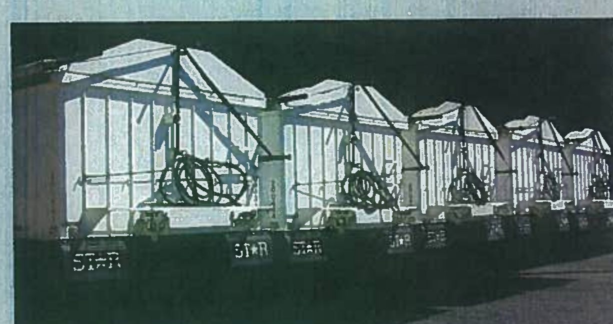


The drop from the conveyor should be limited to 6 inches.

Bin Piler

The bin piler is another significant source of bruise damage as the crop is moved into storage (Fig. 10.4). All rough or abrasive surfaces should be padded with protective foam or rubber cushioning. The piler should be modified to limit all drops to 6 inches or less. If necessary, the receiving end of the piler should be modified so that it can be raised up under the bulk truck's unloading belt sufficiently to minimize the drop of tubers into the hopper. All switches and control levers on a bin piler should be located conveniently for the operator, to ensure operation with minimal damage to the crop. The chain speed of the bin piler and the rate of unloading bulk trucks should be adjusted so that the bin piler conveyors remain filled to capacity at all times. To accommodate different unloading rates, a variable-speed control can be installed in the conveyor system.

When purchasing a new bin piler, look for features that will reduce bruising. Select a unit with a wide, shallow, well-padded hopper with sufficient capacity to prevent spill-out and with fingertip-adjustable height to minimize the drop from the truck. Rubberized draper chain or belted chain on the unloading conveyor is desirable, as it allows any remaining soil to sift out before the potatoes flow into the bin. The length of the boom conveyor should be about double the planned depth of the pile. To avoid rollback, the boom conveyor should never be operated at an angle greater than 45° from the floor. Hugger belts installed on the piler also minimize rollback. Additional features, such as a sorting table, a sizing chain area, a telescoping boom, variable conveyor speed, and multiple receivers, may make bin piling more efficient and may significantly reduce tuber damage during operation. Even-flow bins positioned in the receiving area between the unloading conveyor and the piler allow the conveyor to be kept fully loaded when the truck is not being unloaded.



A self-tarping mechanism eliminates walking on tubers in the truck bed during tarping.

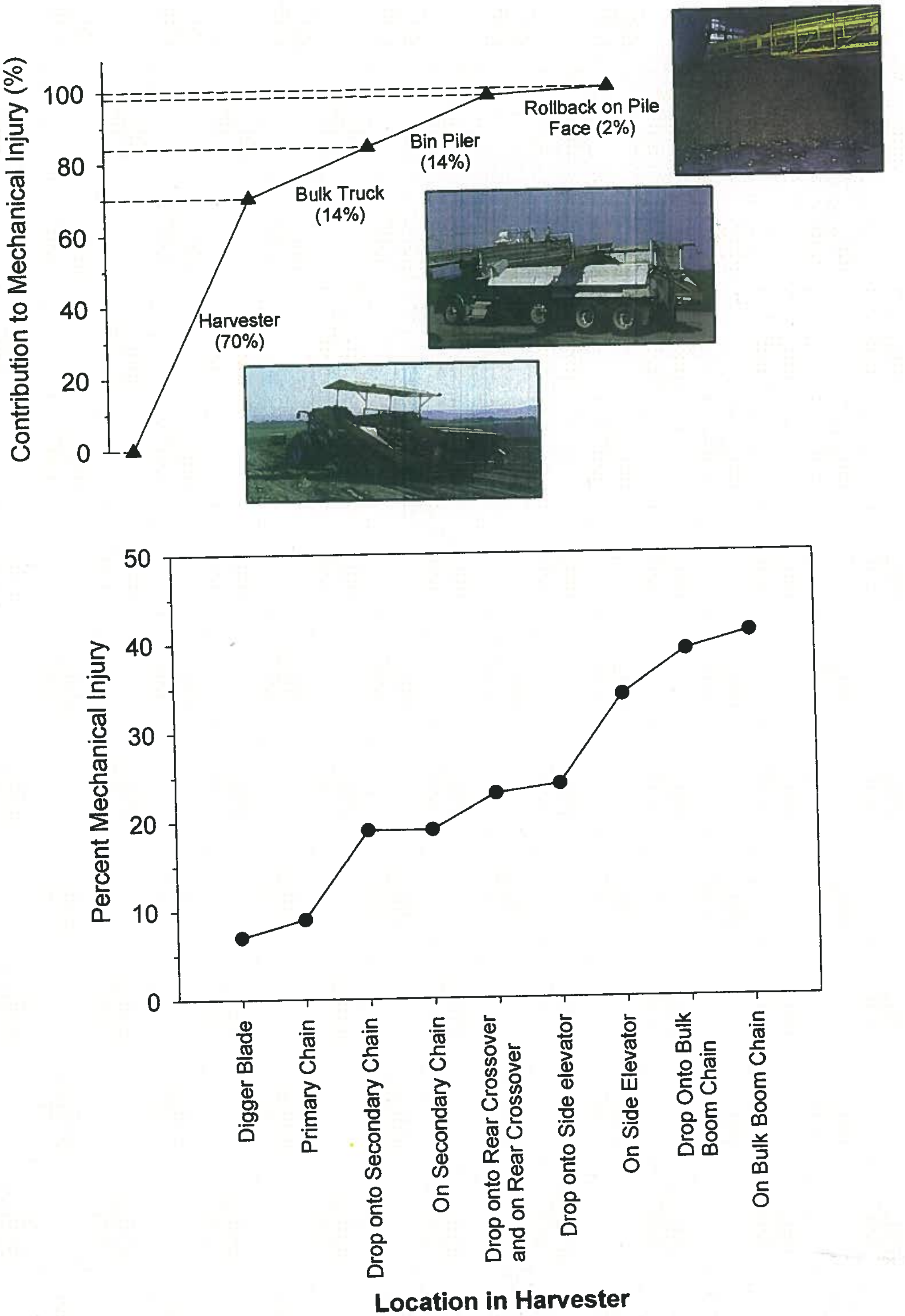


Fig. 10.4. Relative contributions of harvesting and handling equipment to mechanical injury of potato tubers. Mechanical injury is cumulative throughout the harvest and handling operations. Bruise damage to more than 3–4% of the crop is excessive. (Adapted from G. D. Kleinschmidt and M. K. Thornton, 1991, Bruise-free potatoes: Our goal, Bulletin 725, University of Idaho Cooperative Extension System)

for worn bearings. Gearboxes, transmissions, hydraulic lines, and reservoirs should be checked for leaks and repaired. Electrical systems should be inspected and repaired as needed. Rubberized chains that have become hard and brittle from being stored outside and exposed to bright sunlight should be replaced, because they will no longer protect tubers from bruising during harvest. Before use, all equipment should be thoroughly cleaned and sanitized to reduce the potential for contamination of freshly harvested tubers with disease organisms (Chapter 7).

Managing the Harvest Operation

Training Personnel in Low-Bruise Philosophy

Personnel involved in the potato harvest are just as important as the equipment in minimizing harvest damage. A properly trained crew working together with bruise control as a common objective is necessary to ensure the delivery of healthy tubers into the storage. The entire harvest staff must understand that even though the best management practices have successfully readied the crop for harvest, tubers remain very susceptible to skinning and bruising when handled. A team attitude should be developed, with each member of the crew constantly striving to protect quality at each step as potatoes move from the field to the storage bin.

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Operators of harvesters, windrowers, bulk trucks, and bin pilers are key staff in minimizing tuber damage during harvest. They should ensure that all drops are held to 6 inches or less. They should be made aware of the damage that can result from improper operation of their equipment, inattention, and neglect of maintenance. All staff should be trained to examine equipment during routine maintenance and lubrication shutdowns and to identify and correct any problems that may cause tuber damage.

Harvester and windrower operators should be instructed to maintain enough soil on the primary beds to cushion the tubers as they move across and ensure an even flow onto the secondary beds. Operators should be reminded that agitation of the primary bed chains should be held to the absolute minimum necessary to achieve adequate separation of tubers from soil. Bulk truck operators should be instructed to coordinate field operations closely with the harvester operator, to avoid dropping tubers into the truck from excessive heights or allowing the loading boom to plow into potatoes piled on the truck (Fig. 10.5). Once loading is complete, the load should be carefully covered with a tarp without walking on the tubers. Truck and bin piler operators must work together to match the flow of potatoes out of the truck with the capacity of the bin piler, keeping the piler conveyor filled to capacity at all times.

