Research Review for
on
Preserving Potato Skin Finish During Storage

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PRESERVING POTATO SKIN FINISH DURING STORAGE

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1. Grower summary

Skin finish describes the visual appearance of potato tubers. Factors that affect skin finish include blemish diseases, skin shininess (or bloom), netting, and appearance of lenticels.

Blemish diseases such as black dot (*Colletotrichum coccodes*), silver scurf (*Helminthosporium solani*) and skin spot (*Polyscytalum pustulans*) increase during storage. However, it is important to minimise the development of these diseases in the field in order to obtain the best skin finish out of store. This is best achieved by minimising the growing period of the crop. Blemish disease control is also possible during the early storage phase. This is done by either rapidly cooling the crop (i.e. black dot and silver scurf) or adequately curing the crop (i.e. skin spot) soon after loading into store. Deciding which strategy is best will depend on whether factors such as variety, seed health, and previous cropping history indicate a risk of skin spot.

Factors, other than diseases, that affect skin shininess, netting/russetting and enlarged lenticels include: variety, soil texture, planting depth, nutrition, soil temperature, water stress, water logging, length of growing season, and curing regime after store loading. The most important of these factors are variety, soil type and water stress (irrigation scheduling and water logging). For example, water stress should be minimised, especially fluctuations in water stress, and water logging should be avoided by good soil management. Soil types that produce tubers with good skin finish are those that have a high water holding capacity and a low sand content (low abrasiveness). However, there is currently no good, objective information on suitability of soils for best skin finish.

Rapid cooling during early storage has been shown to delay the loss in skin shine. Maintaining a high humidity during storage did not produce any consistent effects on skin appearance. However, storage at 98% RH reduced crop weight loss compared with storage at 90% RH.

We finish this review by listing some gaps in knowledge and suggest some ways in which these gaps can be addressed.

- In order to maintain good skin finish during storage, we recommend that crops are cooled as soon as possible after store loading (provided there is adequate skin set and that the variety is not highly susceptible to skin spot). Also, the crop should be ventilated with dry air during the early stages of storage to remove surface moisture. Aim to store the crop below 4.0°C.

2. Introduction

2.1. Definitions

The term 'skin finish' relates to the visual appearance of the potato tuber. More specifically, a good visual appearance is attributed to an intact tuber skin without physiological or pathological blemishes. Factors that are normally considered when evaluating skin finish include: blemish diseases, shine (or bloom), netting, and appearance of lenticels.

The periderm is a specialised protective layer on the outside of a potato tuber consisting of three types of cells: phellum (suberised cells that provide the tuber with protection against disease and water loss); phellogen (the lateral meristem layer); and phelloderm (which connects the periderm to the underlying cortical, or storage, tissue). Definitions of what constitutes 'skin' of potato tubers, vary. Some authors consider the skin and periderm to be synonymous (Napier & Andrews, 2005; Hiller *et al.*, 1985). However, Lulai (2002) defined skin as the phellum portion of the periderm because when the skin is scuffed, the line of fracture is along the phellogen and it is the phellem that becomes detached. In this review we recognise that the term 'skin' can have different meanings in scientific literature. Thus, the technical meaning (phellem or periderm) is given in brackets where required for clarity.

Definitions of some technical words used in this report are given in the glossary.

2.2. Scope of the review

This review seeks to cover skin finish of set-skinned table potatoes. Aspects of skin finish covered by this review include:

- implications of periderm development and structure;
- methods of assessing skin finish;
- bloom;
- netting and russeting;
- appearance of lenticels;
- effects of blemish diseases;
- effects of crop husbandry on skin finish at store intake;
- changes in skin finish during storage;
- considerations at store unloading.

2.3. Importance of skin finish

The dominance of washed and packed potatoes within the fresh market means that producing and maintaining tubers with a good visual appearance is vital for securing premium returns in this sector. In GB alone, it is estimated that the value of the fresh sector is worth around £834 million per annum (Anon, 2005). As a consequence of this, causes of rejections or downgrades – for example poor skin bloom or high levels of a blemish disease, such as black dot – are important and costly concerns for the industry.

3. Skin development and structure

3.1. Introduction

An understanding of periderm structure and development is necessary for an appreciation of how commercial practice can influence potato skin finish in store. This section of the report provides a summary of skin structure, leading to conclusions about properties of potato skins that are important for commercial skin finish.

3.2. Periderm structure

The outer tissues of a potato tuber are collectively known as the periderm. The periderm is a protective layer which minimises water loss from underlying parenchyma cells, and provides defence against soil pathogens (Peterson, Barker & Howarth, 1985). The periderm is made up of three types of cells: the phellem (cork), the phellogen (cork cambium), and the phelloderm (Figure 1).

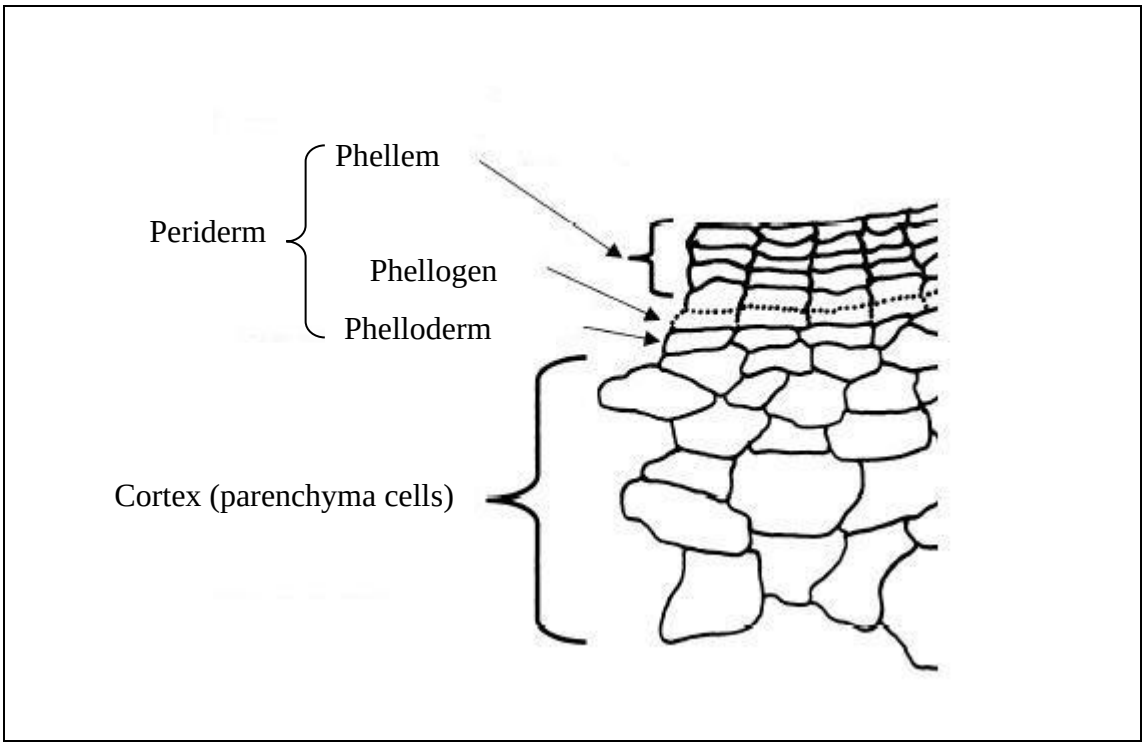

Figure 1. Diagramatic representation of the periderm, adapted from Lulai (2002).

