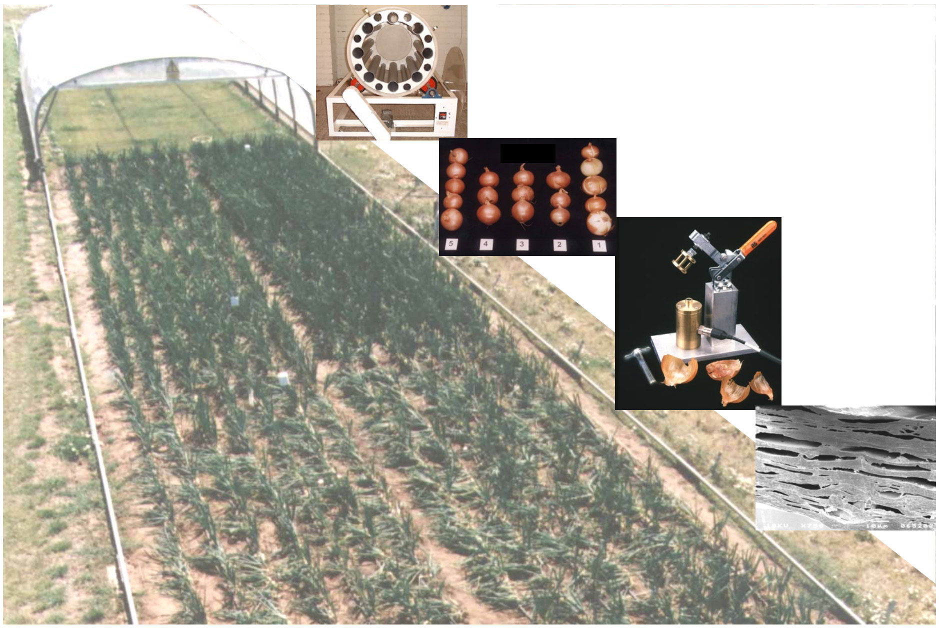

Final Report **(FV 110a)**

The impact on onion skin quality of bulb and skin development.

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AUTHENTICATION

I declare that this work was done under my supervision according to the procedures described herein and that this report represents a true and accurate record of the results obtained.

Signature ....

Dr D Gray

Head of Crop and Weed Science

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Date.............................

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PRACTICAL SECTION FOR GROWERS

Objectives and background

The principal objective of this project is to provide information that will lead to an improvement in the resistance of onion bulbs to skin damage.

Appearance of onions in retail is of great importance. A survey by the British Onion Producers Association (BOPA) showed that 9 out of 10 customers regarded the condition of the skin as an important criterion in deciding whether to purchase onions. Leading retailers also report poor sales when skin quality deteriorates. Poor quality is represented by skin cracking and puncturing, skin loss, particularly where this leads to exposure of underlying fleshy scales, and soft outer bulb scales. These characteristics usually worsen with time in store. This may depress prices of the UK product and make it less competitive if better quality is available in imported produce. It is likely that good visual appearance and skin quality have contributed to the increase in imports from Australia, New Zealand and Chile over the March to July period, when the stored UK crop becomes less presentable. These imports amount to more than 20% of national onion consumption. Quality in this instance is defined only by the degree of splitting and exposure of underlying flesh. Staining and skin colour are not considered.

This project was designed to reveal the importance of conditions during growth of the crop to subsequent skin quality. Manipulation of factors such as water and nitrogen fertiliser application has been used to influence bulb growth rate and, potentially, skin characteristics. Their effects have been compared with those of variety, maturity and storage time. The study indicates how these effects on the quality of raw material are carried over into store and to the consumer.

The problem of skin damage has been addressed by examining physical characteristics of skins and the relationships between these and skin damage/peeling losses. By measuring skin characteristics we hope to understand why bulbs from particular backgrounds vary in their susceptibility to skin damage. Skins are likely to be more susceptible to damage if they are stiffer and/or weaker. A skin that stretches well and which will bend more easily is less likely to crack. Similarly if it is strong, it will break less readily when it is bent or stretched. Thickness and water content of skins are likely to be related to these mechanical characteristics.

Summary of Results

1. **Overall quality was determined by damage assessment (based on a commercial system) after a "drum rolling" test. Skin quality in this context is affected by both environmental and genetic factors. The effect of cultivar was much more consistent and larger than that due to environmental manipulation.** Better quality was associated with:
   - **choice of cultivar** (cv. Hysam better than cv. Crossbow)
   - **earlier harvest** (in mid- to late August compared with mid-September)
   - **lower rate of nitrogen** (60 kg ha^{-1} compared with 120 kg ha^{-1})

2. **From a survey of commercial onions subjected to the "drum-rolling" test, better retention of overall quality in store was associated with bulbs from sandy soils rather than peat soils.**
   - In this same study, there was an indication that **quality declined with higher nitrogen application.**
   - Other variables such as irrigation, variety, harvest date and total rainfall showed little association with quality.

3. **Skin strength, stiffness, thickness and moisture content are also affected by treatments**.
   - **Cultivar had** the largest effects on these variables, with cv. Hysam possessing thicker, stronger skins than cv. Crossbow. Hysam's inner skins also retained more moisture. This effect is consistent with that of variety on overall quality in the drum-rolling test.
   - **Later harvest**, when leaves had senesced, resulted in stronger, thicker skins with higher moisture content, than earlier harvest when leaves were still green
   - **Higher nitrogen** was also associated with stronger, thicker skins
   - These environmental effects (harvest and nitrogen) are in fact the opposite of what was found for overall quality from drum testing.

4. **The environmental history of plants and of individual leaves had minor influences on skin properties**.
   - Both nitrogen application rate and water availability had large effects on yield, but only small effects on skin thickness, strength and stiffness.
   - Complete removal of a leaf blade did not affect the strength of the skin subsequently formed from that leaf base and decreased its thickness very little.

5. **Variation in skin quality between samples of bulbs from the different treatment backgrounds was strongly related to the number of skins per bulb and to skin thickness, particularly that of the outer two skins**.

6. **Relationships between mean skin quality and mean skin strength were variable.**

   For treatments in 1998, there was little relationship, but for different cultivars in 1997 a significant relationship was evident.
   Similarly skin stiffness and moisture content showed little relationship with skin quality in 1998.

7. **There was a strong relationship between the mass per unit area of individual skins and their strength. This accounted for many of the effects of treatment factors.**

8. **Much of the variation in skin characteristics was due to variation between individual bulbs and skins rather than between collective samples of bulbs from different blocks, treatment plots, storage times and years. This suggests that there is still much that we do not understand about the processes involved in skin formation and how these determine skin quality.**

9. **There was a strong relationship between moisture content of individual skins and their stiffness. This accounted for many of the effects of treatment factors.**

10. **The mechanical properties of "dry" skins can be altered by the humidity of their environment. Skins from very humid conditions are stronger and more flexible than those from drier backgrounds**.

Knowledge transfer, Exploitation and Action points for growers

Knowledge Transfer

1. A poster exhibit illustrating the work is planned for a BOPA (British Onion Producers Association) meeting on September 7, 2000 organised by D O'Connor and for a VEGEX show on 13/14 September 2000 which will highlight other HORTLINK projects.

2. The work will be presented at a 'platform' session at the BOPA conference in 2001.

3. An HDC Factsheet will be prepared and distributed by HDC Communications early in 2001

4. Two scientific papers will be prepared from the work for December 2000. Agreement of the Consortium will be obtained prior to submission.

    i) The effects of variety and agronomic practices to influence leaf growth rate on skin quality.

    ii) Relationships between skin quality and skin physical properties.

    Both will be submitted to Journal of Horticultural Science and Biotechnology.

Exploitation

Potential routes for exploitation of the research and for developing practical benefits to growers fall into four areas; varieties, production, storage and techniques.

Varieties
The results of the work on the main crop types of onion have shown that genotype is the predominant factor influencing skin quality following storage. Environmental and cultural influences examined in this study are significant but are less important.

- Selection for good skin quality in breeding programmes will be the most effective means of improving skin quality. Some of the techniques, developed in this programme, for assessing whole bulb quality and measuring skin physical characteristics could be used to improve plant breeding selection procedures and variety trialling (see below).

ACTION - HRI will follow this up by a meeting between the Consortium with onion breeding companies to outline the opportunities to them. The meeting is planned for Autumn 2000.

- There was a sufficiently good correlation between consumer evaluation of skin and bulb quality following commercial procedures and 'drum-rolling' tests to suggest that growers could use the drum technique to evaluate varieties.

- As the environmental effects were relatively small compared to genotype in affecting quality, assessment of skin quality amongst genotypes could be made at one site. However, before this approach could be recommended 'on-farm' trials would need to be carried out and there is a need to extend the work to other groups of onions.

ACTION - HRI will demonstrate to Consortium members (in particular Bedfordshire Growers and Rustler Produce ((Sainsbury nominated growers)) how to conduct 'Drum' tests for skin quality. HRI will make available technical drawings of the Drum in September 2000.