Monitoring Bruise Damage

Some bruise damage to potato tubers is obvious upon inspection, but fresh bruises often involve hairline cracks or internal shatter bruises that are difficult to detect visually. Tissue bruises that can develop into blackspot may also occur beneath unbroken skin and cannot be detected without peeling.

Several techniques can be used to monitor bruise damage at harvest and pinpoint operational and mechanical adjustments to minimize bruising. In large operations, managers frequently collect 20- to 30-pound test samples at regular intervals and determine the amount of damage as a percentage by weight. An autosampler on the front of the bin piler is ideal for random sampling of tubers entering the storage. The samples are then incubated, hand- or steam-peeled, and scored for bruising. Internal blackspot does not begin to develop in bruised tissues for 6–8 hours after the damage has occurred, and symptoms do not develop fully for a day or so. To detect blackspot bruising, tuber samples can be held at room temperature for at least 24 hours and then peeled. The holding period can be shortened to 8 hours if the tuber sample is held at 100°F. Blackspot is readily apparent as a bluish gray to black discoloration just under the skin (Chapter 23).

When tubers are being checked for blackspot, the first sample should come from the storage pile. If blackspot is found, samples should be collected at other harvesting and handling points to determine where the damage is occurring (Fig. 10.4). Large tubers are most susceptible to blackspot and should be selected for the first sample. If significant bruising is found, progressively smaller tubers should be tested.

Many processors include a bruise-damage clause in their contracts and penalize commercial producers for delivery of potatoes with excessive mechanical damage. Processors tra-

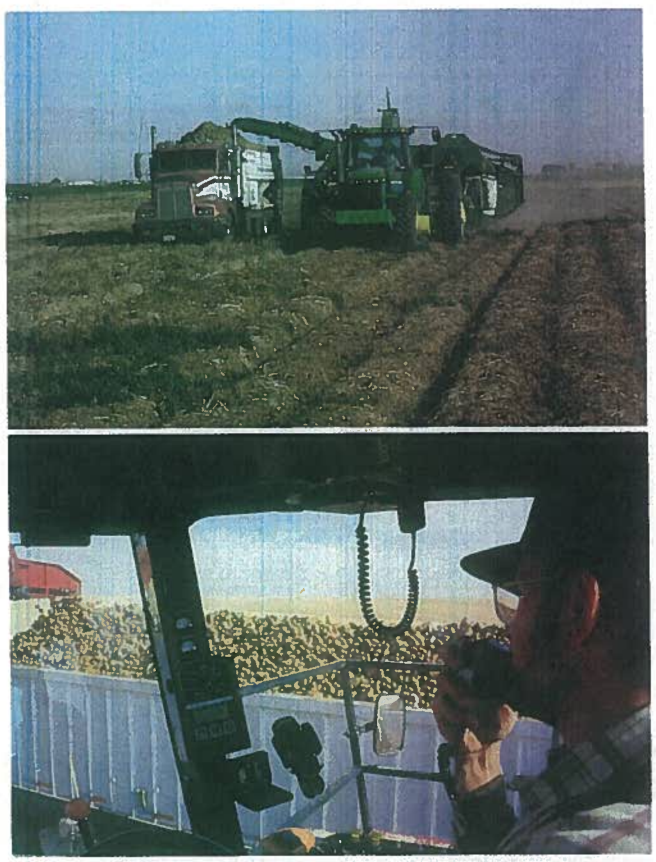

Fig. 10.5. Good coordination and communication between the harvester operator and the bulk truck operator are necessary to avoid dropping tubers into the truck from an excessive height or allowing the harvester's loading boom to plow into the pile of tubers on the truck. (Courtesy Washington State Potato Commission [top] and M. J. Pavek [bottom])

ditionally collect samples from delivered loads, hold them for 1 or 2 days, and then steam- or abrasion-peel them to detect blackspot bruises. A federal or state inspector is often present, with the approval of the producers, to make impartial judgments about the extent of bruise damage in the delivered potatoes.

Timing the Harvest

The timing of harvest can significantly affect tuber health throughout storage and marketing. In northern areas, the harvest should begin early enough to be completed before a hard frost is likely. For many cultivars, potatoes intended for long-term storage should not be harvested until the vines have been dead for 10–14 days, to allow for full skin set to occur. Immature tubers easily skin or "feather" during harvest and handling and are more difficult to handle and store. However, recent experience with **green vine harvest** of some cultivars shows that it can be done successfully with careful control of skinning, bruising, and initial weight loss during storage.

Soil moisture and temperature must be monitored closely once harvest has begun. Optimal harvest conditions are 60–65% available soil moisture and tuber pulp temperatures of 50–65°F. Tubers harvested from cold and wet soil are more susceptible to bruising, more difficult to cure, and more prone to breakdown in storage.

The amount of tuber hydration closely parallels soil moisture. Overhydrated tubers harvested from wet soil are highly sensitive to shatter bruise, especially when the pulp temperature is below 45°F (Fig. 10.6). Slightly dehydrated tubers taken from dry soil are less sensitive to shatter bruise but are highly sensitive to blackspot (Chapter 23). An intermediate level of tuber hydration is the best compromise to minimize overall bruise damage (Fig. 10.6). Soil moisture at harvest also has other effects. Dry, cloddy soil may result in more bruising, and overly wet soil is difficult to separate from tubers. Tubers from wet soil may also become oxygen-starved, and their lenticels may become enlarged; these conditions increase their susceptibility to internal blackheart (a physiological disorder caused by reduced oxygen) and decay. Ideally, the soil should contain enough moisture that it cushions the tubers until they reach the secondary conveyor on the harvester, at which point the soil should separate completely from the tubers.

Proper pulp temperature at harvest is critical. Harvest operations should not begin until tuber pulp temperatures are at least 45°F, and preferably 50–65°F. Tubers become much more sensitive to bruising at pulp temperatures below 45°F (Fig. 10.6). If the soil is frosty or the air temperature is near or below freezing, it is best to begin the harvest later in the day, when temperatures have risen, and then work into the evening. Soil temperatures are usually highest from 11 A.M. to 11 P.M. (Fig. 10.6).

Tuber pulp temperatures can also be too high, and harvest should be delayed if they are above 65°F. Tubers harvested with pulp temperatures of 70°F or higher are very susceptible to breakdown due to bacterial soft rot (Chapter 18) or Pythium leak (Chapter 19) in storage. Moreover, it is difficult to remove the field heat from these tubers once they are in storage. Thus, in warm weather, early morning may be the best time for harvest. Harvest scheduling is often unpredictable, with weather always a significant factor. Fall rains and early frosts often hamper operations. Harvest decisions should be based on soil and crop conditions, weather forecasts, long-term weather records, and grower experience. In spite of the best intentions, harvest conditions are not always optimal, and compromises sometimes must be made. However, if harvest operations can be conducted under favorable environmental conditions, a healthier crop can be delivered to storage.