The phellem is the outermost tissue of the periderm that resists water loss, is mechanically strong and acts as an effective barrier to pathogenic bacteria and fungi. The phellem cell walls are secondarily thickened with deposits of suberin. Suberin is a hydrophobic polymer composed of phenolic and aliphatic compounds (Peterson, Barker & Howarth, 1985). It is a complex biopolymer, and the details of the molecular arrangement and the precise localisation of the suberin deposits within the cell wall are unknown, but are likely to influence water permeability (Schreiber, Franke & Hartmann, 2005). The phellem is readily seen to be rich in suberin by autofluorescence and from the staining of dyes such as Berberin (Napier & Andrews, 2005), and this clearly distinguishes the phellem cells from the adjacent cells. Phellum cells are approximately 'brick' shaped, abutting closely to each other without

intercellular spaces (Artschwager 1924). This arrangement increases resistance to tuber water loss.

The phellem and phelloderm cells are produced by periclinal divisions (divisions in a plane running parallel to the surface of the tuber) of the phellogen cells (Sabba & Lulai, 2005). Thus, the phellogen functions as a meristem in immature tubers, producing new layers of phellem as the tuber grows and outer layers are sloughed off.

Artschwager (1924) gives the typical thickness of the periderm as between 100 and 170 µm in a range of varieties. More recently, Yamaguchi, Timm & Spurr (1964) reported that the periderm of Russet Burbank tubers, at a soil temperature of 55–60°F (approximately 13–16°C), was 7–18 cell layers thick and 105–210 µm thick.

Periderm overlaying a previously cut or wounded surface is called 'wound periderm', in contrast to the 'native periderm' of an undamaged tuber surface. Wound periderm is similar in structure to native periderm, with phellem, phellogen and phelloderm layers, but with cells appearing to be less regularly organised than in native periderm (Sabba & Lulai, 2004). Despite similarities in structure between native and wound periderms, a comparison of water permeability after one month of storage showed that water permeability of wound peridem was on average 100 times greater than that of native periderm (Schreiber, Franke & Hartmann, 2005).

Lenticels are small pores on the surface of the tuber, sometimes visible as small white dots. Lenticels are thought to allow gaseous exchange between the internal tuber tissues and the external tuber environment, but are also possible entry points for pathogens (Artschwager, 1918; Cutter, 1992; Adams, 1975). An attempt to estimate the number of lenticels on a tuber showed a range between 74 and 141 (Cutter, 1992). Lenticels are usually circular, forming a crater that is filled-in with cells, sometimes forming a dome in the centre. Under dry conditions a suberized layer is present below the lenticels (Cutter, 1992), and the filling cells also become suberized (Adams, 1975). In wet conditions, the suberized layer becomes ruptured and parenchyma cells proliferate and erupt through the centre of the lenticel, and protrude above the tuber surface (Cutter, 1992; Adams, 1975), influencing the appearance of the tuber.

3.3. Periderm formation and development

A potato tuber is a modified stem, which begins to differentiate as a swollen internode close to the apical bud of a stolon. The outer layer of the stolon is the epidermis, which has widely scattered stomata (Cutter, 1992). While the tuber is very young, the epidermis is replaced by the periderm, beginning at the stem end of the developing tuber and soon extending over the entire surface. The periderm is well developed when the tuber has reached the size of a pea (Artschwager, 1924).

As the periderm is formed, cells immediately below the positions of the stomata actively divide and form the lenticels (Artschwager, 1924).

During tuber growth and periderm development, the phellogen is an active lateral meristem. The phellogen cells divide and new cells towards the outside of the tuber become phellem cells. Production of phellem cells by the phellogen, and loss of phellem cells via sloughing-off at the tuber surface are approximately in balance as the tuber grows (Artschwager, 1924). The phelloderm also arises from the phellogen.

Suberisation of phellem cells is a secondary thickening of the cell walls and is driven by the activity of cell wall peroxidases (Napier & Andrews, 2005). The suberisation and closely-packed arrangement of phellem cells result in a very effective barrier to water movement and infection.

Lulai & Freeman (2001) showed that, as the tuber matures, the cell walls of the phellogen thicken and strengthen. Immature periderm has an actively-dividing phellogen layer and, contrastingly, mature periderm (typical of potatoes in store) has a phellogen layer that is meristematically inactive (Sabba & Lulai, 2002).

Skinning injury (known scientifically as excoriation) of immature tubers has been shown to be related to fracture of the phellogen cell walls, allowing separation of the phellem from the adjacent phellogen cells, and was consistent in six cultivars studied (Lulai, 2002). As the tuber matures, excoriation occurs less easily, and the skins become 'set'. This is related to thickening of the phellogen cell walls, inceasing their resistance to fracture. The phellogen also becomes inactive as a meristem as the tuber matures. Thus, as skin set occurs, production of new phellem cells ceases. No differences in suberisation of phellem cells, before and after skin set, have been detected (Napier & Andrews, 2005). It has been shown that adhesion strength has no clear relationship with variety, skin thickness, cell size or degree of suberisation (Bowen, Muir & Dewar, 1996). Tensile strength of the phellem has also been studied in relation to skin set, but this does not contribute to skin set development (Lulai, 2002).

Wound periderm is formed when the tissue is damaged, and tissue underneath the native periderm is exposed, often with removal of an area of native periderm (Cutter, 1992). The first response to wounding is the formation of a suberised layer at the surface, and then a new phellogen layer forms under the suberised surface (Sabba & Lulai, 2002). Localised cell division occurs and spreads throughout the damaged area (Artschwager, 1924). Wound periderm is then formed by division of the phellogen cells.

3.4. Implications for commercial skin finish

The term 'skin' is sometimes used to mean the whole periderm, and sometimes used to mean the phellem. Skin finish relates to the external appearance of the phellem, but this may be influenced by the state, or activity, of the phellogen.

There does not appear to be a clearly defined distinction between netting and russeting. Both are a network of fine cracks or fissures in the outer layers of the phellem (Ginzberg *et al.*, 2005; Napier & Andrews, 2005). Yamaguchi, Timm & Spurr (1964) describe russeting as having a cracked periderm "divided into plaques or patches of thick tissue (russeting) surrounded by areas of thin tissue (cracks)". Netting has been described as fracture of the phellem (Napier & Andrews, 2005), but it is not known whether a netting fracture penetrates through all layers of the phellem cells, or just through some of the layers. Factors that influence expression of netting and russeting are discussed in Section 5.2.

Under wet conditions, tuber lenticels can become swollen and discoloured. If this adversely affects the visual appearance of the tuber, this can lead to the downgrading of whole stocks.

When the skins are set, the phellogen is inactive, and new layers of phellem cells are not formed (Sabba & Lulai, 2002). The implication of this is that, as outer layers of phellem are sloughed off in store, these layers are not replaced. It is probable that removal of phellem cells in store by this means is very limited, and that the outer layers become increasingly rough as they deteriorate, leading to a less smooth skin, made visible through a loss of bloom.

Bloom is the term used to describe the shine of the skin surface. A tuber with good bloom is a tuber with a good shine or lustre. In other situations (for example when referring to vine fruits), bloom means the powdery or waxy deposit on fruits. However, bloom as used in this review refers to the relative smoothness of tuber periderm surface.

Unsetting of skins in early storage has been reported anecdotally in some varieties, and has been found to occur within two hours after harvest. The tuber environment (in particular excess moisture pre- and post-haulm destruction), and small impacts when handling the crop, were shown to exacerbate unsetting (Wiltshire, Milne & Peters, 2005). We speculate that this phenomenon may be a manifestation of the phellogen becoming active again for a short period, after becoming inactive when skins have set.