If 'on farm' testing is feasible the nominated growers will use a drum constructed by them for their own 'in-house' variety trials.

HRI in discussion with NIAB (M Day) will identify how the 'Drum' test can be used to assess skin quality in HDC/UKASTA funded variety trials relating this to the specific skin weight and to test for genotype x environment interactions. These discussions, to be conducted in autumn 2000, are likely to lead to the development of a proposal to HDC from HRI and NIAB to extend the scope of onion variety trialling. This approach will need to be discussed at an appropriate BOPA R&D meeting.

Production

- There was evidence from tests on commercial crops that skin quality as assessed by the 'drum test' was maintained in store for longer by growing crops on mineral as opposed to organic soil (confirming industry experience). This was not addressed systematically in the project and might well represent an important source of environmental variation in quality.

ACTION - HRI to discuss with the Consortium the need for further work in this area funded directly or by HDC with a potential start date of 2001.

- The current advice to the industry based on HRI work of several years ago is not to apply high rates of N especially late in growth of the crop. However, there is evidence from this work that later N application can influence skin strength. In view of the variable response further work using a number of different rates and timings is required.

- Harvesting bulbs after leaf senescence gave stronger, thicker skins than harvesting earlier when collapsed leaves were green. This needs to be quantified in more detail to assess whether there is scope to modify practice in the 'harvest' period of growth to improve skin quality and if so, how large the improvement would be.

ACTION - There was insufficient evidence that the effects, though significant were large enough to warrant a change of practice by growers at this stage.

Storage

- There is potential to obtain better skin quality by enhancing skin moisture content during handling. Moist skins are more pliable and less prone to damage and shedding.

ACTION - Bedfordshire Growers (a Sainsbury nominated grower) will assess the scope for modifying store and packhouse relative humidity to change skin moisture content and hence skin 'flexibility' during the handling and grading phase.

Techniques

- A range of techniques for measuring skin strength, stiffness, water vapour and O_2/CO_2 exchange through skins have been developed for the first time.

ACTION - These could be exploited in further research on onion skins and directly by the industry especially in assessing the suitability of varieties for CA storage. Further discussion will take place with BOPA initiated by HRI. Drawings of equipment can be made available to Consortium members on request.

- The 'drum test' (see above) could be exploited to assess differences between varieties in skin quality.

- Skin dry weight per unit area correlates well with other skin physical characteristics. Based on this, a rapid test could be developed for use by breeders to select for desirable skin properties. This would need to be exploited in co-operation with breeding companies (see above).

ACTION - There is a need to investigate whether micro-wave or other rapid drying tests would improve efficiency. Seed companies to be approached for funding (see above).

Although the study has emphasised the importance of variety over environmental influences, it should be noted that the post-harvest environment through to drying and curing of skins was not a part of this project. However, this phase could also contribute substantially to variation in skin quality and there is a need for further R&D to assess the interaction between 'physiological state' of material at harvest in relation to curing and the early storage environment.

Assessing the value of the work

Sainsbury would be able to provide information by analysis of QA records of skin quality as they operate a 1-4 scale for quality. These samples could be made available for produce at the start and completion of the project and at stages following completion, though the retrieval of the information would incur a cost.

Action points for growers

- Variety choice is the most important factor influencing skin quality for material cured and stored under Industry protocol conditions. The work has shown how new techniques could be used to improve selection for better skin quality in breeding programmes and for improving discrimination in these characters in official and 'on-farm' variety trials.

- Environment of production appears to be less important in contributing to differences in skin quality though bulbs grown on mineral soils maintained their quality in store better than those grown on peat soils.

- There were major effects of nitrogen application rate and irrigation on leaf growth and bulb yield. Whilst there were also significant effects on skin quality they were insufficient to warrant a change in current practice. For example, although 120 kg ha^{-1} of N gave tougher skins than 60 kg ha^{-1} of N and later harvesting also gave tougher skins, adopting high rates of N and delaying harvesting would present a high risk for securing the crop for storage.

EXPERIMENTAL SECTION

Introduction

A survey by the British Onion Producers Association (BOPA) showed that 9 out of 10 customers regarded the condition of the skin as an important criterion in deciding whether to purchase onions (HDC, 1993 and Love, 1995). Leading retailers also report poor sales when skin quality deteriorates. Undoubtedly, poor quality resulting from skin cracking and puncturing, loss of skins, and soft outer bulb scales may depress prices of the UK product and make it less competitive if better quality is available in imported produce. It is likely that good visual appearance and skin quality have contributed to the rapid increase in imports from Australia, New Zealand and Chile over the March to July period, when the stored UK crop is becoming less presentable. These amount to more than 20% of national onion consumption.

No published information has been found on the factors that affect formation of skins, their development and physical properties. Skin loss is greatest in bulbs with thin skins. These have lesser tensile strength than thicker skins (Tanaka *et al*., 1985). This loss is associated with:

i) vertical cracking resulting from mechanical shock or humidity-initiated changes in shape during storage,

ii) expansion of root initials, which takes place during loss of dormancy.

Tanaka's study showed good correlation between degree of peeling and skin strength, both of which are under genetic control. However, skin strength also varies between site and season (Knott, 1933) indicating that it may be influenced by environmental factors, including crop nutrition. Unconfirmed reports indicate that larger numbers of skins and thicker skins may be associated with softer bulb scales. This condition can lead to watery scale and to misshapen bulbs which give rise to loose fitting skins after a period of storage.

Outer skins also contribute indirectly to internal quality by affecting moisture loss from the bulb and hence bulb firmness. Weight loss and respiration is greater in bulbs with thin skins than in those with thicker and more skins (Apeland, 1969). The quantitative role of onion skins in determining permeability to gas and water vapour is not known. Similarly there is no knowledge of how differences in skin properties affect permeability and storage potential.
A study funded by HDC (FV110) showed that skin damage and loss increased as bulbs moved from the field through the storage, handling and retail chain. It also showed that the level of loss and damage at point of sale reflected the initial level of damage after harvesting. It was not clear from these data which factors during cultivation and harvest contributed to initial differences in 'skin quality' because different varieties and cultural methods were used.

The objectives of this study (as stated in Schedule 1 (Revision 1) were:

1. To establish the origin and development of onion skins in varieties with contrasting thickness and number of skins. [Conclusions 1, 2 and 3]

2. To quantify the relationships between skin strength, skin thickness and cell dimensions as they are affected by variety, nitrogen, water. [Conclusions 4 to 14]

3. To measure the forces required to compress the mature bulb and bulb scales relating this to tissue water status and cell dimensions. [Conclusion 15]

4. To identify the effect of varietal and cultural factors in 2) on onion skin qualities for samples subjected to commercial treatment in storage and in handling during grading and retail chain. [Conclusions 16 and 17]

5. To quantify the permeability to oxygen, carbon dioxide and water of skins of different physical characteristics and thickness. [Conclusions 18 and 19]

Conclusions

Objective 1: To establish the origin and development of onion skins in varieties with contrasting thickness and number of skins. [Conclusions 1, 2 and 3]

The purpose of this objective was determine whether the developmental sequence of leaves giving rise to skins contributed to differences in numbers of skins and skin thickness between varieties. Broadly this was not the case.

1 **In any year, the position of skin-forming leaves in the developmental sequence was not affected by genetic background. There was an indication that a lower input of water might result in skins being formed from bases of earlier leaves.**

2 **In different years, leaf bases of different number in the developmental sequence gave rise to skins in the stored bulb** (Table 1)**.**
   - In 1997 and 1999 when tissue was weaker, skins arose predominantly from “lower” leaves; 5 and 6 in 1997 and 6, 7 and 8 in 1999.
   - In 1998, when skins were stronger, they were derived from leaves 7, 8 and 9.
   - It is possible that the bases of earlier-formed leaves generate skins that are not as resilient as those from later-formed leaves. This requires further investigation.

3 **However, the history of individual leaves has only a minor influence on skin properties.**
   - Complete removal of the leaf blade did not affect the strength of the skin formed from the corresponding leaf base. There were minor effects on the thickness and moisture content of the skins (see Results text for the field experiment in 1998). Thus a fairly drastic event during leaf development had little consequence. This was unexpected in view of anecdotal reports of dramatic effects of leaf infection and associated damage on subsequent skin quality. The processes affected or induced by infection may be quite different from mechanical removal.

Objective 2: To quantify the relationships between skin strength, skin thickness and cell dimensions as they are affected by variety, nitrogen and water. [Conclusions 4 to 14]

In order to achieve this objective, effects of variety, nitrogen and water were examined. From these data, relationships were established between the various skin characteristics at an individual skin level, where measurements on the same skins were possible, and between means for samples of bulbs where paired measurements on skins were not possible.
The number of skins on a bulb is an important feature of quality. More skins generally means that outer skins are more readily expendable during handling after storage. Thicker skins are likely to be stronger which means they should withstand the rigours of handling. Flexibility of skins is also important. Skins that stretch more easily and further before breaking, even if they are weaker, are likely to be less prone to fracture.