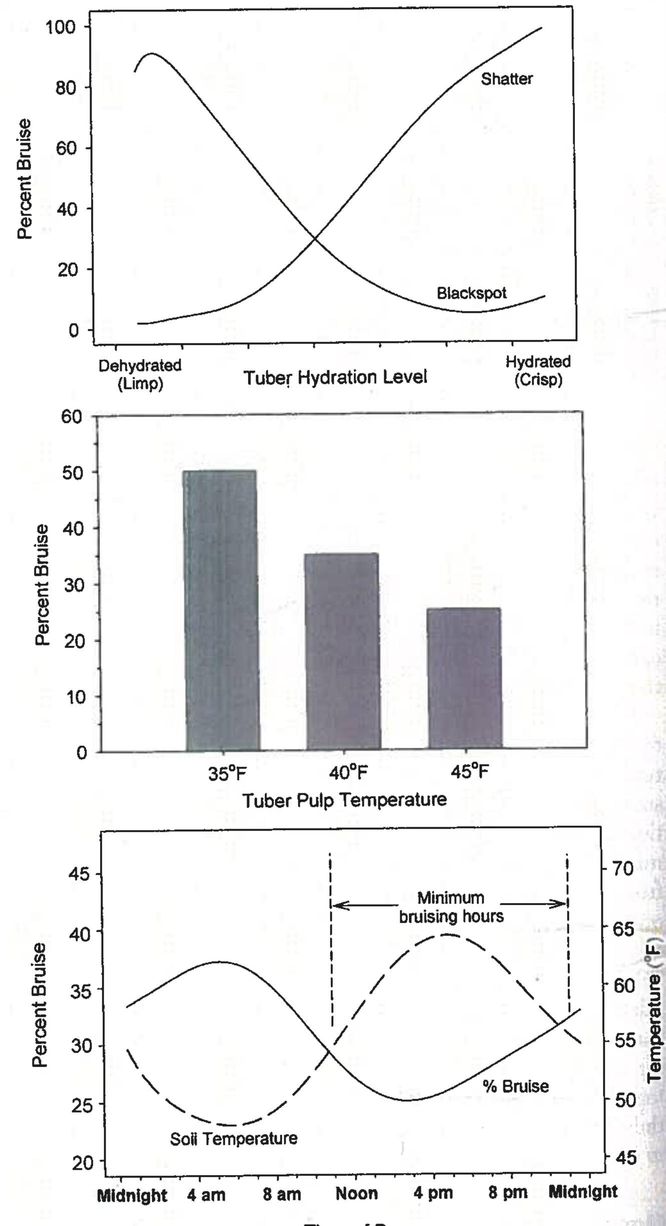

Fig. 10.6. Effects of tuber hydration, pulp temperature, and time of day on bruise injury to potatoes. Bruising is minimal when tuber pulp temperatures are 50–65°F. In northern production areas, tuber pulp temperatures will be highest when the soil has warmed, usually between 11:00 A.M. and 11:00 P.M. The timing of harvest should be planned accordingly, to minimize bruising. (Adapted from R. E. Thornton and H. Timm, 1990, Influence of fertilizer and irrigation management on tuber bruising, American Potato Journal 67:45–54 [top], and Kleinschmidt and Thornton, 1991 [middle and bottom])

Operating the Harvester

The most important principle in minimizing bruise damage during digging is that the volume of soil, tubers, and other material moving through the harvester should be held at capacity at all points in the machine. Operating the harvester with the conveyors filled below capacity allows tubers to bounce and roll excessively and thus increases bruise damage. Operating with the conveyors overfilled also increases bruising, due to excessive rollback.

The digger blade must be set deep enough to lift the maximum amount of tubers with minimal damage. If it is set too deep, the machine becomes overloaded with soil, and the result is poor separation of tubers. For each inch the blade is set too deep, the harvester handles about one additional ton of soil per minute for each row. If the blade runs too shallow, however, it cuts many tubers, and insufficient soil is carried up the primary conveyor. It is important to carry a layer of soil one-half to two-thirds of the way up the primary conveyor to cushion the tubers. Supplemental agitation of the primary conveyor should be closely monitored and reduced if tubers are bouncing. Conveyor agitation should be stopped if an appropriate cushion of soil cannot be maintained up the primary, as often occurs with dry, sandy soil.

To keep the machine filled to capacity with soil and tubers, forward speed and conveyor agitation must be adjusted as conditions change within the field. Some harvesters are equipped with a variable conveyor speed, allowing an additional adjustment. The harvester operator should visually judge changing conditions and adjust the forward speed by shifting gears, not by adjusting the engine speed or the blade depth, to maintain the desired amount of soil on the primary conveyor.

Windrowers are used routinely in some production areas. Two or more rows are dug with a windrower, and the tubers are placed on the ground between adjacent undug rows (Fig. 10.7). A harvester then follows and harvests these adjacent rows, picking up the windrowed tubers at the same time. This procedure not only increases the efficiency of the harvester but also helps lower overall bruising, by increasing the volume of tubers going through the machine, thus making it easier to keep the conveyors filled to capacity at all times.

Weather governs the management of windrowing operations. If tubers dug by the windrower are damp, they can be allowed to dry on the ground for 30–45 minutes before being harvested. Dry tubers, however, should be picked up immediately, to avoid dehydration. If pulp temperatures are near 50°F and the air temperature is below that, windrowed tubers should be picked up immediately to avoid further cooling. If pulp temperatures are closer to 65°F and the air temperature is above that, they should also be harvested immediately to avoid further warming. Thumbnail cracking (Chapter 23) can be accentuated while tubers are in windrows. Windrowed potatoes should not be left lying on warm, moist soil in bright sunlight; these conditions favor greening and sunscald in the field and the rapid development of Pythium leak in storage. Windrowed potatoes exposed to rain should be kept separate and marketed immediately, as they may not store well.

One of the most serious errors is to harvest potatoes from low, poorly drained areas of a field where water may have accumulated. Moisture levels are also usually excessive in the center of a pivot irrigation system, and planting within 80–100 feet of the pivot center should be avoided. Tubers harvested from this area are likely to be under increased disease pressure because of overwatering and should not be placed in storage, as they are much more susceptible to breakdown from blackheart, bacterial soft rot, Pythium leak, pink rot, and late blight. If harvested and mixed with healthy tubers in storage bins, tubers from overly wet areas of the field can be a major source of breakdown during storage. It may be best to leave tubers in overly wet areas, but if they are harvested, they should be kept separate and marketed immediately.

One of the most serious errors is to harvest potatoes from low, poorly drained areas of a field where water may have accumulated.

In areas where potatoes are grown in stony soils, some harvesters are equipped with air-vacuum devices to assist in separating tubers from stones as they pass by on the conveyor. The air-vac system takes advantage of the lower density of potatoes (a potato may weigh half as much as a stone of the

Fig. 10.7. A windrower digs two or more rows and places the tubers on the ground between adjacent undug rows. A harvester follows, harvesting these adjacent rows and picking up the windrowed tubers at the same time. (Courtesy N. Olsen)

same size) to lift them from among the stones and place them on the sorting or boom conveyor. With ideal soil moisture, harvesters equipped with air-vacs are 95–98% effective in separating potatoes from stones. Machines equipped with air-vacs have been shown to cause less bruise damage under these conditions than some conventionally equipped harvesters. Harvester operation must be monitored closely. The volume of stones plus tubers must be considered to determine the appropriate ratio of forward speed to conveyor speed needed to minimize tuber damage. After stones have been removed by an air-vac, the appropriate conveyor speed is related only to the volume of tubers. Because stony soils compound the potential for bruise damage during harvest, a management plan should be developed for removing stones from the field.

Placing the Crop in Storage

Bulk trucks should be covered with a tarp after loading, for several reasons. Chilling injury predisposes potatoes to breakdown in storage. Exposure to sun during transport may warm tubers excessively. Mild sunburn interferes with wound healing in storage and may promote the development of Pythium leak or Fusarium dry rot. It is especially important to protect harvested tubers from rain, which can greatly increase the potential for decay in storage.

To ensure tuber health in storage, unloading must be managed as carefully as harvesting. One person who is properly trained in low-bruise operation should be assigned to operate the bin piler. Personnel should not walk on the potatoes during unloading. The tubers should be fed out of the truck at an even rate, onto an unloading conveyor placed up under the truck unloading conveyor. A rubber chute is useful for buffering tuber drop onto the conveyor. The drop from the unloading conveyor to the receiving conveyor should not exceed 6 inches. Bin-loading conveyors must be operated fully loaded to prevent bouncing and rollback. To accomplish this, the conveyor speed must be matched to the rate of unloading the truck, and the speed of each successive conveyor must be matched to the delivery capacity of the preceding one. Hugger belts installed on bin-loading conveyors also help reduce bouncing and rollback (Box 10.3). When a truck has been unloaded, all conveyors should be shut off but left full. Even-flow bins positioned following an unloading conveyor allow the subsequent conveyors to be kept fully loaded when the truck is not being unloaded.

If significant disease or frost damage is evident or if excessive amounts of stones or debris are present, the tubers should be graded to remove damaged and diseased tubers, stones, and debris before being placed in storage. Potatoes should not be washed before they are placed in storage; washed potatoes do not store well. Crops containing over 1–2% blighted or soft-rotted tubers should be isolated from lots of healthy tubers and marketed quickly, as long-term storage of such crops is usually unsuccessful. If fungicides are applied as a fine mist, a low-volume application rate should be used, to avoid wetting the tubers before putting them into storage.

In bin piling, a progressive or **stepped piling procedure** minimizes rollback on the pile face (Fig. 10.8). An even flow of tubers should be maintained on the bin piler, which should be kept as full as possible to avoid rollback. High conveyor speed can cause potatoes to be flung against the storage structure and should be avoided. The boom should be kept close to the top of the pile, to minimize the drop. Short, frequent movements of the piler limit the height of the drop and evenly distribute any soil or debris carried onto the face of the pile. Pockets of soil within the pile prevent uniform airflow and may promote bacterial soft rot. In-floor air duct slots (Fig. 10.8) located under conveyors and bin pilers should be protected during the piling operation to prevent them from being filled with soil, which would interfere with air distribution after the pile is formed. Tubers should not be piled more than 16–18 feet deep, to avoid excessive pressure bruise, which is cultivar-dependent.