Skin finish for the fresh market is largely determined by the external appearance of the native periderm. If damage has occurred, skin finish may be judged worse than for an undamaged sample, but the appearance of the wound periderm is not an important factor, and we are not aware of any studies relating to this.

4. Methods of assessing skin finish

4.1. Introduction

Given that poor skin finish can reduce the value of a crop, most quality control laboratories for commercial packers ensure the suitability of produce by inspecting samples of tubers throughout the production process. Currently, most quality traits are investigated by eye. However, recent developments in image analysis make it possible for some commercial packers to use grading lines with a camera and software to detect tubers which have blemishes (for example, greening) that are cause for rejection. Systems exist that are capable of grading and sizing up to 60 tonnes of potatoes per hour ('Pomone II', Maf Roda/Tong Peal Engineering, UK). The system grades using optical sensors that can measure diameter and volume, and can recognise shape and gross colour defects.

4.2. Tuber quality charts

Currently most QC labs use quality charts to help staff visually assess tuber quality relative to pre-determined categories represented as images on monochrome or colour charts. Examples of these charts are provided in Annex 1. Quality charts are used because they are cheap to produce (and are often supplied by the customer), and it is relatively quick and easy to train QC staff in their use. However, assessments that rely on operators to match quality traits on samples against visual representations are subjective and prone to error, as one assessor's assessment will differ from another. It is, therefore, vital that assessor's results are checked regularly to ensure accuracy of data.

4.3. Optical devices for measuring skin shine

A previous BPC-funded study identified an optical technique that provided an objective measure of skin bloom (Gray *et al.*, 2003). The bloom (sometimes also called shine or lustre) is measured as the specular (i.e. direct or mirror-like) component of optical reflection from the potato skin surface. The diffuse component of reflected light provides the colour information. A small hand-held optical meter ('Bloom Meter') was developed at SAC for the BPC, to objectively assess small areas on a tuber surface (approximately 10 mm^2 of flat surface) and grade them according to a pre-defined scale that related to the bloom of the potato tuber surface (Figure 2). The output was a bloom index on an integer scale from 1 (bright, shiny skin) to 5 (dull, matt skin). An example of potatoes with different bloom values is shown in Figure 3. The Bloom Meter is a useful tool for research laboratories. However, this device was never put into large-scale production and, therefore, is not generally available. Also, it can be argued that the scale, limited to 5 graduations, does not provide sufficient resolution.

Figure 2. The pre-production version of the BPC/SAC Bloom meter.

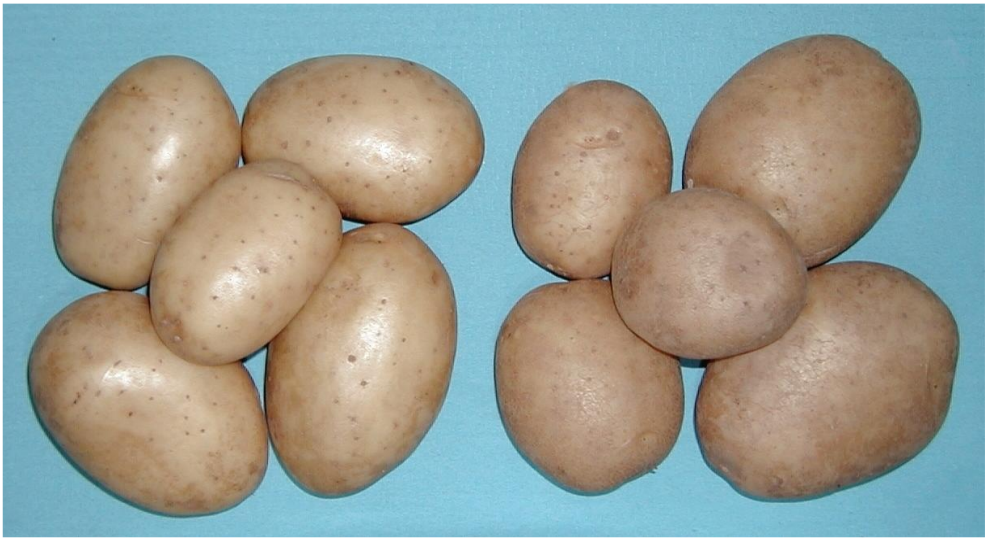

Figure 3. Differing levels of bloom in cv. Estima: bloom index values of 2 (left) and 4 (right).

Commercially available 'gloss meters' perform the same function as the bloom meter. One, the Novo-Gloss Lite™ (Rhopoint Instrumentation Ltd, UK) was used by SBEU to investigate the deterioration of skin bloom in potato tubers during storage (unpublished). The Novo-Gloss Lite operates in much the same way as the bloom meter except that light is transmitted at an angle of 60° (rather than the 45° angle utilised by the Bloom Meter) and the amount of specular reflection detected by the internal sensor is converted to a reading from 0 (completely matt) to 100 (mirror-like). The Bloom Meter index values of 2 and 5 correspond to gloss meter values of approximately 15 and 4 respectively.

5. Skin finish at store intake

5.1. Introduction

Generally, skin finish does not improve during storage, so skin quality at store intake is of the greatest importance. For crops to achieve a premium in the pre-pack or punnet market, and maintain this premium throughout the storage term, it is vital that the agronomy is appropriate for attaining the best skin finish possible. With available storage techniques, it is possible to maintain a good skin quality for upwards of 35 weeks but only if the quality of the crop meets customer specifications at harvest.

5.2. Non-pathological effects of crop husbandry

Field factors that are known or suspected to affect non-pathological aspects of skin finish at harvest and store intake include the following:

- variety,
- soil texture,
- planting depth,
- nutrition,
- soil temperature,
- water stress,
- water logging,
- length of growing season.

Skin finish varies between varieties. Differences between varieties are well known within the packing industry, but skin finish characteristics of varieties are not well documented.

Soil type is also known to influence skin finish, but the effects of soil texture are not scientifically characterised in detail. Braue *et al.* (1983) describe work done in Scandinavia (Nielsen, 1968) showing that tubers grown in sand had more phellem cell layers than those grown in humus. It is known within the packing industry that skin finish is best on tubers grown in silt or clay soils compared with more abrasive, sandy soils. Tubers grown in peat soils may also have a smooth skin finish, but appearance of these tubers can be affected by staining. These anecdotal observations, together with the findings of Neilsen (1968) suggest that the phellem is thicker on tubers grown in more abrasive soils, with detrimental consequences for good skin finish. There seems little doubt that skin finish is related to soil texture, but experimental work would be required to establish a detailed relationship.

It has been suggested that deep planting produced thinner skins compared with shallow planting, and that nutrition affected skin thickness in some studies, but not others (Artschwager, 1924). Ashiv Mehta & Singh (2004) found that application of N, P and K together, or application of manure, increased the thickness of the phellem and the combined thickness of the phellogen and phelloderm, compared with application of N alone.

In conditions of high soil temperature (28–33°C) tubers have relatively thick skins and are more prone to russeting and netting (Ginzberg *et al.*, 2005). Yamaguchi, Timm & Spurr (1964) also reported that the skin of Russet Burbank tubers showed increased roughness as soil temperature increased in the range 45–80°F (7–27°C), with marked russeting of tubers grown in soil above 65°F (18°C). Work with cv. Estima has also shown increased skin (periderm) thickness with increased temperature of the tubers during growth in hydroponic conditions (Table 1), and this increase in thickness was correlated with a greater number of suberised (phellem) cell layers (Anon., 2005). The same study showed that the incidence and severity of netting was increased at higher tuber temperatures.