4 **Numbers of skins varied with variety and between years** (Table 2)**.**
   - There were fewer skins on bulbs of cv. Crossbow than cv. Hysam in experiments done in 1997 and 1998, but more in 1999.
   - Skin number was not markedly or consistently altered by water availability,

nitrogen application rate, harvest at different maturities or storage time.

5 **Characteristics of skins, such as strength, stiffness, biological mass per unit area (specific dry weight), thickness and water content were all affected by environmental and genetic factors** (see Results text on "skin characteristics" and Tables 3 to 7).

- Generally it can be concluded that imposed environmental treatments during growth had smaller effects on these characteristics than did genetic influence.
- Changes in store were also relatively small and not unexpected. For example, inner skins became drier and thinner with time in store (Tables 5, 6).
- Differences between cvs Hysam and Crossbow were generally more significant than those due to other experimental treatments. Skins of cv. Hysam were usually stronger and thicker than those of cv. Crossbow and had greater mass of biological matter per unit area (skin specific dry weight. Tables 3, 5, 7).
- Variation in properties between skins developing from different leaves was also large. This was principally a result of the skin's position within the bulb and its developmental state. Inner skins were generally more flexible with higher moisture content and thus were thicker (Tables 4, 5, 6).
- Moisture content is not the only reason for variation in skin thickness. Even "dry" skins vary in thickness, as revealed by their specific dry weight, which was greater for outer skins and declined with skin position towards the fleshy scales. However, inner skins in cv. Hysam were just as resistant to fracture as outer ones. In cv. Crossbow there was a small decrease in strength with skin position.
- Much of the variation in these skin characteristics was associated with differences between individual bulbs and skins rather than at the level of samples from different years, blocks, treatment plots, storage and harvest times.

6 **It is well known that availability of nitrogen in the soil has marked effects on leaf growth. For this reason it was anticipated that nitrogen fertiliser supply might affect onion skin properties and thus quality. Nitrogen application rate (in experiments) affected skin strength only in 1999, when higher rate led to increased strength. It affected skin thickness and skin specific dry weight in the same way. Bulb yield was increased by greater nitrogen supply in both 1998 and 1999** (Tables 3, 5, 7 and appendix 3)**.**

- The effects of nitrogen on bulb yield illustrate that nitrogen application was effective in both years. Nitrogen clearly can influence skin properties, but the effect is variable.
- In view of the correlation between quality scores for each treatment plot and mean skin thickness (see Conclusion 12 below), there are environmental factors other than nitrogen which affect skin properties and are likely to influence quality.
- It is important to note that higher rate of nitrogen application improves skin characteristics which would be expected to lead to better quality. However, lower rates of nitrogen were associated with better quality from assessments of overall quality.

7 **The stage of development and senescence of leaves at the time plants are**

removed from the soil, may have a profound effect on the subsequent development of their leaf bases into skins. Time of harvest may therefore influence skin quality. Harvesting bulbs after leaf senescence resulted in more favourable skin properties than earlier harvest when collapsed leaves were still green (Tables 3, 5, 6, 7).

- Later harvest resulted in stronger skins after 3 months storage than earlier harvest.
- Bulbs harvested at this later stage possessed skins that were thicker, irrespective of position on the bulb.
- Later harvest resulted in bulbs with inner skins that contained more moisture, more mass per unit area and were less stiff.

8 **It is well known that onions are shallow rooting and respond well to a plentiful supply of water. Since this will have a dramatic effect on plant growth, it was expected that manipulating water supply would affect skin characteristics. Water availability to the plants during growth had a very small effect on the moisture content of inner skins, but no marked effect on any other skin property** (Tables 4, 6, 7)**.**

- Plants not sheltered from rainfall and supplied with plentiful irrigation had more moist inner skins after long-term storage than sheltered, infrequently watered plants.

9 **Variation in skin stiffness between factors was almost entirely accounted for by variation in skin moisture content** (Table 9, Figure 2)**.**

- Decreasing stiffness with skin position was mostly described by differences in moisture content, though a small residual effect of skin position remained.
- Effects of cultivar and harvest were entirely accounted for by differences in skin moisture.
- This is an important observation, because it increases awareness of the importance of not over-drying the bulb and emphasises the value of exposing the "younger, fleshier", inner skins at as late a stage as possible.

10 **Mechanical properties of "dry" outer skins can be altered by the concentration of water vapour in the surrounding atmosphere, which increases skin moisture content** (Tables 10, 11)**.**

- Skin strength was increased and skin stiffness decreased by exposing mature, dry, outer skins to high humidity. This finding indicates practical possibilities for conditioning skins during handling and processing. Although there was not a good correlation between overall skin quality and our measurements of strength or stiffness, it is difficult to believe that a stronger more flexible skin would not contribute to improved maintenance of quality.
- This observation provides an additional strategy to the one noted in Conclusion 10, that the loss of moisture and thus flexibility can be reversed.

11 **Much of the variation in skin strength between factors was accounted for by variation in skin specific skin dry weight** (Figure 1, Table 9,).

- The method of measuring skin strength by burst testing does not take into account the thickness of skins, so it is to be expected that skins with more biological mass per unit area will be stronger.

- This relationship between strength and skin specific dry weight entirely accounted for the differences between cvs Hysam and Crossbow in 1998 and 1999 and for most of the cultivar effect in 1997.
- It explained differences between skins within bulbs in 1997.
- The greater strength of skins from bulbs harvested later in 1998 was not described by specific skin weight.
- These results clearly demonstrate that the amount of structural cell material concentrated into a fixed area of skin has a marked effect on its resistance to fracture. It is related to the thickness of skins, but this latter measurement is also affected by the moisture content of the skin, particularly of young skins that are still losing moisture from the cellular interior. Skin thickness is also quite difficult to measure accurately without resorting to microscopic examination. Specific skin weight is more easily measured and integrates over the area of the material sampled. Measurements of skin thickness do not.

12 **Overall skin quality is strongly related to the number of skins, skin specific dry weight and skin thickness for data from experiments in 1998 and 1999. For this same set of data, relationships with skin strength and stiffness were less significant and associated with inner skins only. In 1997, relationships between quality and strength were better.**

- Forty-eight samples representing the entire range of experimental treatments in 1998 showed strong correlation with the number of skins, skin specific dry weight and thickness of skins 1 and 2 (Table 15, Figure 4). Since bulbs of acceptable quality must have two skins, it is self-evident that some relationship with numbers of skins will occur. However, the relationship is constructed from measurements on different samples of bulbs, so our sampling procedure was effective. More importantly, the trend appears to be present across the entire range of skin numbers and not just associated with the lower end from one skin to two. Thus quality would seem to be better for three-skinned bulbs than for those with two skins. The significant association of quality with skin specific dry weight suggests that this could be used as a screen for breeding purposes. The highly significant positive correlations of quality with mean skin specific dry weight and skin thickness (particularly skins 1 and 2) is notable in relation to the low significance of relationships with skin strength, stiffness and moisture content. It is also interesting in view of the significant correlations between strength, stiffness and thickness on an individual skin basis.
- For the four cultivars examined in 1997 (Crossbow, Durco, Hysam and Sherpa) skin quality was strongly associated with skin strength (see text associated with Figure 5) and skin thickness (Figure 5).

13 **The thickness of skins and the amount of dry matter per unit area of skin must be determined by the underlying cellular structure. Cell size and the number of cells contributing to skin thickness were not affected by any treatment factors** (Table 12)**. It is therefore likely that these properties are more dependent on cell wall thicknesses and other material that may be synthesized during skin formation than on the number of cells and their sizes during growth.**

14 **Bulb size had a small influence on overall skin quality but was related only to**

differences between years in skin characteristics (Table 8)**.**

- Although associated with bulb size, differences between years in measured skin characteristics (not overall quality) may not have been caused by differences in bulb size. These may have resulted from a common factor that affected all variables.
- The desirable commercial size range for pre-packed onions is 60 - 80mm diameter (now increasing to 65 – 85mm). For many reasons, size may influence susceptibility to damage. In this work, we have attempted to use bulbs approximating to this range. For practical reasons, such as limited availability of bulbs from experimental plots or the effect of experimental treatments, bulbs outside this range have been used. The effect of treatments also introduces size-biased influence. Although such influences can confound the results of experiments, they can also be advantageous. In the statistical techniques applied, bulb size was included as an additional covariate or regression variable and its influence examined. The significance of nitrogen and harvest time on the proportion of acceptable bulbs (overall quality) was significantly decreased by the inclusion of bulb size, whereas that of variety was unaffected.

<u>Objective 3: To measure the forces required to compress the mature bulb and bulb scales relating this to tissue water status and cell dimensions. [Conclusion 3]</u>

15 This objective proved to be inappropriate in relation to skin fracture. Expansion forces from the bulb are not a source of stress that leads to skin splitting. Splitting is more a consequence of impact damage and movement of the base plate during dormancy break in late storage. The original hypothesis underlying this objective was based on analogy with carrot splitting and potato bruising, both of which are dependent on tissue water relations and internal generation of forces and their dissipation. In onion skins, inherent mechanical properties such as resistance to fracture and compliance (reciprocal of stiffness) were found to be much more important. Tension in fresh onion bulb scales can be demonstrated by cutting through the outer layers of flesh and observing the resulting gape of the tissue. However this tension dissipates readily with moisture loss from the fleshy scales and thus is a diminishing force with time in store. Also, individual scales retain much of their own tension rather than exporting it to outer skins.