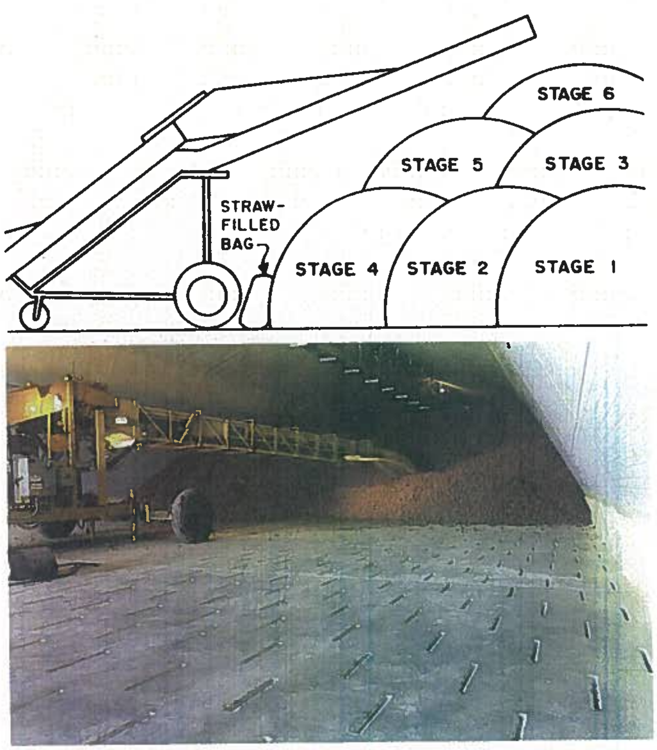

Fig. 10.8. A progressive or stepped bin-piling procedure minimizes the rollback of tubers on the pile face. (Drawing reprinted, by permission, from Kleinschmidt and Thornton, 1991. Photo courtesy R. Hesse, Suberizer, Inc.)

Maintaining Tuber Health Through the Storage Cycle

Even the best storage can only maintain the quality of the tubers put into it. Tuber health never improves in storage. Despite being dormant during much of the storage period, potato tubers utilize oxygen and produce heat, moisture, and carbon dioxide. A proper storage environment is essential for managing respiration, water loss, and sprouting by promoting wound healing and preventing disease development and progression, pressure bruise, loss of dry matter, and excessive accumulation of reducing sugars—all factors that reduce tuber quality.

Tubers undergo several distinct physiological stages during storage: (1) a curing period, or "sweat" period, during which harvest wounds heal, (2) a cooling period, when the pulp temperature is lowered to a level that is appropriate for the intended use of the tubers, and (3) a holding period, during which the tubers are dormant at first and respiration is low, and then dormancy ends and tubers are able to sprout. When sprouting occurs there is an increase in respiration and generation of heat and carbon dioxide. Modern storages (Fig. 10.9) are designed to provide the storage manager with the equipment required to control temperature, humidity, and air movement during each physiological stage (Table 10.1). Minimizing losses in tuber weight and quality during storage is critical to profitability. Precise temperature management during these stages is also essential for controlling the physiological aging of seed potatoes, which can have a tremendous impact on subsequent productivity (Chapter 7).

The Curing Period

Despite all precautions taken during harvest and handling, some injury to tubers will occur. The susceptibility of tubers to weight loss and infection by various pathogens is highest during the first weeks of storage, and up to half the shrinkage over an entire storage season can occur during this critical initial phase of storage. Environmental conditions must be managed to minimize weight loss and maximize the development of wound periderm during the curing period. Curing results in the production of a suberized wound periderm, which effectively protects underlying tissues from desiccation and invasion by pathogens during long-term storage. Proper wound healing at the beginning of storage is vital to

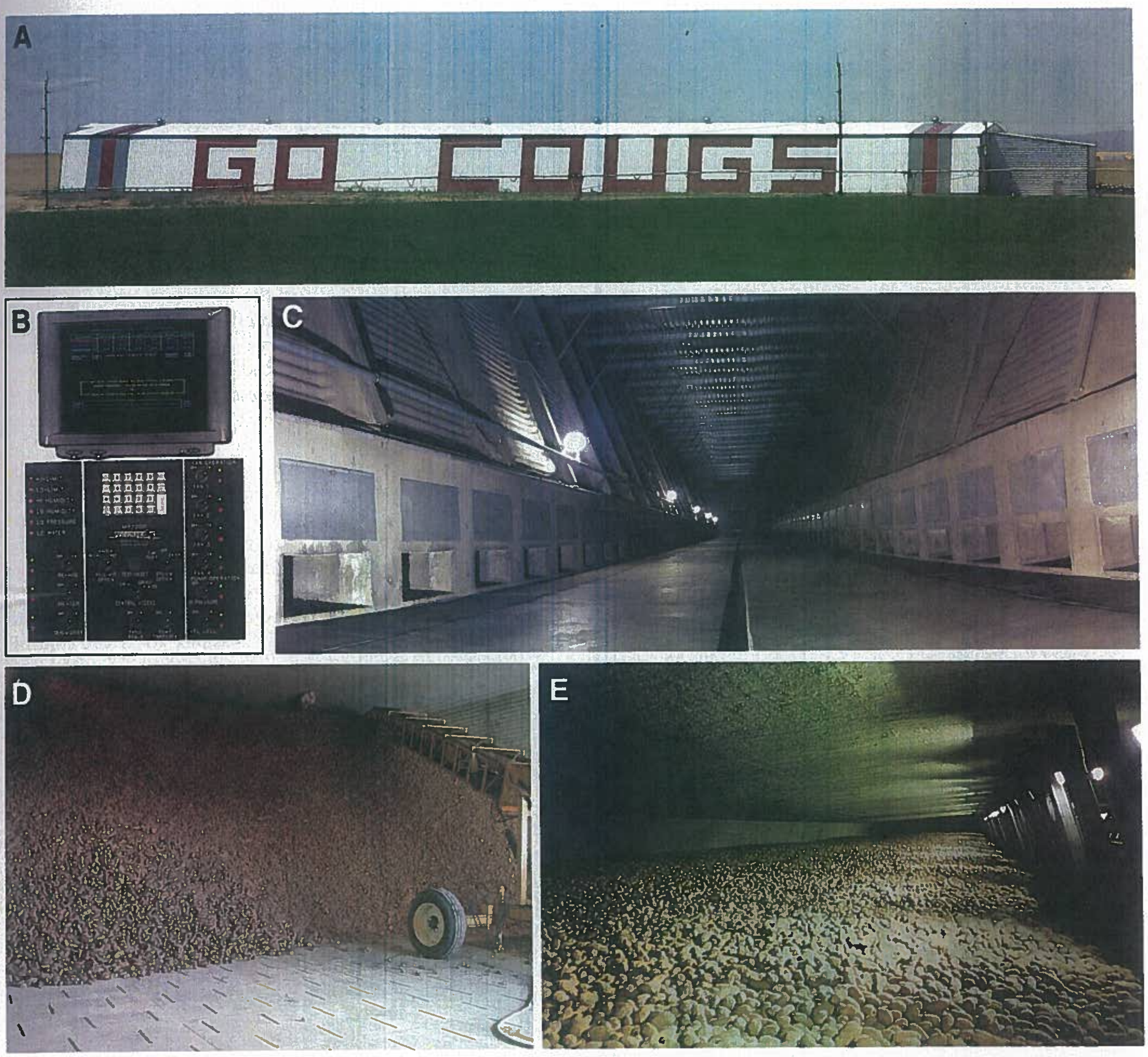

Fig. 10.9. Modern potato storage facilities (**A**) are equipped with control panels and environmental sensors (**B**) to control temperature, humidity, and airflow. Recent designs have a duct system (**C**) with air outlets built into the concrete floor (**D**). Dampers (**C**) can be selectively closed to direct air to specific areas of the pile. Minimizing condensation is paramount and depends on adequate insulation. Ceiling condensation can be reduced with small circulating fans between the top of the pile and the ceiling, but fans are not necessary in state-of-the-art storages where a vapor barrier is an integral component of the insulation (**E**), which is designed to prevent condensation. (**B–E** courtesy R. Hesse, Suberizer, Inc.)

maintaining tuber health and minimizing losses later in storage (Chapter 7).

Wound healing can be completed in a few weeks under ideal conditions, but many storage bins are filled over a period of several weeks. The period during which a bin is being filled should be as short as possible but should not exceed 7–10 days, to minimize the period of exposure of tubers to the high temperatures needed for curing. Freshly dug potatoes have a high rate of respiration, which contributes substantially to the initial heat load and potential weight loss in the first days of storage. Therefore, as a storage bin is being filled, the immediate concerns are to remove field heat and stabilize the temperature of the bulk pile as quickly as possible. Ideally, the temperature should be lowered to between 50 and 60°F within days of entering the storage by maximizing the movement of cooled and humidified air through the pile. The curing period begins when the first potatoes are placed in the bin and ends when wound healing is complete for the last potatoes placed there, usually a total of 3–5 weeks. Crop management during this time sets the stage for the entire storage season.