Table 1 Effect of temperature of tubers (cv. Estima) on periderm thickness, during growth in hydroponic conditions (Anon., 2005).

Temperature (°C)	10	20	30
Peridem thickness (µm)	120	164	182

Ginzberg *et al.*, 2005 showed that rapid haulm destruction improved skin finish (netting and russeting), by shortening the exposure time of tubers to high soil temperatures.

These effects of soil temperature and the effects of soil texture both provide evidence of an association between skin (phellem) thickness and skin appearance.

Water stress during growth increased netting in cv. Estima grown in a hydroponic system (Anon., 2005), and increased resistance to water stress in cv. Russet Burbank, grown in pots in a glasshouse (Braue *et al.*, 1983). However, field observations have shown a relationship between netting symptoms and distance between the tuber and the soil surface (Anon., 2005). Surprisingly, netting was worse as distance from the soil surface increased. Clearly, there is a complex relationship between tuber environment and netting, but it appears that soil temperature and water potential are important factors.

Waterlogging is thought to increase netting, skin dullness and cause raised lenticels, but there is little or no published evidence to support this (Allen & Scott, 2001).

The length of the growing season has been shown to affect skin finish: longer duration crops tended to have duller skins (less shiny) after prolonged storage (Wiltshire, Milne & Peters, 2005). However, this effect was smaller than the variation between seasons. More recent work (Peters, unpublished) suggests that skin shine in Maris Piper was inversely proportional to the length of time from desiccation to harvest (i.e. shorter harvest intervals produce brighter skins than long harvest intervals).

5.3. Blemish Diseases

Blemish diseases such as common scab (*Streptomyces scabies*), powdery scab (*Spongospora subterranea*) and black scurf (*Rhizoctonia solani*) can affect skin finish and are the cause of downgrades in the fresh market. However, these diseases are evident at harvest and do not develop in store, and therefore, will not be considered further in this review. However, black dot (*Colletotrichum coccodes*), silver scurf (*Helminthosporium solani*) and skin spot (*Polyscytalum pustulans*), do increase during storage and each disease is dealt with separately below.

5.3.1. Black dot

In GB, the high importance of black dot is mainly due to the extent of downgrades caused by skin blemishing. However, the pathogen, *Colletotrichum coccodes*, can also, in some years, reduce the marketable yield of tubers and increase crop senescence (Read & Hide, 1995). Where high levels of black dot were observed on tubers, Read & Hide (1995) also found an increase in weight loss during storage.

The fungus is both seed and soil borne, surviving from one season to the next as microsclerotia on the surface of tubers or on plant debris in the soil (Davis & Johnson, 2001). Crop rotation is unlikely to reduce soil borne inoculum because of the potential for survival of the pathogen on alternative hosts. *C. coccodes* has been shown to survive, and potentially reproduce, on at least 35 other hosts (representing 13 families) including cucurbits, legumes and other solanaceous plants (Mordue, 1967). Also, at least 15 weed species have also been shown to act as hosts to the pathogen (Raid & Pennypacker, 1987). The pathogen can also be introduced via infected seed. However, this is considered to be more important for the inoculation of previously clean, uninfested soils than for infection of the immediate crop (Wale *et al.*, 2005).

Currently, azoxystrobin is the only chemical that has approval for the control of black dot in the UK. Azoxystrobin is applied to the soil at planting. The chemical probably reduces the amount of viable inoculum in the soil and so delays the onset of disease symptoms (Anon., 2006).

Workers have shown that the severity of black dot symptoms on roots, stem bases and tubers is correlated with season length (Read & Hide, 1995; Wale *et al*., 2004). Increasing the length of time that the crop was in the ground causes an increase in the incidence and severity of disease levels on tubers at harvest. Data, adapted from Gray *et al*., 2003 and Wiltshire, Milne & Peters, 2005, showed that the relationship between black dot at harvest and crop duration in cv Estima over 5 seasons followed that of a logistic model in four of the five years (Figure 4). However, in one year (2001) the relationship between disease severity and crop duration was approximately linear and overall black dot levels were low. As the crops were irrigated in all five seasons (and, therefore, the impact of differences in rainfall from one season to the next was minimised), it is possible that variation in black dot development between seasons could be due to differences in inoculum levels either on seed or in soil.

The potential for high levels of disease on tubers at harvest strongly suggests that an effective management strategy must include control of the disease prior to store loading. For a more comprehensive review on the disease and its control, see Lees & Hilton (2003).

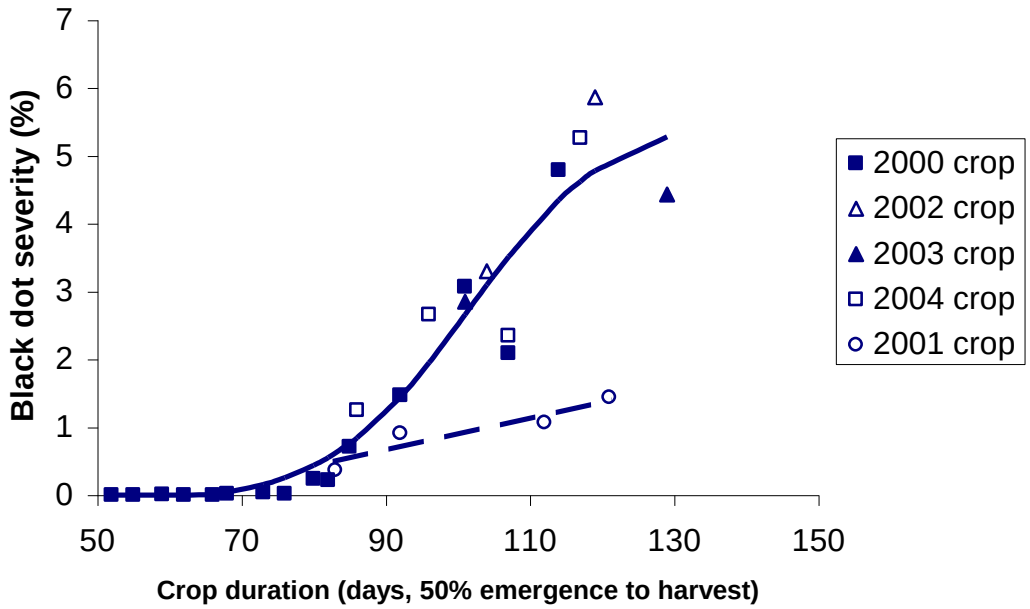

Figure 4. The severity of black dot on cv Estima tubers at harvest plotted against crop duration (days, 50% emergence to harvest) over 5 growing seasons. (Data from Gray *et al*., 2003 and Wiltshire, Milne & Peters, 2005).

5.3.2. Silver scurf

Silver scurf, caused by the fungus *Helminthosporium solani*, is mainly considered to be a blemish disease of potato. The primary source of inoculum is from infected seed tubers (Errampalli, Saunders & Holley, 2001). Pathogen conidia can survive from one season to the next but the role of soil-borne inoculum is likely to be most important in introducing the pathogen to silver scurf-free seed stocks (Mérida & Loria, 1994; Bains, Bisht & Dee Ann Benard, 1996). Errampalli, Saunders & Holley (2001) in their review of silver scurf, provide a useful section on cultural practices that have been shown to help manage silver scurf. These include: planting clean seed, minimising seed tuber size, minimising the growing season length and planting density. Although planting of clean seed is considered an effective method of minimising silver scurf levels on progeny crop, even low levels of infection (<5% surface area) could result in severe infection in progeny tubers (Mérida, Loria & Halseth, 1994). As with black dot, the length of growing season affects the level (severity and incidence) of disease at harvest (Firman & Allen, 1995) and severity of silver scurf during storage (Errampalli, Saunders & Holley, 2001).