<u>Objective 4: To identify the effect of variety and cultural factors on onion skin qualities for samples subjected to commercial treatment in storage and in handling during grading and retail chain. [Conclusions 4 and 5]</u>

In addition to measuring the characteristics of skins which are likely to benefit overall skin quality in terms of splitting, it is important to measure overall quality in a way that is comparable with commercial handling and assessment. This was done using a drum-rolling test. This was designed to simulate commercial handling situations. Samples from experiments and from commercial sources were tested in this way.

16 Differences in skin quality between varieties and between samples from different commercial sources of bulbs can be determined using a specially-constructed drum which caused damage by simulating conditions experienced during commercial handling (Appendix 4 Figure 4).

- Relationships between quality assessment (QA) from this procedure and QA after the bulbs had been subjected to commercial handling were statistically significant, but not as close as had been hoped for.

17 **The quality of onion skins is clearly affected by both environmental and genetic factors** (Tables 13 and 14).

- Skin quality, assessed after damage in the drum simulator, was better for cv. Hysam than cv. Crossbow, in both 1997 and 1998 experiments.
- Other cultivars, Sherpa and Durco, also produced bulbs that were more resistant to damage than Crossbow in 1997.
- Varietal differences in quality were much greater than differences between treatments such as nitrogen fertiliser rate, water availability and harvest date applied in experiments.
- The effect of duration in store was inconsistent between years: an improvement with time in store in 1997, but no change in 1998.
- In a survey of commercial sources of bulbs, deterioration in quality in store was greater for those sites that were based on peat soils compared with sandy ones.
- In this survey, the only other variable that showed any relationship with skin quality was the amount of nitrogen fertiliser applied. This ranged from 43 to 185 kg ha^{-1} and the analysis suggested that quality was better at lower nitrogen. [Contrast this with effects of nitrogen on skin characteristics.]

18 **Conclusion 12 (above) on the relationship between overall quality and skin characteristics is also relevant to this objective.**

<u>Objective 5: To quantify the permeability to oxygen, carbon dioxide and water of skins of different physical characteristics and thickness [Conclusions 17 and 18]</u>

Exchange of respiratory gases and water vapour between bulb scales and the surrounding atmosphere may have a profound effect on bulb quality. The rate of water loss will affect shrinkage and turgidity of bulbs. It is also thought to be important in the occurrence of translucent skins (watery scale). While it has been demonstrated that exchange can occur through the neck and base plate, the importance of movement directly through skins has not been investigated.

19 **Permeability of onion skins to water vapour and respiratory gases is extremely variable and no effect of cultivar or environmental treatment in the experiments was found.**

- A range of rates, varying tenfold from minimum to maximum, was measured.

20 **Inner skins are less permeable to water vapour than outer skins, but permeability is not related to skin thickness** (Table 16, Figure 6)**.**

- It was expected that skin permeability would be related to skin thickness. That it is not may reflect the fact that onion skins have a complicated heterogeneous structure. The presence of pores and/or micro-fractures could facilitate the passage of gases and vapours irrespective of thickness. Chemical components comprising variable fractions of skins could provide variable barriers to the passage of vapour. Although moisture loss is known to occur through the necks of bulbs, the importance of gaseous transfer directly through skins and its implications for skin quality have not been characterised.

Results and Discussion

<u>Objective 1: To establish the origin and development of onion skins in varieties with contrasting thickness and number of skins. [Conclusions 1, 2 and 3]</u>

1. Identity of skins at harvest with order of formation of leaves

There were no significant differences between any treatments in the mean number identity of the leaf base forming the first entire skin at lifting in September or after storage until December. There was a significant increase in the mean leaf identity of skins, between lifting and sampling after storage until December (Table 1) consistent with loss of skins during storage. There was a suggestion that this loss was affected by sheltering plots. The increase in skin identity was greater for bulbs from sheltered plots than those from unsheltered plots. A better analysis might be to examine the frequency with which particular leaf bases occur, but inspection of the data suggest that this is unlikely to alter any conclusions which might be drawn from analysis of variance. In 1999, mean leaf identity of the outermost skin was 6.3 and, as in 1998, there was an indication that withholding water resulted in the first skin being formed from an earlier leaf (Table 1). This only reached significance at 10% probability. For 1997, when the crop was sown (not planted as in 1998) mean leaf identity of the outermost skin was lower (5.5).

Table 1. Identity of outermost skin as leaf number in order of formation. Field experiment 1998.

Water Availability	At lifting	After storage until December	LSD p=0.05
<u>1998</u>			
Sheltered	7.1	7.8	1.0 for comparison within same level of water treatment.
Unsheltered	7.5	8.0	
<u>1999</u>			
Sheltered		5.9	1.2
Unsheltered		6.6	

Note that if the difference between mean values is greater than the least significant difference (lsd, p=0.05), then they are significantly different at 5% probability level. Applies to all tables.

2. History of individual leaves: effect of removing leaf blade 7 on skin properties

Leaf blades were removed from some plants of each plot in the main experiment in 1998. This was done on 13 July when the leaf was well developed. The purpose of this treatment was to determine whether subsequent skin formation of the leaf base would be affected.

There was no effect of this treatment on skin strength (control: 1.17 MPa versus "clipped": 1.29 MPa, LSD (0.05) = 0.171). The thickness of skins was slightly greater in control bulbs (0.044 mm) than "clipped" bulbs (0.034 mm, LSD (0.05) = 0.0069). Skins developing from clipped leaves had a slightly greater water content (19.3%) than those whose leaves were not removed early (15.0%; angular transformed means are 25.7% vs 22.6%, LSD (0.05) = 1.52). These results were determined from "t" tests of bulbs from all treatment plots. Analysis using REML (see Materials and Methods section 13), which separated variances associated with the designed structure of the experiment, confirmed only the effect on water content.

Objective 2: To quantify the relationships between skin strength, skin thickness and cell dimensions as they are affected by variety, nitrogen and water. [Conclusions 4 to 14]

3. Skin characteristics

Measurements of skin strength (burst pressure), stiffness (modulus), thickness, mass per unit area (specific skin dry weight) and moisture content were recorded. For practical reasons, burst pressure and stiffness were measured on skins of different bulbs. Thickness, moisture content and numbers of skins were measured on all of these bulbs. Specific skin weight is only available for bulbs used for burst pressure measurement. In the following description of the results, important effects only are dealt with. If a factor is not mentioned, then it had no significant effect. Most of the random variation in these variables is between bulbs and skins with a much smaller proportion attributable to different years, field blocks, plots and sampling. For example, for burst pressure 7% of the variance was associated with year, block, sub-block and plot, while 38% was due to variation between bulbs and 55% to variation between skins.

3.1. The **number of skins** on bulbs is likely to determine whether a skin of acceptable quality is present after handling. This is the only characteristic which can legitimately be examined by analysis of variance for bulb averages since this is a true “bulb” variable. Other skin characteristics are affected by the number of skins and their locations (see Methods section 13 on statistical analysis). Skin numbers were significantly affected by:

- **cultivar**
- **year**
- **harvest time**
- **nitrogen fertiliser**

Table 2. Mean numbers of skins per bulb for factors having a significant effect.

Treatment	Year 1997	1998	1999
Cultivar			
Crossbow	2.1	2.0	2.7
Durco	2.5		
Hysam	2.5	2.3	2.4
Sherpa	2.4		
lsd (p=0.05)	0.14	0.17	
Harvest time			
August		2.3	
September		2.1	
lsd (p=0.05)		0.18	
Nitrogen			
lower rate		2.3	2.4
higher rate		2.1	2.6
lsd (p=0.05)		0.17	

The effect of cultivar was inconsistent. In 1997 and 1998, Hysam had more skins than the other cultivars, but in 1999 this was exceeded by cv. Crossbow (Table 2). In 1999, more skins were present on bulbs from plots with a higher rate of nitrogen, but in 1998 there were fewer skins at the higher rate. Harvesting bulbs at a later date when the leaves had senesced resulted in a greater number of skins. There was also interaction between the effects of nitrogen fertiliser, watering regime and storage time that made it difficult to draw any a useful conclusion about the effects of these factors (not illustrated).

3.2. **Burst pressure** measures the multi-directional resistance of skins to fracture. It was anticipated that this test should represent a skin characteristic that had an important bearing on susceptibility to damage. Burst pressure was significantly affected by:

- **year**
- **cultivar**
- **harvest time**
- **nitrogen fertiliser**

Skins formed in 1998 resisted pressure stress better than those formed in 1999 (Table 3). There was little difference in burst pressure between different skin positions on the bulb for cv. Hysam whose skins were consistently stronger than those of cv. Crossbow. For cv. Crossbow there was a slight, but significant decline in burst pressure towards the inner skins. This trend was also observed for the four cultivars in 1997, when skins from cv. Crossbow were the weakest. Hysam's skins were generally the strongest. A greater pressure was required to break skins from bulbs harvested later, when foliage had senesced and also for bulbs from plots that received greater nitrogen input. This latter effect was evident only in 1999, when skins were generally weaker.