Wound healing and suberization are greatly affected by temperature; oxygen and carbon dioxide levels; and relative humidity. Wound healing is most rapid at about 70°F, but a compromise temperature of 50–60°F during the curing period is recommended, to minimize the potential for desiccation and limit tuber decay. Most pathogen activity declines at lower temperatures. If the crop is generally healthy, the **curing temperature** can safely be maintained at 55–60°F for 2–3 weeks. However, if any significant amount of tuber disease is present, a curing temperature nearer to 50°F is preferable. Tuber pulp temperatures should be monitored continually with a pulp thermometer or with thermocouples placed in tubers within the pile. Wireless temperature sensors can be placed at strategic locations within the pile during bin filling to monitor temperatures during curing and throughout the season. The temperature of the return air supply should also be monitored, since it indicates conditions at the top of the pile.

Air movement within the pile is essential during the curing period. Wounded potatoes have high rates of respiration, and wound healing is an aerobic (oxygen-requiring) process. Evenly distributed airflow is necessary for controlling temperature and providing oxygen while removing carbon dioxide and excess moisture. The ventilation systems in modern potato storages are equipped to provide up to 25 cubic feet per minute (cfm) per ton of potatoes (Fig. 10.9). The airflow and humidification should be sufficient for cooling without causing tuber desiccation. To prevent weight loss and promote rapid formation of suberized wound periderm, the **relative humidity** of the supply air must be kept above 95%. It is, however, very important that condensation not develop on the tubers. Free water on tuber surfaces inhibits the exchange of oxygen and carbon dioxide and promotes bacterial soft rot.

Since relative humidity and air temperature are interrelated, differences between the supply air temperature and tuber pulp temperature must be monitored closely. If saturated air much colder than the tubers is forced through the pile, it will be warmed by the tubers, and the relative humidity will drop considerably, resulting in tuber dehydration and increased pressure bruising. Conversely, if saturated air warmer than the tubers is introduced, condensation will occur on cold tuber surfaces, favoring the development of bacterial soft rot. The best practice is to monitor the pulp temperature of stored tubers carefully and **keep the supply air just a few degrees lower than the tuber temperature** until the pile reaches the desired curing temperature. After that, the supply air should be adjusted to maintain a temperature differential of 0.5–2°F from the bottom to the top of the pile. This is accomplished most efficiently and economically by adjusting fan speed to reduce ventilation when the temperature differential is small and increase ventilation when the temperature differential increases toward the high end of the optimum range. Fans equipped with variable-frequency drive are especially efficient for this purpose.

Tubers with pulp temperatures below 50°F should not be placed in storage, if possible. Cold tubers must be warmed to wound-healing temperatures (55–60°F), and condensation on cold tuber surfaces during the warming process is the major concern. Condensation (free water) will enhance tuber decay, especially during this critical period before wound healing has occurred. Cold tubers should be warmed with dry air (no humidity added). If possible, allow the cold tubers to warm naturally, using limited airflow if no field frost

Table 10.1. Environmental management for maintaining potato health in storage

	Curing period	Cooling period	Holding period	Marketing period
Temperature	Maintain tuber pulp temperature at • 55–60°F if tubers are healthy • 50°F if tuber decay is present	Rapidly cool seed and fresh-market tubers to the appropriate holding temperature Slowly cool processing tubers, lowering pulp temperature by 2–3°F per week	Maintain tuber pulp temperature at • 38–40°F for seed • 38–50°F for fresh market • 44–50°F for french fry processing • 50–55°F for chip processing	Warm slowly to 50–55°F over several weeks
Relative humidity	Maintain at 95–99%	Maintain at 95–99%	Maintain at 90–95%	Maintain at 90–95%
Ventilation	Supply at high rates to remove field heat, stabilize pile temperature, reduce CO_2 buildup, and provide O_2 for wound healing	Supply at high rates to control cooling and maintain a temperature differential of 0.5–2°F from the bottom to the top of the pile during cooling	Supply at reduced rates, adjusted as necessary, to supply O_2, remove CO_2, and maintain a temperature differential of 0.5–2°F from the bottom to the top of the pile	Supply at reduced rates to allow heat of respiration to raise pulp temperature to 50–55°F and thus minimize bruising during removal from storage

is present. Once healing temperatures have been reached, the pile should be managed as described above.

It is critical to be aware of the amount of disease in each lot of tubers coming into storage to properly manage the curing period for each lot. **Storing tubers with a high level of disease** is difficult. If more than 1–2% of the tubers have symptoms of bacterial soft rot, late blight, pink rot, or leak, or if a similar proportion is frost-damaged, they should be cooled to below 50°F immediately after being placed in storage (Box 10.4). The problems of weight loss, subsequent pressure bruise, and reducing sugar buildup must be considered secondary to potential losses from decay. In this situation, the use of humidifiers should be avoided, and fans should be operated continuously to dry the diseased tubers and prevent the buildup of free moisture in the pile. In warm weather, no attempt should be made to store a heavily diseased crop unless pulp temperatures throughout the pile can be brought down and maintained below 50°F. If tubers at the top of the pile cannot be cooled properly, decay will start there, and the entire pile may "melt down" and be lost. It is preferable either to grade tubers in this condition carefully and market them straight from the field or to delay harvest until the weather

Box 10.4

Storing Problem Potatoes

J. P. McMorran, A. R. Mosley, and M. I. Vales
Department of Crop and Soil Science
Oregon State University, Corvallis

Blighted, frozen, wet, or otherwise compromised potatoes call for extraordinary storage measures. Common storage rules must sometimes be bypassed to save the crop. The following guidelines for harvesting and postharvest handling should be considered in managing problem potatoes.

- Market straight from the field, if feasible; if not, sell at the earliest reasonable opportunity.
- Avoid problems by harvesting dry, sound potatoes with a pulp temperature between 45 and 65°F.
- Where potatoes are frozen or blighted, wait a few days, if possible, to allow symptoms to fully develop before harvest.
- Leave rotten, frozen potatoes and debris in the field if possible. This may call for additional people on the harvester.
- Sort tubers as they are placed in storage. Provide sufficient light, people, and time to do the job properly.
- Prepare the storage and ensure that it is at the proper temperature, with the air delivery and control systems in good order. Provide an adequate flow rate (25 cfm per ton) in all areas of the storage. Add portable systems to otherwise airless storages. Good air movement is absolutely essential for storing problem potatoes.
- Cure the tubers at the lowest possible temperature (50°F), or eliminate the curing period altogether, depending on the condition of the crop. Problem potatoes are usually wet and infected with decay organisms and therefore should be cooled and dried as quickly as possible.
- Quickly cool the pile to the final storage temperature (about 38°F for seed, 42°F for table stock, 45°F for french fry processing, and 50°F for potato chips). It may be necessary to cool and hold processing potatoes well below the levels typically recommended for frozen processing (45°F) and chips (50°F).
- Do not humidify. The potatoes are probably much too wet already.
- Run fans continuously until the crop is dry and decay is under control. Running fans does not necessarily call for ventilation. Recirculate air through the potatoes at all times during the problem period, even when outside air is not being introduced.
- Keep the pile as shallow as possible, to promote air movement and easy removal of potatoes in hot spots. Rotting tubers and dirt sometimes form barriers to air movement.
- Monitor the storage daily. Thermometers suspended at various depths in the pile provide a good indication of the average temperature. Infrared guns are helpful in locating hot spots before they begin to sink and spread.
- Do not expose cold potatoes to warm outside air. A layer of free water will condense on the tubers. Try to use air no warmer than about 5°F above the desired tuber temperature. Water on tubers tends to suffocate them, and it favors soft rot bacteria.
- Do not expose tubers to air at or below the freezing point.
- When unloading the storage, do not wash dry seed potatoes unless they are covered with dried slime. Washing will probably help wet slimy seed. If seed is washed, use sprays rather than a dip tank. Try to use multiple nozzles, so that all surfaces are washed clean. Misting washed potatoes with a 10% sodium hypochlorite solution is recommended (check the labeling for your area). Add 1 gallon of bleach to 9 gallons of water and mix well before applying in a well-ventilated area. Problem seed that requires washing should be planted as soon as possible, if soil conditions are suitable.