Imazalil and thiabendazole (TBZ) are effective in controlling silver scurf both in minimising development during storage and in reducing spread from mother to daughter tubers (Hide, Boorer & Hall, 1994; Carnegie *et al.*, 1998). TBZ is a systemic, broad-spectrum fungicide, and was widely used in the 1970's to control silver scurf. The fungicide disrupts the cytoskeleton of the pathogen (Errampalli, Saunders & Holley, 2001). However, in 1977, isolates of *H. solani* were found that

were insensitive to TBZ (Hide Hall & Boorer, 1988). Since then, the use of TBZ in stores has diminished mainly because TBZ-resistance has developed in *H. solani* and other fungal pathogens. Currently, imazalil is the most widely used storage fungicide on GB potatoes (Struthers, 2005) but is now restricted to seed store use. The combined use of imazalil and TBZ has been shown to be more effective at reducing disease development during storage than the individual chemicals used on their own (Carnegie *et al*, 1998). In the same trial, the timing of fungicide application did not consistently alter the amount of disease developing on daughter tubers. Control in the daughter tubers of some crops was improved when fungicides were applied during the previous harvest; and in other crops control was best when the fungicide was applied at planting.

5.3.3. Skin spot

This section provides a general overview of skin spot and its control. However, for a full literature review, see Wale, Sutton & Peters (2004). The blemish disease, skin spot, is caused by the fungus, *Polyscytalum pustulans*. Pathogen inoculum (conidia or sclerotia) infects stem bases, roots and stolons of potato plants, often causing brown lesions (Franc, 2001). The disease is expressed on tubers following a storage period of at least 6 weeks (Allen, 1957). Skin spot control in the field relies on cultivar selection, timely lifting and avoidance of over-irrigation (Hide, Hall & Read, 1994).

Skin spot is primarily seed borne (Franc, 2001). However, inoculum can survive in soil as sclerotia that can persist for 7 years or more (Carnegie & Cameron, 1990; Hide & Ibrahim, 1994). Seed tubers are an important source of inoculum but there is often no relationship between seed tuber infection and disease on progeny tubers (Hide & Adams, 1980) because weather, season length and soil conditions are likely to have a large influence on disease development. Hide, Hall & Read (1994) established that early lifting reduced skin spot. However, this trend was not consistent between years.

Many fungicides have been shown to effectively control skin spot. For example, thiabendazole, imazalil and 2-aminobutane (2-AB) have been shown to reduce the development of symptoms during storage when applied shortly after harvest (Carnegie *et al.*, 1986; Hall & Hide, 1992; Carnegie *et al*., 1998). These fungicides can also reduce the spread of disease from seed to progeny crop when applied just prior to planting (Carnegie *et al*., 1998). The presence of thiabendazole-resistant isolates of *P. pustulans* is well documented (Carnegie and Cameron, 1992; Carnegie *et al.*, 1994). Therefore, imazalil or 2-AB are currently the fungicides of choice for treating seed potatoes. However, this may change as 2-AB has approved essential use until 31 December 2007 (Anon., 2004) and the continued use of this product after this date is not guaranteed. This means that an integrated approach to the control of skin spot is essential.

The use of resistant varieties is a good method of disease limitation provided that the grower is able to choose varieties on the basis of resistance to a particular disease. Hide, Hall & Read (1994) demonstrated that good control of skin spot in a susceptible variety, King Edward, could be achieved when seed tubers were treated with fungicide (an imazalil/thiabendazole mixture) and progeny tubers dry cured for two weeks. Control was often better the earlier tubers were harvested.

6. Changes in skin finish during storage

6.1. Introduction

Some aspects of skin finish are already determined at the time of harvest, and change little in store. For example, this is true for netting and for some diseases such as common and powdery scab, and black scurf. However, many aspects of skin finish can deteriorate during storage. These include: skin bloom, lenticel appearance, black dot, silver scurf and skin spot. These are further considered below.

6.2. Changes in skin physiology

The surfaces of tubers lose their bloom (shine or lustre) over time. Ultrastructure work carried out by Napier & Andrews (2005) confirmed that skin bloom is related to the degree of smoothness of the skin surface. The pattern of skin bloom deterioration in cvs Estima and Desiree followed that of either a logistic (sigmoidal) or exponential (asymptotic) decline (Wiltshire, Milne & Peters, 2005) (Figure 5). This deterioration in bloom was shown to be caused by cell collapse in the phellum layer (Napier & Andrews, 2005) (Figure 6). This collapse occurred sometime during the 14-day curing period at 12°C (John Andrews, Pers. Comm.). The collapse was considered by Napier & Andrews (2005) to be caused by water loss during the curing period. The change in periderm structure resulted in a roughening of the skin surface producing a poor bloom (or dull appearance).