Table 3. Mean burst pressures (MPa) for factors that had a significant effect.

Treatment	1997	Year 1998	1999
Year mean	1.20	1.50	1.20
lsd (p=0.05)		0.09	
Cultivar			
Crossbow	1.13	1.21	
Durco	1.34		
Hysam	1.47	1.49	
Sherpa	1.34		
lsd (p=0.05)	0.25	0.13	
Harvest time			
August		1.25	
September		1.45	
lsd (p=0.05)		0.08	
Nitrogen			
lower rate		1.47	1.06
higher rate		1.54	1.35
lsd (p=0.05)		0.08	

Data analysed as square root transformation, so errors are approximate

Generally, the position of skins in the sequence on the bulb was not significant. However, in the 1998 and 1999 experiments there was a small decrease (0.14 MPa) in burst pressure with position towards the inside of the bulb for cv. Crossbow. For cv. Hysam there was no such trend.
Mean burst pressure for skins from commercially produced bulbs (1.76±0.63 MPa) was slightly higher than for experimental material (1.34±0.12 MPa) and there were no significant effects of site, centre or duration in store.

3.3. **Stiffness** of skins should indicate the extent to which they can be bent or stretched before they fracture. Thus stiffer skins may break more readily - even if they are stronger. Skin stiffness was affected by:

- **skin position in sequence on the bulb**
- **cultivar**
- **harvest time**
- **water availability**
- **duration in store**

Skin position was of over-riding importance (Table 4). Outer skins were up to ten times more stiff than innermost skins (1900 MPa compared with 190 MPa). Inner skins of bulbs stored for six months (March) were stiffer (50-70%) than those stored for three months (December), so stiffness increased with time in store. These effects were consistent across years (1998 and 1999), so averages for each year have not been provided. Other significant effects were much smaller and are not illustrated in Table 4. For cv. Crossbow, inner skins were slightly more stiff (15-25%) than those of cv. Hysam. Inner skins were also more stiff (18-34%) from bulbs harvested earlier compared to those harvested later. Where water was withheld, inner skins were slightly less stiff (6-26%) than where water was readily available. There were no significant effects on the mean stiffness of outer skins.

Table 4. Mean stiffness for skins of different position after storage for different times. Data are from experiments done in 1998 and 1999.

	Stiffness ($\log_e$ MPa)	
Time from store	December	March
Skin position (from outside)		
1	7.56	7.49
2	6.45	6.89
3	5.23	5.76
lsd (p=0.05)	0.19	

Analysed as $\log_e$ of the stiffness modulus. Examples of proportional changes described in text are based on untransformed means.

The large effect of skin position and the increase in stiffness with time in store were also clearly evident in data from the comparison of varieties in 1997 (not illustrated). It would seem likely that these changes are dependent on changes in moisture content which also decreases for inner skins with time in store (see Results section 3.5.).

3.4. **Thickness** of skins should provide some indication of whether skins are more or less likely to fracture. In the burst test it is not corrected for. In measurements of stiffness it is included in the calculation, so stiffness should be independent of thickness. Skin thickness represents both the structural biological matter and water. In our data, there was in fact a stronger correlation between thickness and fresh weight per unit area (correlation coefficient, r=0.913) than thickness and dry weight per unit area (r=0.537). Thus estimates of thickness may reflect strength (conferred by structural mass), but they may also indicate flexibility (conferred by water content). The factors principally affecting skin thickness were:

- **cultivar**
- **duration in store**
- **harvest time**
- **year**
- **nitrogen fertiliser**

Skins of cv. Hysam were thicker than those of cv. Crossbow in the field experiments done in 1998 and 1999 (Table 5). This was also confirmed by observations from the comparison of cultivars in 1997. In 1998 and 1999 the difference between cultivars was greater for skins 2 and 3. In 1997, the effect of cultivar was present for all skins. Inner skins of bulbs that had been stored for six months were thinner than those stored for only three months. There was no difference for outside skins. Given the close relationship of thickness to fresh weight per unit area, this change is likely to be related to drying during prolonged storage. Inner skins were also thicker for bulbs harvested at a later stage (measured after three months storage only).
The effects of year and nitrogen showed interaction. Higher nitrogen input resulted in slightly thicker skins than lower nitrogen input in 1999 when skins were thinner.

Table 5. Mean skin thickness (mm) for factors that had a significant effect.

Treatment	Year 1997			Year 1998		Year 1999
Skin number	1	2	3	1	2	3
Storage time						
December	0.050	0.070	0.081	0.050	0.054	0.072
March	0.056	0.056	0.070	0.053	0.046	0.058
lsd (p=0.05)		0.0112			0.0058	
Cultivar						
Crossbow		0.062		0.046	0.041	0.052
Durco		0.075				
Hysam		0.086		0.058	0.060	0.081
Sherpa		0.072				
lsd (p=0.05)		0.0108			0.0081	
Harvest time						
August				0.053	0.045	0.060
September				0.050	0.055	0.069
lsd (p=0.05)					0.0081	
Nitrogen						
lower rate				0.058		0.048
higher rate				0.060		0.057
lsd (p=0.05)					0.0066	

Data analysed as $\log_e$ transformation, so errors are approximate.

There was no effect on the thicker skins formed in 1998. In fact year and nitrogen also showed interaction with water availability and skin position. However, the interaction

was small, very complex and difficult to explain in any simple way. It is therefore not described here.
For comparison with bulbs produced in experiments, mean thickness of skins from commercial samples was 0.07mm.

3.5. **Moisture content** of skins partly reflects their developmental state, in that younger inner skins usually are more moist than older outer skins. Moisture content can also vary with the atmospheric environment surrounding the skin. (See section 6 on humidification).
Factors that most affected skin moisture content were:

- **skin position in sequence on the bulb**
- **duration in store**
- **harvest time**
- **water availability**
- **cultivar**

Skin position was the single most important factor. All of the other factors interacted with this and their effects were smaller. As expected, moisture content is much higher in inner skins than outer skins (Table 6). None of the factors affected moisture content of the outer skins. Inner skins show decreased moisture content after storage for six months compared with three months. This would be expected as the skins dry out and bulbs lose water. This reflects the changes in thickness remarked on above (section 3.4). Inner skins contained less moisture, if harvested earlier when foliage was greener (measured after three months storage only).

Table 6. Mean skin moisture content (%) for factors that had a significant effect.

Treatment		Year 1997		1998		1999
Skin number	1	2	3	1	2	3
Storage time						
December	24	38	48	19	32	55
March	27	33	44	17	25	44
lsd (p=0.05)		2.2			3.8	
Cultivar						
Crossbow	26	33	44	18	26	47
Durco	25	35	47			
Hysam	25	38	49	18	30	51
Sherpa	25	34	44			
lsd (p=0.05)		3.8			3.3	
Harvest time						
August				18	25	47
September				19	31	51
lsd (p=0.05)					3.4	
Water availability						
Sheltered				19	26	47
Unsheltered				18	30	51
lsd (p=0.05)					3.3	

Data analysed as $\log_e$ transformation, so errors are approximate.

This effect also reflects changes in thickness. Inner skins from bulbs that received less water during growth (sheltered) contained less moisture than those supplied with ample water. Inner skins of cv. Hysam were more moist than those of cv. Crossbow. This latter observation corroborates the results from 1997. It may result from slower loss of moisture from Hysam because of its thicker skins. However, this conclusion is not supported by our measurements of skin permeability (see Results section 11.). More complex, higher order interactions between skin position, duration in store and water availability and between year, skin position, water availability and nitrogen were identified. These are not reported and described here, because they seemed to add little to the principal effects.

3.6. **Specific skin weight** (dry mass per unit area) represents the amount of structural material present in skins. If this is important, then it may prove more useful than thickness, which varies with moisture content and which is difficult to measure accurately. The following factors significantly affected specific skin weight:

- **skin position in sequence on bulb**
- **year**
- **duration in store**
- **cultivar**
- **nitrogen**
- **harvest time**
- **water availability**

Table 7. Mean skin dry weight per unit area (mg cm^{-2}) for factors that had a significant effect.

Treatment	Skin number 1	2	3
Year			
1998	5.5	4.6	4.7
1999	4.8	4.3	3.9
lsd (p=0.05)		0.51	
Cultivar			
Crossbow	4.6	3.8	3.4
Hysam	5.7	5.1	5.1
lsd (p=0.05)		0.45	
Storage time			
December		4.4	
March		4.9	
lsd (p=0.05)		0.38	
Nitrogen fertiliser			
Lower rate	4.6	4.2	4.2
Higher rate	5.7	4.7	4.3
lsd (p=0.05)		0.42	
Harvest time			
August	5.3	4.4	4.1
September	5.0	4.5	4.4
lsd (p=0.05)		0.20	
Water availability			
Sheltered	5.3	4.6	4.2
Unsheltered	5.0	4.3	4.4
lsd (p=0.05)		0.25	

Errors are approximate, because strictly each comparison requires its own error. However, those provided serve to illustrate significant effects.