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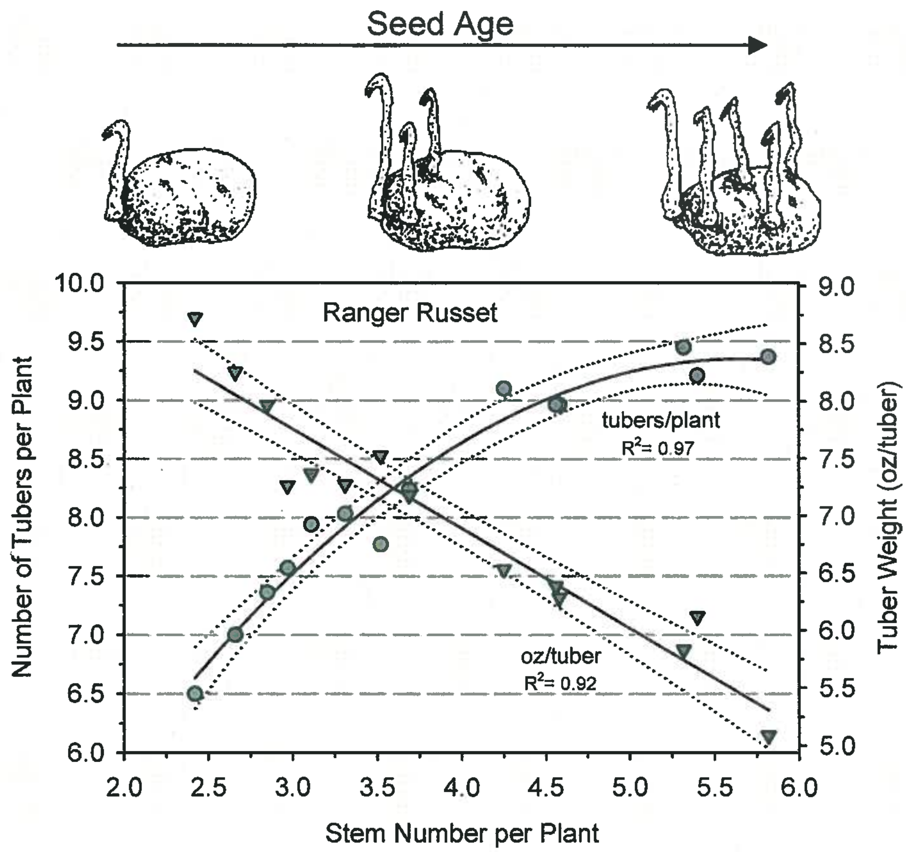

Fig. 10.10. Stem number and tuber set of plants grown from Ranger Russet seed tubers and weight of tubers produced over a 150-day growing season in the Columbia Basin of Washington. The stem number is indicative of the physiological age of the seed tuber, which increases with the accumulation of heat units during handling and storage. The physiological age in turn affects the tuber size distribution (Table 10.2). (Drawing by G. N. M. Kumar. Adapted from N. R. Knowles and L. O. Knowles, 2006, Manipulating stem number, tuber set, and yield relationships for northern- and southern-grown potato seed lots, Crop Science 46:284–296)

permits rapid cooling in storage. Delayed harvest will also allow time for infected tubers to decay totally in the field, so that they won't be harvested.

If more than 2% of the tubers have symptoms of bacterial soft rot, late blight, pink rot, or leak, or if a similar proportion is frost-damaged, they should be cooled to below 50°F immediately after being placed in storage.

The Cooling Period

Storage temperatures should be lowered to holding levels after the curing period (Table 10.1). Potatoes to be sold as **seed tubers** should be cooled to 38–40°F if a minimum number of stems per hill is desired in the subsequent crop. Higher temperatures can stimulate physiological aging of seed, which may affect stem number, tuber set, tuber size, and yield in the succeeding crop. Seed tuber age can have a tremendous impact on productivity. While the biochemical basis of seed age is not fully understood, research has shown that the accumulation of heat units above 39°F results in early dormancy break and reduced apical dominance. This leads to the production of multiple sprouts and thus multiple stems in the progeny crop (Box 7.2). The resulting effects on productivity are cultivar-dependent and can be either positive or negative, depending on length of the growing season and market requirements for tuber size of seed, fresh, and processing tubers.

After vine kill, the accumulation of heat units by a particular seed lot is additive and need not be continuous. High pulp temperatures after vine kill, as tubers set their skin and mature, and during harvest, transport, wound healing, storage, warm-up prior to transport, and post-storage transport and handling at the cutting facility all contribute to physiological age and variation in the productive potential of seed lots.

Aged seed tubers produce more stems per seed piece, which in turn affects tuber set and size development in a predictable manner (Fig. 10.10). The number of tubers set per hill increases with increasing stems per seed piece. This increases competition among tubers within a hill for carbohydrate and other resources during growth, resulting in smaller tubers. In areas with long growing seasons, such as the Columbia Basin of Washington, yield of marketable U.S. No. 1 tubers and total yield remain relatively constant over a wide range of stem numbers, and thus only the tuber size distribution will be affected (Table 10.2). In other growing regions, both tuber yield and size distribution are affected by seed tuber age. Therefore, the optimum seed tuber age for a specific yield and tuber size distribution will differ according to the growing conditions unique to various geographic areas of production.

Seed growers should keep records of the degree-days accumulated by their crops, starting at vine kill and continuing through storage to final sale. This will help to answer questions that may arise later concerning performance of the commercial crop. Daily heat units are calculated by subtracting a base temperature of 39°F from the average daily tuber temperature; the sum of the daily heat units for each day in a specified period (e.g., from vine kill through storage), expressed in degree-days, represents the total accumulation of heat units by the crop. Maintaining a constant number of degree-days in seed lots from year to year will decrease year-to-year variability in seed performance and better enable commercial growers to optimize management (e.g., in-row spacing) to get the best yield and tuber size distribution possible, within the constraints of their growing region.

Tubers for **fresh consumption** can be stored at 38–50°F. Lower temperatures delay dormancy break, inhibit sprouting, and lengthen the overall storage period. However, a gradual conversion of starch to reducing sugars at low temperatures (38–42°F) will cause tissues to turn off-color and lead to an undesirable waxy texture in many fresh-market cultivars. Optimal cooking and culinary quality for fresh-market potatoes is maintained at 44–48°F. In contrast to processing potatoes, seed and fresh-market potatoes may be cooled relatively rapidly by careful introduction of outside air or by refrigeration. Care must be taken to maintain high relative humidity in the cooling air, to prevent desiccation. Precautions regarding temperature differences and condensation during the curing period apply here as well. The supply air temperature should never be more than 2°F lower than the tuber pulp temperature during cooling.

Table 10.2. Yield of potato cultivars Russet Burbank and Ranger Russet in relation to number stems per seed piece in the Columbia Basin of Washington State[a,b]

	Average stem number of:			
	Russet Burbank seed pieces		Ranger Russet seed pieces	
	3.2	5.4	3.2	5.4
Total yield (tons/acre)	30.9	28.7	31.5	31.0
Marketable yield (tons/acre)[c]	28.8	27.2	31.5	31.9
U.S. No. 1 (tons/acre)	25.8	22.1	28.4	26.6
Tuber grade[d]				
<4 ounces (%)	10.8	18.5	10.5	16.3
4–6 ounces (%)	17.4	23.4	14.4	22.4
6–10 ounces (%)	32.8	32.9	29.5	31.7
10–12 ounces (%)	12.1	9.1	11.1	9.9
12–14 ounces (%)	8.4	5.8	9.4	7.2
>14 ounces (%)	18.3	10.4	25.8	11.1
Tubers per plant	7.7	9.0	7.6	9.2
Average tuber weight (ounces)	7.0	5.7	7.7	6.1
Tubers per acre	130,200	156,500	139,000	168,500

[a] Adapted from Knowles and Knowles, 2006.
[b] Russet Burbank and Ranger Russet seed tubers were stored at temperatures above 39°F for various periods directly following harvest, to produce different numbers of stems per seed piece. Tuber set and tuber size distribution are affected by the number of stems per seed piece, which increases with the physiological age of the seed tuber. In areas with a long growing season, such as the Columbia Basin, tuber size distribution is affected more than yield.
[c] Total yield minus culls.
[d] Percentage of total marketable yield.

Tubers for processing must be cooled more slowly than seed and fresh-market potatoes, preferably by no more than 2–3°F per week. Rapid cooling to holding temperatures can induce a subsequent buildup of reducing sugars, which results in unacceptable darkening of chips and french fries during processing. To produce acceptable chip fry color, reducing sugars must not be allowed to accumulate during the curing and storage periods (Fig. 10.11).

The final holding temperature for processing potatoes is determined by the cultivar and the intended use. The region of production can have a significant effect on storability, because of different environmental and agronomic conditions in different production areas. Therefore, for a particular cultivar, the ideal storage temperature for preservation of processing quality may vary somewhat among geographic areas. Growers are encouraged to consult local crop advisors to determine cultivar-specific holding temperatures for locally grown crops. General guidelines for storage temperatures follow.