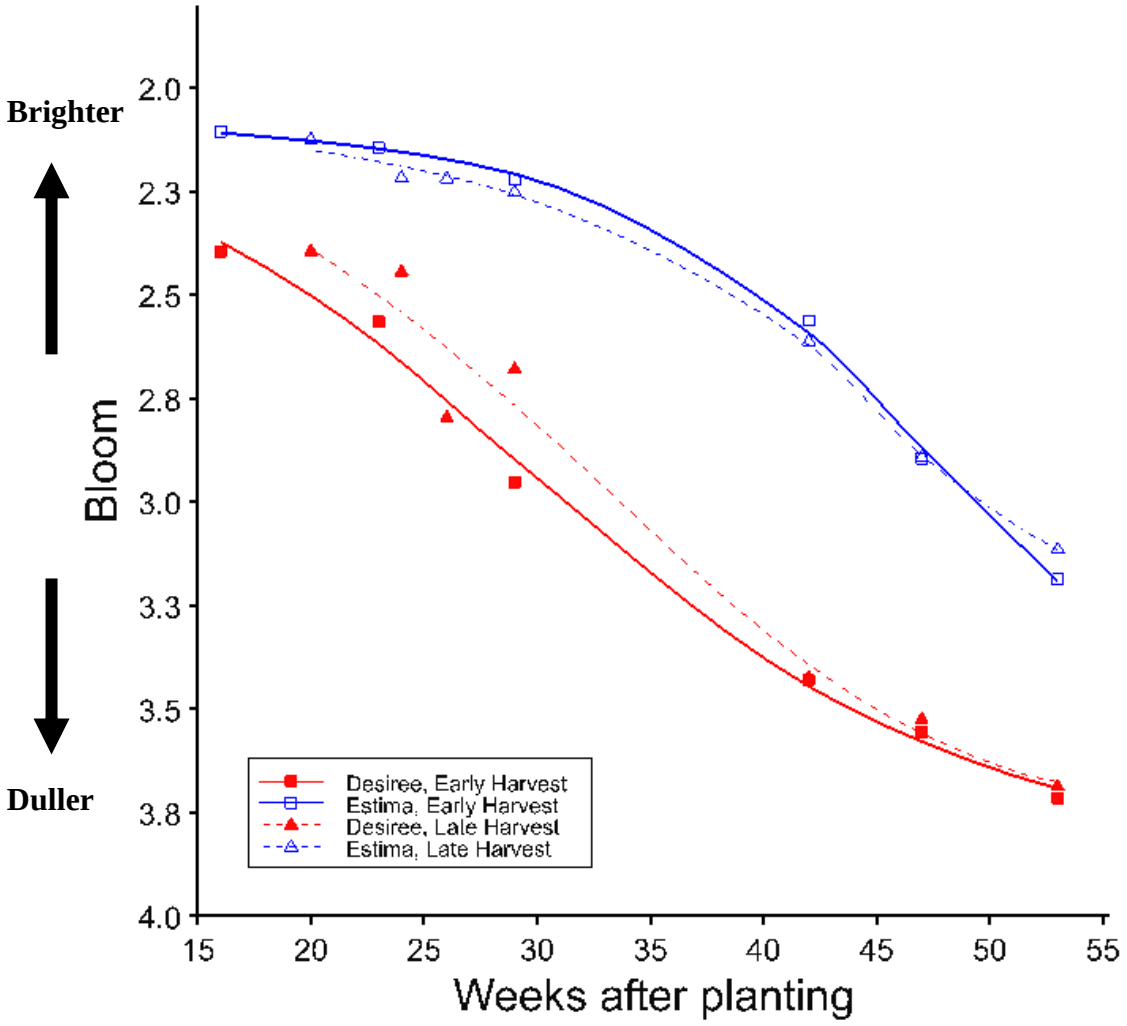

Figure 5. Pattern of shine deterioration in Desiree and Estima tubers stored at 4°C (Wiltshire, Milne & Peters, 2005). Unbroken lines represent early harvest treatments, and broken lines represent late harvest treatments. Data represent bloom (or shine) values measured using the Bloom Meter, whereby a value of 3 or less is acceptable for pre-pack standards. The variance accounted for was 98.5%. $LSD_{(P=0.05)}=0.12$.

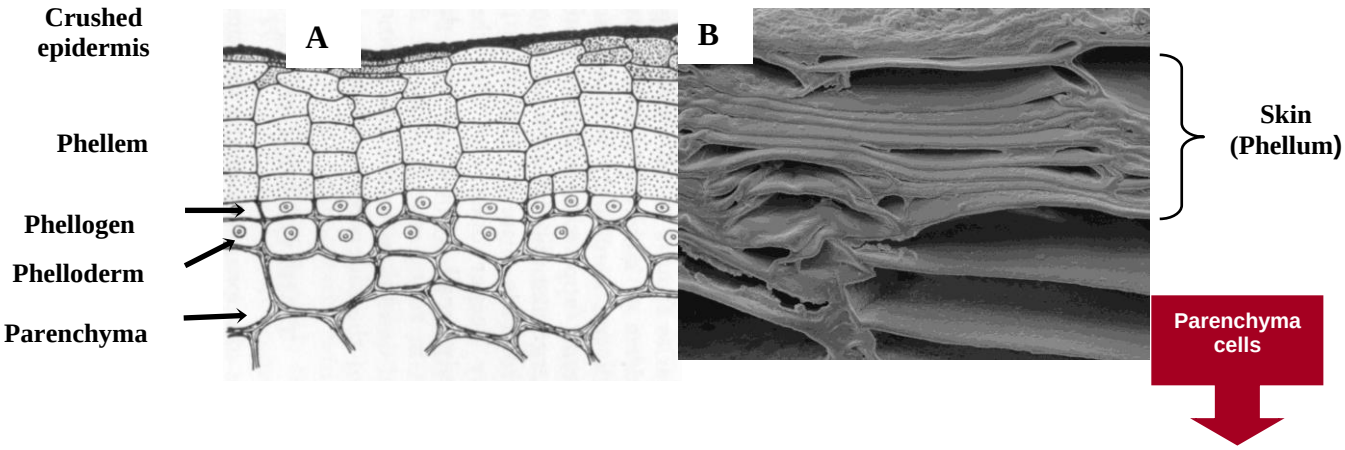

Figure 6. Diagram A shows schematic representation of tuber periderm (comprising phellum, phellogen and phelloderm) (Esau, 1953). Micrograph B shows collapse of phellum cells during curing, courtesy of J Andrews, Warwick HRI.

Storage treatments generally had minimal impact on the decline of skin bloom in work reported by Wiltshire, Milne & Peters (2005). In that study, storage temperature, CIPC and ventilation fan speeds did not affect the models fitted to skin shine data. In Desiree, humidity had a marginally significant effect, whereby tubers stored at 98% relative humidity (RH) had better skin shine (i.e. brighter skins) than tubers stored at 90% RH. Humidity did not affect bloom deterioration in Estima. However, storing tubers at an RH of 98% reduced the weight loss from 5.1% (in crop stored under 90% RH, no RH control) to 4.4% (P<0.001). Immediate crop cooling helped maintain a better skin finish compared with tubers that had been cured prior to pull-down (Wiltshire, Milne & Peters, 2005). For example, in early harvested Estima tubers (83 and 92 days from 50% emergence to harvest), a 14 day curing period at 12°C caused bloom to deteriorate, on average, 18 days sooner than for tubers that had been cooled immediately following store loading. This suggests that skin appearance might be affected by water loss (exacerbated by high temperatures) during the early stages of skin curing.

Anecdotal evidence suggests that under storage conditions that are likely to induce stress in potatoes (for example poorly ventilated stores with elevated CO_2 levels), lenticels can undergo physiological deterioration. Also, enlarged lenticels are susceptible to infection by colonising *Erwinia* species and breakdown may develop during storage if free water is present on tuber surfaces (Thornton, 2001). Therefore, to prevent physiological and bacteriological deterioration, it is important to ensure that crops are adequately ventilated and dried after store loading.

6.3. Blemish disease control

During the early stages of storage, usually within the first three weeks after store loading, it is important to: 1) remove surface moisture from tubers; 2) maintain crop at a temperature that will allow wounds to heal; and 3) cool the crop to holding temperature (Pringle & Cunnington, 2001). Effective drying of the crop is critical for the control of black dot, silver scurf and skin spot. However, there are control practices that are specific to individual diseases and these are dealt with below.

6.3.1. Black dot

Workers (Wiltshire, Milne & Peters, 2005; Peters *et al.*, 2006) have shown that the severity of black dot, and the incidence of outgrades due to the disease, was correlated with crop duration (days from 50% emergence to harvest). Decreasing the length of time that the crop was in the ground caused a decrease in the incidence and severity of disease on tubers at harvest. Consequently, reductions of black dot severity on tubers at harvest also translated into reduced disease levels throughout storage (Figure 7, Peters *et al.*, 2006). Further control of black dot could be achieved by immediately cooling the crop by 0.5 degC per day compared with curing at 12°C for 10 days prior to cooling (Figure 8, Peters *et al*., 2005).

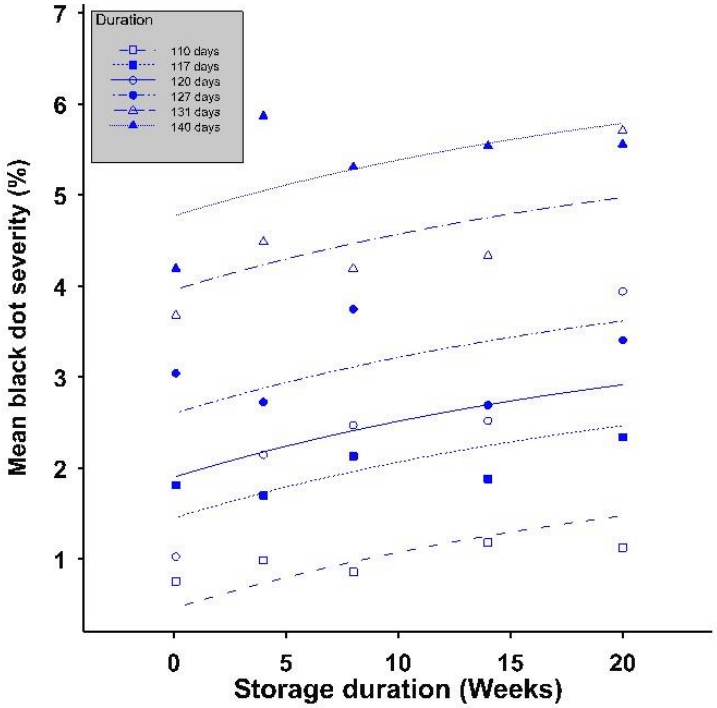

Figure 7. Black dot severity (%) plotted against storage duration (Peters *et al.*, 2006). The legend shows crop duration of treatments (in days from 50% emergence to harvest). The overall R^2 value for parallel fitted regressions is 0.87.