The concentration of dry mass was greater for outer skins than inner skins (Table 7) and was greater for skins produced in 1998 compared with 1999.
In store, skin specific weight appeared to increase with time from December to March. This is difficult to explain since water loss should not affect it and skin loss ought to lead to lower specific weight. Cultivar differences were very large; as big as differences between skins. Hysam had much greater specific skin weight than cv. Crossbow, for which the decline with position towards the inner scales was greater than in Hysam. The effect of nitrogen was as large as that for cultivar. Higher nitrogen application resulted in greater specific leaf weight for the two outer skins.
There was a small effect of harvest in which the innermost third skin had greater specific weight for bulbs harvested later. This effect on the third skin was complicated by an interaction with nitrogen (not illustrated) which suggested that lower specific skin weight at the earlier harvest was associated with lower nitrogen input. From the later harvest specific weight of the third skin was unaffected by nitrogen. This suggests that the effects of nitrogen may not be straightforward. The effect of water availability was small and also not straightforward. Outer and middle skins from sheltered bulbs had greater specific weight than those from unsheltered bulbs, while for inner skins the effect was reversed. Essentially this means that there was a greater gradient of specific skin weight from outside to inside for bulbs which had received less water (sheltered) than for those which were well-watered.
Specific skin dry weight for commercial bulbs was 6.6 mg cm^{-2}; slightly greater than for bulbs from experiments.

4. Relationships between skin characteristics and bulb size

Bulb size may influence skin quality through associations with variation in skin characteristics. This was investigated by including bulb fresh weight, which is strongly correlated with bulb diameter (r=0.97), as a covariate in the statistical analysis. The effects of treatment factors on skin characteristics were then examined with and without bulb fresh weight. A decrease in the significance of a factor indicates that the covariate is associated with the effect of that factor (Table 8). Overall, there is not a good correlation between bulb fresh weight and any skin characteristic we have measured (r=0.23, for burst pressure, was the best).
The difference in numbers of skins between 1998 and 1999 was associated with the size of bulb (Table 8); larger bulbs in 1998 having fewer skins. Effects of variety, storage and nitrogen fertiliser on skin number were not related to bulb size. Similarly, for burst pressure the difference between years was associated with bulb size, but the effects of other factors (see Results section 3.2.) were not related. The overall poor correlation between burst pressure and bulb size would suggest that bulb size and burst pressure were smaller in 1999 because of common factors that affected them both rather than there being a direct influence of bulb size on skin burst pressure. This may also be true for numbers of skins. Effects of factors on skin stiffness were not influenced at all by variation in bulb fresh weight.
These observations are in broad agreement with those on the effect of bulb size on skin quality from drum testing (see Results section 8). There was little indication that size was related to any of the measured characteristics or that it affected the analysis in any way. Commercial interest is principally in bulbs between 60 and 85mm diameter. The absence of any major associations with bulb fresh weight suggests that the inclusion of bulbs outside this size range did not compromise the applicability of our observations to commercial material.

Table 8. Association of bulb fresh weight with effects of treatment factors on skin numbers, skin burst pressure and skin stiffness. [A decrease in the value of the statistic indicates an effect of bulb fresh weight.]

Variable Treatment	Statistic* indicating significance without bulb fresh weight as covariate	 with bulb fresh weight as covariate
Number of skins		
Year	59.0	0.8
Year.cultivar	43.3	50.0
Year.nitrogen	14.6	17.0
Harvest time	5.8	3.2
Skin burst pressure		
Year	35.9	6.8
Cultivar	36.9	38.2
Harvest time	13.5	10.3
Nitrogen	16.7	12.9
Skin identity.cultivar	10.4	10.5
Year.nitrogen	8.3	7.9
Skin stiffness		
Skin identity	1796	1791
Cultivar	8.9	9.4
Harvest time	4.0	2.9
Storage time	15.9	16.6
Skin identity.storage time	33.0	32.9
Skin identity.harvest time	13.9	13.8
Skin identity.water availability	17.7	17.7
Skin identity.cultivar	13.2	13.5
Skin identity.year.cultivar	13.4	14.2

* Variance ratio for number of skins; Wald statistic for burst pressure and stiffness.

5. Relationships between skin characteristics

Relationships in these analyses are based on measurements made on individual skins and not on mean values for bulbs or samples. The relationships examined are those between skin strength or skin stiffness and skin specific skin dry weight, skin thickness and moisture content. The purpose was to determine whether these relationships reduce the significance of effects of experimental factors (cultivar, nitrogen etc). In the data from experiments done in 1998 and 1999, there was a significant overall correlation (r=0.70) between burst pressure and specific skin weight (Figure 1). Correlation with skin thickness was much poorer (r=0.32), but significant. Specific dry weight cannot be estimated for the 1997 experiment, but correlations of burst pressure with skin thickness were significant (r=0.50).

For skin modulus, there was a significant correlation with skin moisture content (r=0.71).

When specific skin dry weight was included as a covariate in the 1998/99 set of data, the effect of cultivar was entirely accounted for and that of nitrogen partly accounted for (Table 9). Thus skins of cv. Hysam are probably more resistant to fracture because they have greater structural mass than skins of cv. Crossbow. At least some of the effect of nitrogen can also be attributed to mass of material. The effect of harvest

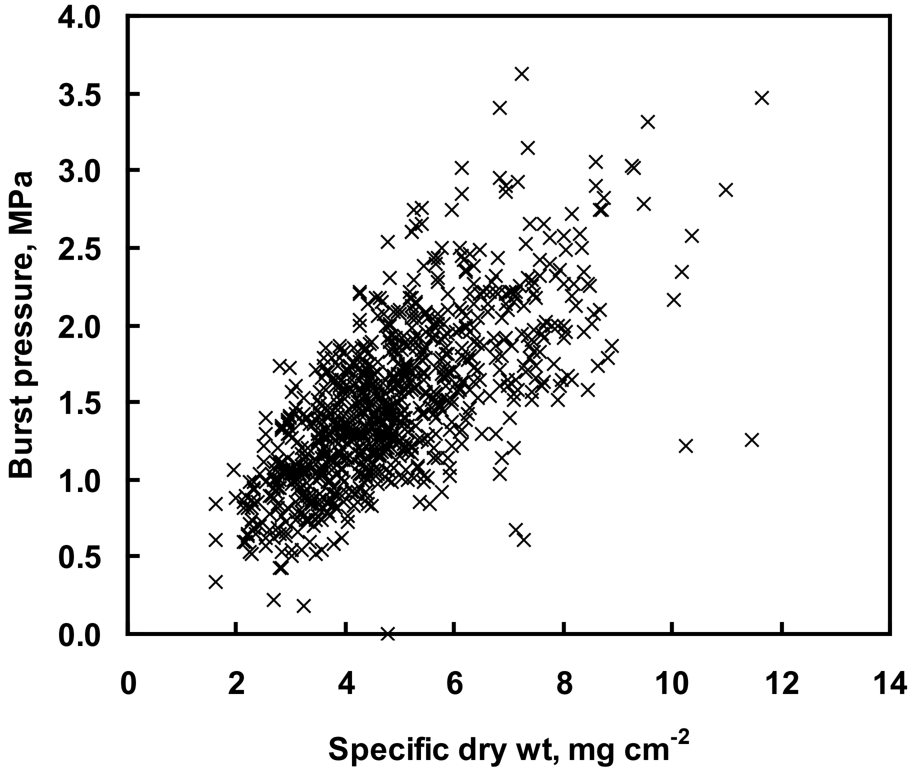

Figure. 1. Relationship between burst pressure and specific dry weight of all skins from 1998 and 1999 experiments.
Skin position is not identified because it provides no additional insight.

time, which gave stronger skins at later harvest, was not associated with variation in specific skin dry weight. Including other variables such as skin thickness and moisture content as additional covariates, did not alter the outcome of the analysis.

The large effect of skin position on skin stiffness was very greatly reduced by including skin moisture content as a covariate (Table 9), though the effect of skin position remained significant. This covariance can be clearly seen in the overall relationship between stiffness and moisture content (Figure 2). However, there is still a wide range of stiffness values for skins at around 20% skin moisture content. This indicates that moisture at this point becomes absolutely critical and that there are other unknown determining factors operating. The effect of storage time was also considerably, but not entirely, reduced (Table 9). The increase in stiffness in inner skins was thus associated with a loss of moisture from the skins, presumably through gradual drying in store. This is not unexpected and is consistent with the effects of humidification of skins on stiffness (see Results section 6.). The much smaller effects of cultivar and harvest time were removed by inclusion of moisture content in the analysis. Using skin thickness as a covariate provided no further useful explanation of variation in skin stiffness.

Table 9. Association of skin specific dry weight, skin thickness and skin moisture content with effects of treatment factors on skin burst pressure and skin stiffness. [A decrease in the value of the statistic indicates an effect of the covariate.]