Tubers stored for processing into french fries generally should be cooled to no lower than 44°F, although individual processors may have specific requirements (usually between 44 and 48°F), depending on the cultivar and the estimated storage duration. The tolerance for sugar-induced color formation is lower in tubers processed into chips than in tubers processed into french fries. Hence, potatoes for chip processing must be stored at a slightly higher temperature, to avoid the accumulation of reducing sugars. Generally, healthy chip potatoes harvested at soil temperatures of 55–70°F may be stored at 48–50°F with minimal concern about reducing sugars. Chipping potatoes harvested during cooler weather may require long-term holding at 50–55°F to ensure acceptable fry color. Chipping cultivars have been developed that recondition well after storage at lower temperatures. The prevailing temperature and rainfall during production and soil temperature at harvest may affect the chipping performance of potatoes removed from storage.

Carbon dioxide (CO_2) buildup in storage can adversely affect tuber quality. The source of CO_2 is tuber respiration, which increases with temperature and varies with the physiological state of the tubers. Immature tubers, wounded tubers, and tubers that have been stressed (e.g., by disease, cold, or heat) respire at a higher rate than mature, suberized, unstressed tubers. Carbon dioxide production by tubers is highest during the curing period and lowest during the holding period when tubers are dormant; it increases as tubers emerge from dormancy and begin to sprout. More frequent ventilation with outside air during periods of high respiration rate is needed to prevent CO_2 buildup in storage. Clogged air ducts and excess soil can restrict ventilation through the bulk pile, so that CO_2 can accumulate in localized pockets, leading to a loss of tuber quality.

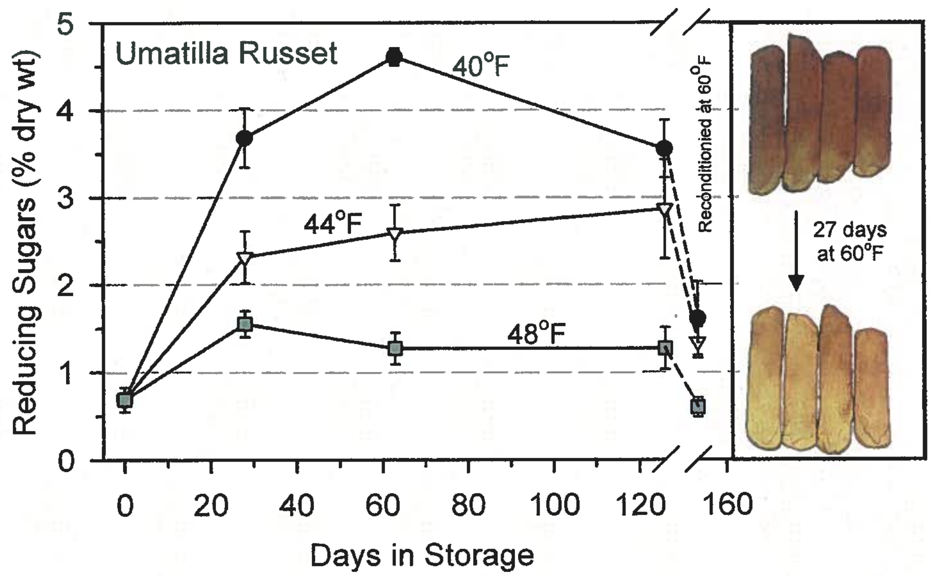

Fig. 10.11. Effect of storage temperature on the concentration of reducing sugars (glucose and fructose) in Umatilla Russet tubers. Low-temperature sweetening results in unacceptable darkening of fries and chips during processing. The reducing sugar content falls when the storage temperature is raised to 60°F to recondition the tubers (from day 126 to day 153, dashed line), restoring processing quality. (Adapted from N. R. Knowles and L. O. Knowles, 2002, Storage management and processing quality of Umatilla Russet potatoes, pages 103–110 in: Proceedings of 41st Annual Washington State Potato Conference, Washington State Potato Commission, Moses Lake)

Tuber respiration results in CO_2 levels of 0.1 to 4–6% in commercial storages. Carbon dioxide levels as high as 4% have been shown to promote soft rot and stimulate the growth of *Fusarium* and other fungal pathogens. Tuber glucose and fructose content may also increase if CO_2 is maintained at 3–4%; however, CO_2-induced sweetening is cultivar-dependent and reversible. Sugar levels usually fall when CO_2 levels return to normal. In addition to causing sweetening and favoring decay, high CO_2 can inhibit suberization, promote physiological disorders (such as blackheart), and stimulate sprouting.

To prevent CO_2-induced loss of quality, ventilation should be managed to maintain CO_2 concentration below about 0.5% (5,000 ppm). This can be particularly challenging in circumstances where respiratory heat produced by the tubers is used to maintain storage temperature (e.g., in regions with cold winters) or where refrigeration is required to maintain temperature. Both situations necessitate reduced ventilation with outside air, which leads to CO_2 buildup. State-of-the-art storages incorporate CO_2 monitors to help determine the frequency of ventilation with outside air, thus enhancing the ability to provide an optimum storage atmosphere for maintaining tuber quality.

The Holding Period: Dormancy

After the appropriate long-term storage temperature has been reached, the frequency of **ventilation** can be reduced, if desired. During the holding period, it is necessary to provide enough air movement through the pile to supply oxygen for tuber respiration, remove carbon dioxide and excess heat, and maintain a constant temperature. The temperature should be maintained within 2°F of the desired holding temperature, and the variation from the top to the bottom of the pile should be no more than 2°F, and preferably less. The ventilation systems in modern storages are capable of maintaining a variation of 0.5°F throughout the holding period. The relative humidity should be kept at 90–95% throughout the holding period, to minimize weight loss and pressure bruising.

Condensation is a problem in some storages. Excess moisture dripping from the ceiling onto the top of the pile creates wet areas, favoring tuber rots. Adequate insulation is the key to minimizing condensation (Fig. 10.9). Condensation will develop in an insufficiently insulated storage even when the outside air is only moderately cool. If necessary, ceiling condensation can be reduced by a constant flow of air between the top of the pile and ceiling, maintained by small circulating fans. Outside air warmer than the potatoes in the pile should never be introduced into the storage, as this can result in condensation directly on the surfaces of tubers.

During the holding period, most cultivars are in a dormant state, characterized by very low respiration and the production of only minimal heat and water vapor. The length of dormancy is a cultivar characteristic. Early-maturing cultivars (such as Russet Norkotah, Norland, and Superior) often have a short dormancy, whereas late-maturing cultivars (such as Russet Burbank) have a longer dormancy. The length of dormancy also depends on tuber maturity at harvest and storage temperature. Ranger Russet, Umatilla Russet, and Russet Burbank will remain dormant for approximately 60, 120, and 135 days, respectively, at 45°F, but only 50, 80, and 120 days, respectively, at 48°F. Knowledge of cultivar-dependent differences in dormancy length will facilitate effective timing of application of sprout inhibitors.

Inhibition of sprouting is required to maintain quality in tubers stored beyond their natural dormant period. The most effective chemical registered for postharvest sprout control is chlorpropham (CIPC). It is applied by licensed applicators as a thermal aerosol fog, which is evenly distributed throughout a bulk pile by the storage ventilation system, usually operating at reduced airflow. After application, the air is recirculated within the storage to facilitate even distribution and deposition of the product on the tubers. Recirculation continues until the fog has settled on the tubers, which normally occurs within 2–12 hours. The storage should then be ventilated with outside air. Longer durations of exposure with no outside ventilation (e.g., more than 24 hours) will lead to a buildup of carbon dioxide, which can induce sweetening and loss of quality of processing potatoes.

Proper timing of treatment is critical to tuber health and effective sprout control. Chlorpropham inhibits cell division. Therefore, it should not be applied during the curing period, as it will inhibit wound healing. For maximum efficacy, CIPC should be applied after curing and well before tubers emerge from dormancy and the sprouts begin to "peek." In the Pacific Northwest, the first treatment normally occurs in November or December. A well-balanced, evenly distributed airflow is necessary during application. Any tuber buds not adequately covered by the CIPC aerosol may enlarge and produce oppressed, rosette-type sprout clusters, which may grow inward to produce ingrown or internal sprouts, especially if tubers have been subjected to desiccation resulting in increased pressure bruising. Since thorough distribution of the material is essential, an inspection of the ventilation and duct system (Box 10.2) by the custom applicator before potatoes are placed in the storage is advisable. Measures taken to ensure uniform airflow through the pile before the storage is filled will prevent serious problems later. This sprout inhibitor should never be applied to seed potatoes, and bins treated with CIPC should never be used the following spring to store incoming seed potatoes (Chapter 7).