Increases in black dot severity on tubers during storage is thought to be brought about both by the expansion of existing lesions (Wiltshire, Milne & Peters, 2005) and the development of symptoms from latent infections (Glais-Varlet, Bouchek-Michiche, Andrivon, 2004; Wiltshire, Milne & Peters, 2005). Therefore, storage temperature should alter the speed of symptom development. In one study (Wiltshire, Milne & Peters, 2005), there was an interaction between harvest date and storage temperature on black dot development in Estima, a susceptible variety. In early lifted tubers, black dot severity, over a 35-week storage period, was reduced by storing the tubers at 2.5°C compared with storage at 4.0°C (P<0.05). No reduction in black dot severity was observed at the cooler temperature in later harvested tubers. In other words, low levels of black dot in the shorter duration crop could be kept low by immediately cooling the crop after harvest and maintaining the tubers at 2.5°C.

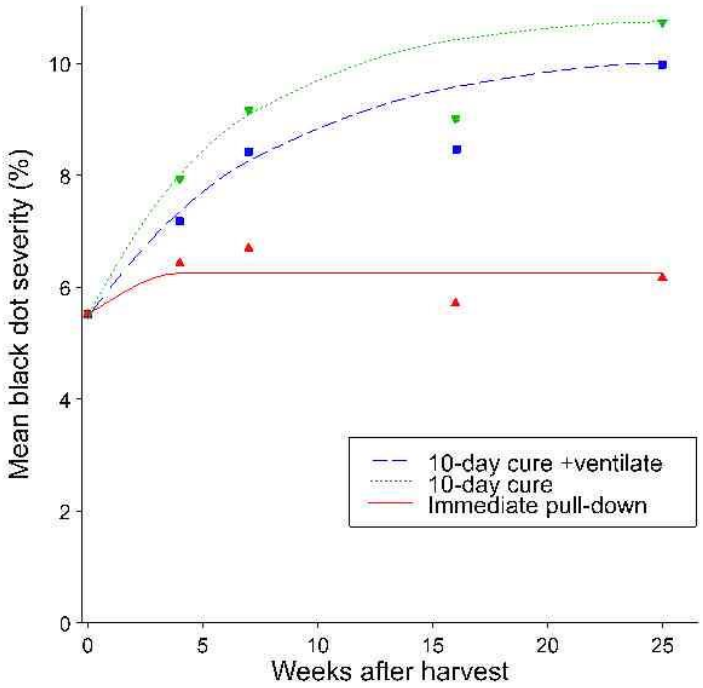

Figure 8. Black dot severity (%) plotted against storage duration (Peters *et al.*, 2005). The legend shows three curing regimes whereby crop was immediately cooled (with constant ventilated air) or cured at 12°**C** for 10 days with and without constant ventilation). The standard error of the difference between the means, SED, is (P=0.05; 62df) = 1.71.

6.3.2. Silver scurf

As with black dot, the severity of silver scurf was correlated with crop duration (Hide, Boorer & Hall, 1994; Mérida, Loria & Halseth, 1994; Peters, unpublished). Low relative humidity and avoidance of free moisture during curing (first weeks after store loading) were shown to minimise silver scurf development (Hide & Boorer, 1991; Hide, Boorer & Hall, 1994; Frazier *et al.*, 1998). For example, Hide, Boorer & Hall (1994) showed that dry curing tubers for two weeks at 15°C and 80% RH reduced the severity of silver scurf by between 35 and 51%, compared with curing at 15°C and 95% RH. Mawson & Cunnington (1994) found that long-term storage at 2.5°C reduced the severity of silver scurf on Estima compared with storage at 4.0°C. However, this difference, whilst significant was small in real terms and was not consistent in all varieties.

Helminthosporium solani sporulates during storage (Rodriguez *et al.*, 1993). Moreover, conidial numbers rose with movement of potatoes in store. Rodrigues *et al.* (1993) speculate that movement of conidia from infected tubers or dust in store can act as fresh inoculum for uninfected tuber tissue. The conidia of *H. solani* were found to remain viable in soil and foam insulation in potato stores for up to 9 months (Frazier *et al.*, 1998). This highlights the importance of good store hygiene practices between storage seasons.

6.3.3. Skin spot

The skin spot fungus, *P. pustulans*, infects tubers through lenticels, eyes or damaged skin (Franc, 2001). Therefore, in order to control skin spot during storage it is critical that wounds or skin abrasions are adequately healed. Maintaining tubers in a dry, warm environment is required for wound healing. The length of time required for adequate curing is temperature dependent (Burton, 1989). Therefore, the rate of pull-down to the holding temperature has implications for the extent of curing the tuber can achieve and, thus, on disease development. The concept of 'dry curing', where air with relatively low RH (i.e. below 90%) is used to ventilate the crop, has been shown by various workers to be an effective method for reducing the development of skin skin spot (Hide & Adams, 1980; Hide, Boorer & Hall, 1994; Mawson & Cunnington, 1995). For example, Lennard (1967) showed that a temperature of 15ºC alone was insufficient to control skin spot: the treatment is only effective if the atmosphere is dry. Hide & Boorer (1991) suggested that dry conditions kill conidia or superficial infections because few spots developed when tubers were later stored in cool and damp conditions that would encourage skin spot. Hide & Cayley (1987) inoculated tubers with *P. pustulans* and stored them at 5ºC, 10ºC or 15ºC in dry or damp conditions for up to three weeks. Disease was progressively decreased on tubers untreated with fungicide by increasing the holding time and temperature in dry, but not damp, conditions. Curing at 15ºC for 14 days in dry conditions reduced the proportion of prick wounds infected from 70% to 4%.

Skin spot development was reduced by storing the tubers under dry conditions for the two-week period immediately following harvest (Hide & Boorer, 1991). Hide & Boorer also found in the same study that disease decreased as the storage humidity decreased during the same two-week period. Also, Mawson & Cunnington (1995) showed that the development of skin spot in a susceptible variety (Cara) was inversely proportional to the amount of accumulated day degrees above holding temperature. Expressed another way, an immediate pull-down of 0.5°C/day to the holding temperature resulted in significantly more skin spot than tubers that had been cured for 1- and 2-weeks at 12°C. Therefore, a combination of curing and ventilating with dry air offers the best option for control of ware crops that are susceptible to skin spot and are being stored for long periods.

7. Store unloading

Once a crop leaves the store, there are technologies available that can monitor (see Section 4), as well as improve, the appearance of tubers. For example, rotary brush barrel washers (such as the Wyma Vege-Polisher) can increase the shine of a potato skin. The various technologies available for post-unloading treatment of potatoes are presented here. However, this topic will only be dealt with at a fairly superficial level because there are sensitive commercial issues involved that precludes the availability of information in the public domain.