Variable / Treatment	Wald statistic with: no covariate	covariate: specific weight	covariates: specific weight & skin thickness	covariates: specific weight & skin moisture
Skin burst pressure				
Year	35.9	7.0	6.0	8.1
Cultivar	36.9	0.7	0.3	0.6
Harvest time	13.5	19.0	16.6	18.9
Nitrogen	16.7	4.2	3.6	4.1
Skin identity.cultivar	10.4	5.8	7.6	6.7
Year.nitrogen	8.3	0.7	0.5	0.7
	no covariate	covariate: moisture content	covariate: skin thickness	
Skin stiffness				
Skin identity	1796	71.4	1850	
Cultivar	8.9	3.8	5.7	
Harvest time	4.0	0.1	0.2	
Storage time	15.9	0.8	37.3	
Skin identity.storage time	33.0	11.3	22.3	
Skin identity.harvest time	13.9	4.6	1.1	
Skin identity.water availability	17.7	7.9	13.5	
Skin identity.cultivar	13.2	6.1	1.7	
Skin identity.year.cultivar	13.4	3.7	4.0	

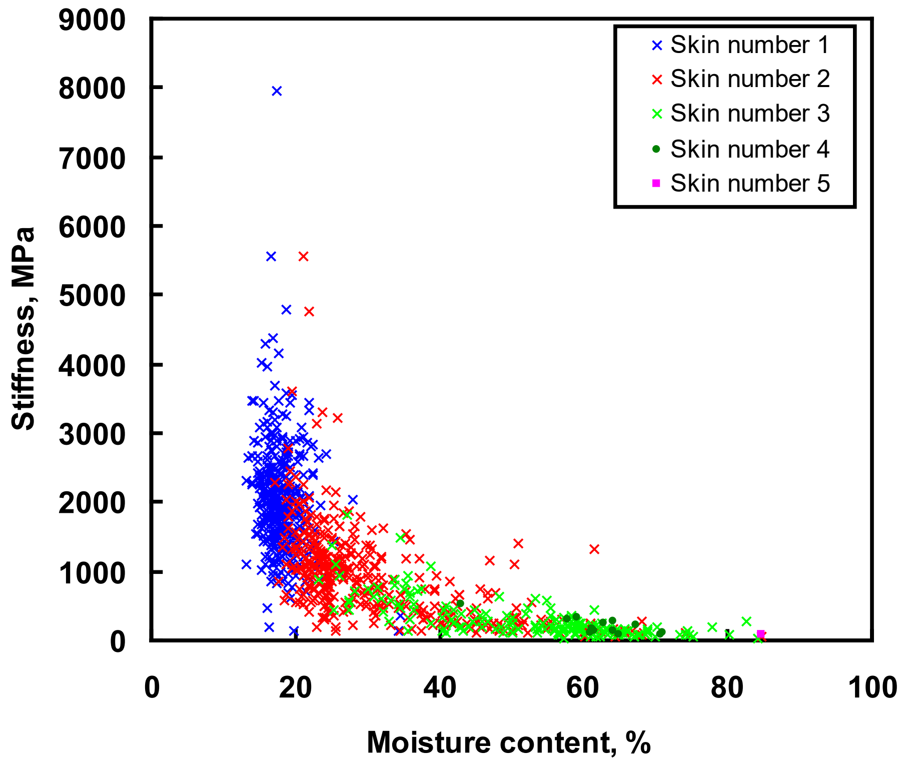

Figure. 2. Relationship between stiffness and moisture content of skins at all positions on bulbs from 1998 and 1999 experiments.

6. Effects of humidity on skin properties

The mechanical properties of onion skins may depend on the aerial environment at the time of measurement. Atmospheric humidity may be of particular importance because it can affect the moisture status of skins. We have examined some properties of outer "dry" onion skins after equilibration at different relative humidities prior to measurement. These studies have implications for ensuring standardisation during measurement. They are also relevant to conditioning of bulbs and skins immediately before handling.
Humidification increased the water content of skins in all experiments (Table10). Skin thickness was increased only where skins were in contact with a wet surface. There was also an increase in the strength of the skins (Table 10) as a result of humidification. This was reversed on return of the skins to a lower humidity.

Table 10. Effect of humidification of onion skins on strength, thickness and moisture content.

Treatment	Skin strength MPa	Skin moisture content %	Skin thickness mm
Experiment a)			
16% r.h.	0.87	4	0.061
100% r.h. (wetted)	1.59	58	0.121
lsd p=0.05	0.356	2.0	0.0177
Experiment b)			
cv. Hysam			
16% r.h.	0.52	3	0.048
100% r.h.	1.56	34	0.054
100% / 16% r.h.	0.54	7	0.045
cv. Crossbow			
16% r.h.	0.32	2	0.033
100% r.h.	1.16	33	0.034
100% / 16% r.h.	0.35	6	0.037
lsd p=0.05	0.252	1.4	0.0091
Experiment c)			
17% r.h.	0.76	4	0.046
31% r.h.	1.05	7	0.049
50% r.h.	0.98	12	0.045
75% r.h.	1.33	13	0.047
95% r.h.	1.42	39	0.064
100% r.h. (wetted)	1.06	68	0.119
lsd p=0.05	0.262	2.0	0.0132

lsds are provided for comparison of means immediately above in the same column and in the same row.

Skin stiffness is also affected by equilibration at different humidities (Table 11). After treatment with air at higher humidity, skins have a lower elastic modulus and are thus more flexible. Humidification had no significant effect on unidirectional strength. This apparent contradiction with the results of burst testing may be related to the visco-elastic nature of biological material. It is possible that the rate of application of stress in the burst pressure test is more rapid and the more flexible moist skins are able to store the energy input for longer before breaking, than drier skins. This ability to stretch further before breaking is illustrated by their greater strain at breakage (Table 11).

Table 11. Effect of humidification on skin stiffness (modulus), strain and stress at breakage .

Treatment	Skin stiffness MPa	Skin strain at breakage %	Skin stress at breakage MPa
Dry	1987	3.5	43.5
Wet	850	8.0	34.0
lsd p=0.05	176	1.51	6.14

lsds are for comparison of means immediately above in the same column.

It is likely that friction between the components of the wafer-like structure of dry skins (Figure 3) is decreased by water behaving as a lubricant.

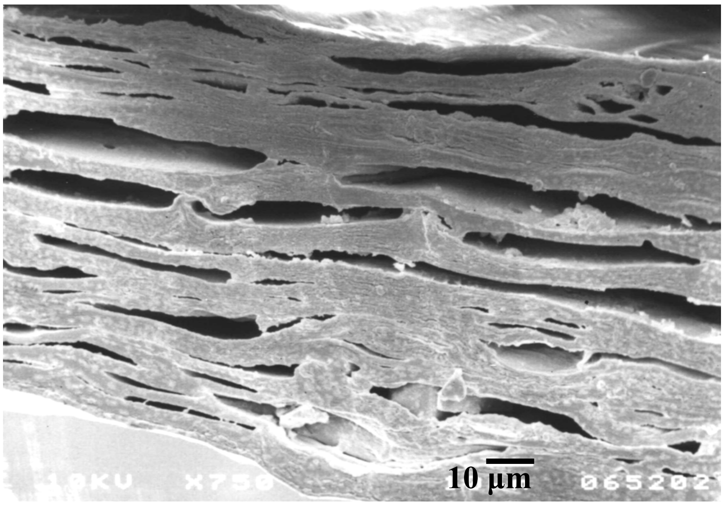

Figure 3. Scanning electron micrograph of dry onion skin. Note the wafer-like structure of the collapsed cell walls. The width of this skin as a living leaf base would be approximately 1.5 mm. As a dry skin it is about 0.065 mm; a shrinkage of 25 times.

7. Anatomical examination of leaf bases

Numbers and sizes of cells across the thickness of leaf bases sampled during growth were examined to determine whether these might contribute to differences in skin thickness and specific skin weight after storage. Analysis of these data showed no differences in either of these features between any treatments (Table 12). There was a significant difference between plots in mean size of the cell dimension across the width of the leaf. This could not be attributed to a specific treatment. Mean numbers of cells between plots were not significantly different.

Table 12. Cell numbers and dimension contributing to width of base of leaf 7.

Treatment	Anatomical variable Number of cells	Cell dimension, mm
Cultivar		
Crossbow	16	0.096
Hysam	14	0.087
lsd (p=0.05)	4.4	0.0290
Water availability		
Sheltered	15	0.089
Unsheltered	15	0.095
lsd (p=0.05	4.4	0.0290
Field plots: range of values	13 to 17	0.081 to 0.112
lsd (p=0.05)	5.5	0.0242

On the basis of this data, it would seem that the clear and repeatable difference between cv. Hysam and cv. Crossbow in skin thickness and skin specific dry weight may depend more on the amount of cell wall in each cell (or specific layers of cells such as the epidermis) than on the numbers of cells in the leaf width cross section.