Other registered sprout inhibitors include the substituted naphthalenes 1,4-dimethylnaphthalene and diisopropylnaphthalene. The mode of action of these chemicals is not entirely understood, but it is likely that they delay sprouting through hormonal action. These compounds are more aptly referred to as sprout suppressants rather than inhibitors, as their effects are temporary. Multiple applications are required to suppress sprouting through a normal storage season. Diisopropylnaphthalene acts synergistically with chlorpropham, allowing chlorpropham to be used at lower rates while maintaining the degree of sprout inhibition achieved by applying it once at a higher rate.

The Holding Period: Dormancy Broken

Stored tubers begin to break dormancy during the holding period. The time when this begins is determined by the dormancy characteristics of the cultivar, tuber maturity at harvest, the storage temperature, and whether sprout inhibitors have been applied. As tubers break dormancy, the respiration rate increases, and internal changes lead to rapid cell division in growing points, resulting in sprouting. The rise in metabolic activity results in increased oxygen demand, generation of heat, and emission of carbon dioxide and water vapor.

Proper storage management becomes critical after dormancy is broken, because tuber health may easily be jeopardized. Maintaining a uniform low temperature throughout the storage facility can significantly extend dormancy in most cultivars. Refrigerated storages are most valuable at this time. For potatoes not treated with a sprout inhibitor, especially seed potatoes, careful management is critical to **avoid sprouting** when bins are frequently opened to market tubers. Premature sprouting enhances desiccation and weight loss and accelerates the aging of seed tubers, potentially resulting in significant loss of vigor in the crop grown from them.

Alternative sprout inhibitors that physically "burn" developing sprouts can be used to limit further sprout growth once dormancy is broken. These suppressants include essential oils such as peppermint, spearmint, and clove. Sprouts are most susceptible to these compounds at the peeping to ⅛-inch-long sprouting stage. Forced evaporation or wick applications are more effective than thermal or cold aerosol fogs of the mint oils. The efficacy of these volatile compounds is somewhat dependent on maintaining a sufficiently high concentration of them in the atmosphere surrounding the tubers, which generally requires frequent reapplication (every 2–3 weeks). Clove oil (eugenol), marketed under the trade name Biox-C, is best applied as a thermal aerosol fog. As plant derivatives, these compounds are approved by the National Organic Program of the U.S. Department of Agriculture for the control of sprouting of organically grown potato crops.

Throughout the holding period, the stored tubers should be monitored closely for changes in temperature or humidity causing condensation of moisture on rafters, floor wetness, wet spots or sunken areas in the pile (Fig. 10.12), objectionable odors, and the presence of fruit flies. All of these are signs of **tuber decay** within the pile. Most modern storages feature adjustable airflow dampers at duct entrances to allow extra ventilation air to be delivered to trouble spots in the storage bin (Box 10.2 and Fig. 10.9). Generally, once a pocket of breakdown occurs in a bin, the prospects for continuing long-term storage are greatly reduced. If decay is detected, the storage humidity should be lowered and the potatoes graded and marketed promptly.

Depending on the cultivar, the duration of storage, and the storage temperature, quality may be compromised by a buildup in **reducing sugars**, which cause an unacceptable darkening of potato chips and french fries during processing. The accumulation of reducing sugars due to advanced tuber age, referred to as senescent sweetening, is irreversible. Cultivars differ in the time of onset of senescent sweetening. For example, under optimal storage conditions (48°F and 95% relative humidity) for processing, Umatilla Russet can begin to sweeten irreversibly 200 days after harvest, while Russet Burbank generally will not undergo senescent sweetening for 300 days or more. The expected duration of storage should thus be matched to the cultivar to avoid loss of processing quality.

Prior to senescent sweetening, tubers that have accumulated reducing sugars as a result of exposure to low temperatures during the storage cycle can be reconditioned to lower the sugar concentration before processing (Fig. 10.11). **Reconditioning** involves raising tuber pulp temperatures at the end of the storage season, in order to lower the reducing sugar content. Storage temperatures of 57–65°F for 3–4 weeks at the end of the storage period stimulate the loss of reducing sugars by increasing respiration and partial conversion of sugars back to starch. The decrease in the reducing sugar content improves the processing quality of the tubers (Fig. 10.11).

The temperature and condition of the pile must be monitored closely during reconditioning. Raising the pile temperature at the end of a prolonged storage season will stimulate sprouting, respiration, and thus weight loss, and it

Fig. 10.12. During the holding period, stored tubers should be monitored closely for wet spots, sunken areas, and objectionable odors, which indicate the presence of disease or decay within the pile.

favors the development of disease and decay. Reconditioning is risky and should be used only as a last-ditch effort to improve processing quality after careful consideration of the risks and potential benefits. Moreover, the extent to which processing quality can be improved through reconditioning is cultivar-dependent. Storage managers are encouraged to seek advice from local extension specialists or consultants in determining the potential for improvement through reconditioning.

The preferred method for maintaining processing quality is to identify the market for which tubers are being stored at the beginning of the storage season and impose temperature and relative humidity regimes that are optimal for the cultivar and the end use. If tuber health can be maintained during storage, then reconditioning, with all its inherent risks, will not be necessary.

Maintaining Tuber Health During Post-Storage Handling

To minimize mechanical damage to tubers while they are being removed from storage for marketing, it is essential to raise the **pulp temperature** gradually to 50–55°F over a period of several weeks. This can be accomplished by restricting ventilation and allowing the heat of respiration to increase the temperature of the pile. Handling cold tubers usually results in a high incidence of shatter bruise or internal blackspot. Rough handling will stress tubers and may cause the accumulation of a significant quantity of reducing sugars in chipping potatoes, resulting in unacceptable fry color. Fresh-market potatoes may develop internal blackspot, after-cooking darkening, or other surface defects that lead to excessive waste during peeling. French fry processors often reject roughly handled loads or impose heavy penalties for accepting them.

Once desired tuber pulp temperatures have been reached and removal from storage begins, **bruise control** is a major concern. The same principles of low-bruise handling applied when loading the storage must be applied when unloading. Careful operation of bulk unloading equipment is essential. Dumping heights in hoppers and trucks should be 6 inches or less. If a bin loader is used to move potatoes into a truck, load through the back to minimize the drop as loading is begun, and then continually adjust the loader as loading progresses. As in filling the storage, bruising is minimized by maintaining the outflow of potatoes at capacity on all conveyors and by padding sharp or rough surfaces on all equipment.

Prior to use, all equipment should be cleaned and sanitized to prevent the spread of bacterial pathogens. If a **fluming system** is used to transport tubers in water, it must be cleaned and sanitized frequently, and the flume water must be changed often. During fluming, tubers should not be submerged more than an inch or two, because the water pressure may force bacteria into lenticels. Clean water should be used for washing fresh-market potatoes on the packing line, and the wash water should not be recirculated. It is very important that washed tubers be well dried before packaging, as a film of moisture on the surface of tubers favors the development of bacterial soft rot in the bag, further down in the marketing chain. Ventilated bags with holes or perforations help to ensure complete drying.

Removing **seed tubers** from storage requires intense precaution to maintain seed quality. If off-farm trucks are used to transport bulk or bagged seed, they must be thoroughly cleaned and properly sanitized before loading.

After packaging, bagged seed or fresh-market potatoes are damaged mainly at the time of loading and unloading. **Bagged potatoes** are likely to suffer severe shatter bruising when dropped onto a hard surface from a height greater than 30 inches. When potatoes are being shipped, the outside temperature should be watched carefully. If it is below freezing, precautions must be taken to prevent frost damage during transit.

Proper **disposal of waste potatoes** is an important management practice to ensure the health of future potato crops. A plan for proper disposal must be in place before cull potatoes are generated in the packing-out operation. Cull potatoes should never be dumped outside in piles where some tubers will survive freezing temperatures. Cull piles are notorious sources of spores of the late blight pathogen, which form on sprouts from surviving tubers. They also serve as reservoirs of some viruses. Acceptable waste disposal methods include using culls as livestock feed, composting them, and spreading them in the winter to freeze on land not intended for potato production the following season. An expensive and less desirable method is to bury cull potatoes at least 6 feet deep. Contamination of groundwater may result from this method.

Mechanical damage continues to be a major factor in potato health management, not only because of the direct results of injury, but also because of the introduction of disease organisms. Healthy seed tubers are critical to the potato industry—they are the vital link from one season to the next. Repeat orders at the processing plant and in the fresh-market supply chain depend on tuber health. The potato grower, along with employees, field advisors, and creditors, must maintain vigilance to ensure that a tuber health management program is followed through harvest, storage, and marketing. Continued profitability in potato farming depends on the ability of the potato health manager to accomplish this objective.