7.1.1. Washing technologies

There are two main systems available for washing potatoes. These are: the rotary barrel brush machines and drum washers. The two washer types are similar in that a revolving barrel washes the potatoes in water. However, in rotary barrel brush systems, the barrel is formed out of brushes that provide some degree of skin exfoliation.

Work at the BPC's Sutton Bridge Experimental Unit (Stroud & Peters, Unpublished) showed that using a commercial drum washer for between 5 and 10 minutes could improve bloom by between 1.0 and 1.5 bloom units (Figure 9). This suggests that adverse effects of crop agronomy and storage can largely be reversed by washing. However, adverse effects on disease (e.g. soft rots), of abrasion following a lengthy washing process, were not investigated.

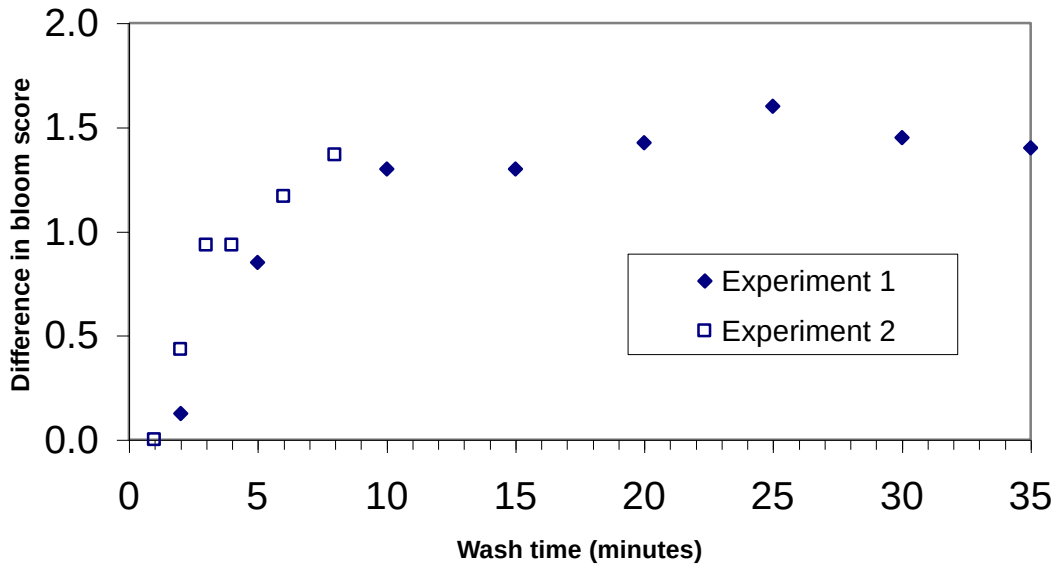

Figure 9. The improvement in tuber skin shine (bloom) with increasing wash time in a rotary barrel washer. Stroud & Peters (Unpublished).

7.1.2. Grading

See Section 4.

7.1.3. Packaging

Modified atmosphere packaging (MAP) and related technologies are increasingly used to extend shelf-life of fresh produce. In potatoes, self modifying atmospheric packaging using film with perforations of varying size and densities are claimed to help minimise greening, sprouting and deterioration caused by rots. However, data is difficult to obtain and, therefore, it is not possible to verify the claims from the film manufacturers regarding improvements of shelf life. However, work carried out by Gunes, Splittstoesser & Lee (1997) indicates that MAP had no significant effect on microbial populations on fresh potato slices compared to non-packaged samples. This suggests that any benefits of MAP in reducing spoilage in potatoes occur through (for example) better aeration rather than by directly reducing bacterial populations.

8. Future research priorities

A Skin bloom and blemish disease control: interactions of yield, tuber size distribution and economic return after storage.

Recent work (BPC project ref. 807/222) has improved the understanding of how to produce potatoes with a good skin finish. Length of growing season appears to be an important factor: there is a positive correlation between length of crop duration and severity of blemish diseases (especially black dot) and netting. Growing for best skin finish will have consequences for yield, tuber size distribution and economic return. The economic impact of these recommendations needs to be quantified. Also, immediate cooling after store loading was recommended for maintaining skin quality. However, the full implication of rapid cooling during early storage on rot diseases needs to be fully determined.

It is envisaged that cost/benefit studies will mainly utilise commercial crops as well as small-scale field and storage trials for investigating relationships between season length, harvest date, yield, tuber size distribution and crop value.

B Quantifying the effect of soil texture on potato skin finish.

It is known within the packing industry that skin finish is best on tubers grown in silt or clay soils compared with more abrasive, sandy soils. The phellem appears to be thicker on tubers grown in more abrasive soils, with detrimental consequences for good skin finish. There seems little doubt that skin finish is related to soil texture, but experimental work is required to establish a detailed relationship. This would allow location of packing crops to be decided more objectively than at present.

C Quantifying the effect of nutrition on potato skin finish.

Previous work indicates that skin thickness is influenced by nutrition and that skin thickness is related to skin appearance. For the benefit of growers and packers, these relationships need to be characterised in crops grown on soils suitable for high quality pre-pack crops.

D Quantifying the effect of barrel washers and skin polishers on potato skin integrity and consequent implications for short-term storability.

It is well recognised within the industry that polishers do indeed improve the appearance of pre-pack tubers. However, anecdotal evidence (S. Bowen, Solanum Ltd, Personal Communication) suggests that excessive polishing can disrupt the integrity of the tuber skin, potentially leading to breakdown in packed potatoes. The effects of washing on tuber skin needs to be measured, with a view to providing practical recommendations on correct washing procedures. In addition, research needs to address the problem of breakdown following washing. In particular, investigations are needed to determine which disinfection and drying systems (perhaps coupled with erwinia monitoring) are best suited for minimising breakdown losses.

E Knowledge transfer: a decision tree for optimal skin finish of potato crops for packing.

The results of this review and previous work would be used to develop a grower guide for best skin finish, applying the best current knowledge. There are options for doing this in a number of ways. For example, workshops, interactive CD, booklet, A3 guide etc.

9. Acknowledgements

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11. Glossary

bloom	the shine of the skin surface
cortex	parenchyma tissue surrounding the vascular tissues
epidermis	specialised, outermost layer of cells, one layer of cells thick
excoriation	injury to the tuber surface, through peeling of the skin
lenticel	small, corky pore on the surface of the stems of woody (usually) plants
meristem	localised region of active cell division
netting	a network of fine cracks or fissures in the outer layers of the phellem
parenchyma	tissue consisting of living, thin-walled cells, permeated by a system of intercellular spaces containing air
periderm	a specialised protective layer, made up of three types of cells: the phellem (cork), the phellogen (cork cambium), and the phelloderm
phellem	corky outer layer of the periderm, sometimes referred to as skin
phelloderm	layer of cells inside the phellogen
phellogen	cork cambium, a layer of cells that divide to produce phellem and phelloderm cells
stoma (plural: stomata)	pore in the epidermis
skin, tuber	See ‘phellum’
suberin	a hydrophobic polymer composed of phenolic and aliphatic compounds

12. Annex 1. Example Quality Control Charts.

Chart 1, brightness; Chart 2, netting; Chart 3, black dot.

BRIGHTNESS SCORE

1

2

3

4

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Photo Specifications
Netting Evaluation Chart

Level 1

Level 2

Level 3

Level 4

Level 5

Level 6

Level 7

Level 8

Photo Specification
Silverscurf/Blackdot Evaluation Chart