Objective 3: To measure the forces required to compress the mature bulb and bulb scales relating this to tissue water status and cell dimensions. [Conclusion 3]

This objective proved to be inappropriate in relation to skin fracture. Expansion forces from the bulb are not a source of stress that leads to skin splitting. Splitting is more a consequence of impact damage and movement of the base plate during dormancy break in late storage. The original hypothesis underlying this objective was based on analogy with carrot splitting and potato bruising, both of which are dependent on tissue water relations and internal generation of forces and their dissipation. In onion skins, inherent mechanical properties such as resistance to fracture and compliance (reciprocal of stiffness) were found to be much more important. Tension in fresh onion bulb scales can be demonstrated by cutting through the outer layers of flesh and observing the resulting gape of the tissue. However this tension dissipates readily with moisture loss from the fleshy scales and thus is a diminishing force with time in store. Also, individual scales retain much of their own tension rather than exporting it to outer skins.

Objective 4: To identify the effect of variety and cultural factors on onion skin qualities for samples subjected to commercial treatment in storage and in handling during grading and retail chain. [Conclusions 4 and 5]

8. Overall skin quality assessment of bulbs from experiments

Overall skin quality of bulbs was based only on the presence of splits and cracks and visibility of underlying flesh caused by damage in the drum-rolling test. Comparison of cultivars in 1997 demonstrated that overall skin quality was **very dependent on cultivar** with cv. Crossbow presenting bulbs that were significantly poorer in quality than those from cvs Durco, Hysam and Sherpa (Table 13). A significantly poorer performance of cv. Crossbow was also present in the results from the 1998 experiment. This varietal difference was much greater than any difference that was environmental in origin. Better skin quality was also associated with

- **harvest time** (in mid- to late August compared with mid-September)
- **rate of nitrogen application** (60 kg ha^{-1} compared with 120 kg ha^{-1})

There was a suggestion that skins suffered less damage at the lower rate of nitrogen application and when harvested earlier while leaves were still green.
These associations were not significant at the 5% probability level, but were significant at 10%. Varietal effects were significant at 0.1%.

Table 13. Effect of treatments on proportion of bulbs (%) classified as acceptable (classes 3, 4, & 5) after drum damage testing. Field experiment 1998.

Treatment	Proportion of acceptable bulbs, % 1997	1998
Cultivar		
Crossbow	26	25
Durco	56	*
Hysam	67	61
Sherpa	62	*
lsd(p=0.05)	10.0	12.9
Nitrogen		
60 kg ha^{-1}	*	48
120 kg ha^{-1}	*	37
lsd(p=0.05)		12.9
Harvest time		
August	*	49
September	*	40
lsd(p=0.05)		10.1

Damage may be influenced by the size of the bulb. It is therefore important to assess whether the effects of factors are associated with this. Analysis of variance showed that cultivar, water availability, nitrogen, lifting time and length of storage significantly affected bulb fresh weight and bulb diameter. Inclusion of bulb size (fresh weight or diameter) as a covariate in the analysis removed the small effects of nitrogen and harvest time on the proportion of acceptable bulbs. The effect of variety was not altered in any way. This suggests that bulb size was associated with differences that might have been caused by environmental effects, but did not influence differences in skin quality between cultivars.

9. Overall skin quality assessment of bulbs from commercial sources.
Samples from eight commercial sources in two years showed large variation in the proportion of acceptable bulbs (20-100%) based on simulation of commercial damage with a drum testing device (see Methods section 3). Averages for the two years and for the two centres on which the eight sites were based were not significantly different. However, quality declined significantly with duration in store and there was a difference in the pattern of decline in skin quality with storage time for the two centres (Table 14). The decline was greater for samples from peat based soils than those from a sandy background.

Table 14. Mean proportion of bulbs of acceptable skin quality from eight sites based on different soil type. Bulbs harvested in September 1998 and 1999 and stored until assessed in the month indicated using drum damage test.

Sites based on:	December	April
Sandy soils	72	60
Peat soils	82	54
lsd (p=0.05)	11.1	

This effect was not apparent in an assessment of quality in these same samples carried out by commercial staff nor was it evident in the "topper" test of the material. Although there were relationships between commercial quality assessment and assessments done at HRI, they were not close ones (Appendix 1 Figures 1 and 2). Relationships with crop history were difficult to establish, because of the inconsistency of comparable factors between the different samples. The only variable that provided any hint of an association with quality was nitrogen fertiliser application. The suggestion was that quality was not as good for higher nitrogen application. However, this variable was partly confounded with soil type.

10. Relationships between skin characteristics and skin quality
This has been investigated by using regression analysis to examine associations between mean quality for each plot, determined by drum testing and means of skin characteristics estimated from parallel samples.
Significant correlations were found between **proportion of acceptable bulbs** and:

- **specific skin dry weight of skins 1, 2 and 3**
- **thickness of skins 1, 2 and 3**
- **strength of skin 2**
- **number of skins**
- **moduli of skins 2 and 3** (Table 15).

Table 15. Significance of relationships of skin characteristics with skin quality for plot mean data of field experiment 1998.

Skin variable		Variance ratio	Significance
Number of skins		31.2	p<0.001
Specific dry weight	skin 1	41.2	p<0.001
	skin 2	44.7	p<0.001
	skin 3	11.1	p<0.01
Thickness	skin 1	40.0	p<0.001
	skin 2	40.5	p<0.001
	skin 3	9.75	p<0.01
Strength	skin 1	3.53	NS
	skin 2	10.2	p<0.01
	skin 3	0.21	NS
Modulus	skin 1	1.74	NS
	skin 2	6.99	p<0.01
	skin 3	9.80	p<0.01
Moisture content	skin 1	0.03	NS
	skin 2	2.00	NS
	skin 3	1.52	NS

Importance of variables is indicated by the size of the variance ratio from the simple linear regression of each characteristic

Relationships with skin specific dry weight, skin thickness and the number of skins were of much greater significance than for the other characteristics for the field experiment in 1998. The specific dry weight and thickness of skins 1 and 2 was more

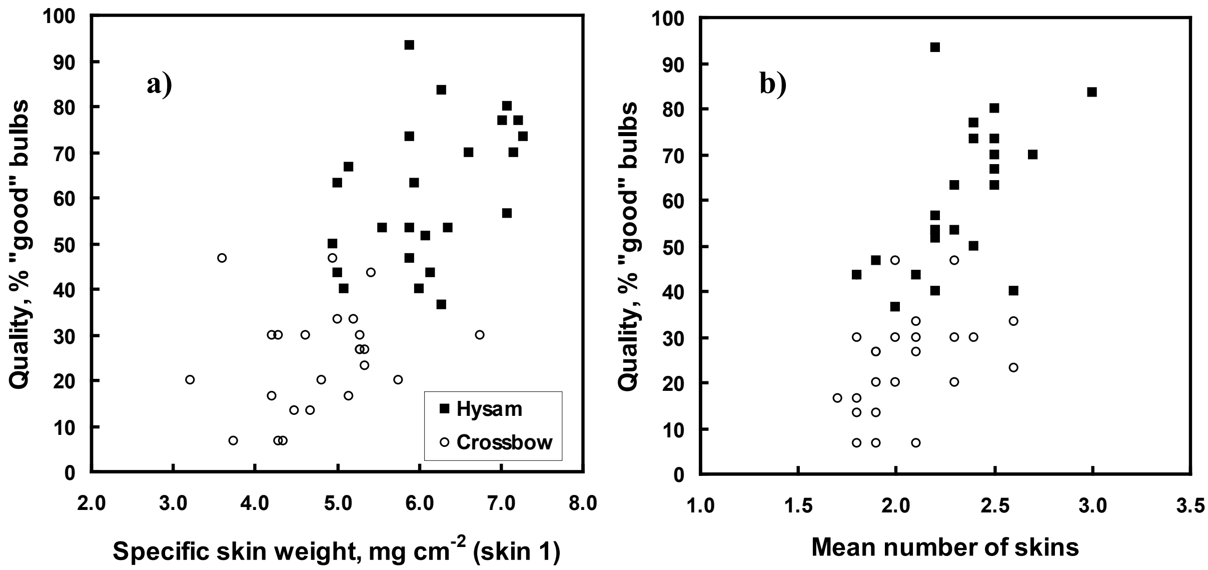

Figure 4. Relationships between skin quality of bulbs from field experiment 1998 and a) skin specific dry weight and b) number of skins. The points represent mean values for samples of each treatment plot taken from two liftings and two occasions after storage.

important than that of skin 3. A regression model including skin numbers and specific dry weight of skins 1 and 2 accounted for about 68% of the variation.

Although these correlations are significant, some caution in interpretation needs to be exercised. It is evident that some of these relationships with quality result from trends between groups of points for each cultivar (Figure 4). Within cultivars, the relationship is poorer and may differ for each variety.
Comparison of four cultivars in 1997 also showed a relationship (Figure 5) between mean quality for each field plot and both mean skin thickness (r=0.589) and strength (r=0.555). These relationships were also present in the variety means (not illustrated). Specific dry weight was not available for this data. However, there was a close correlation between plot means for this and skin thickness in 1998 (r=0.8).

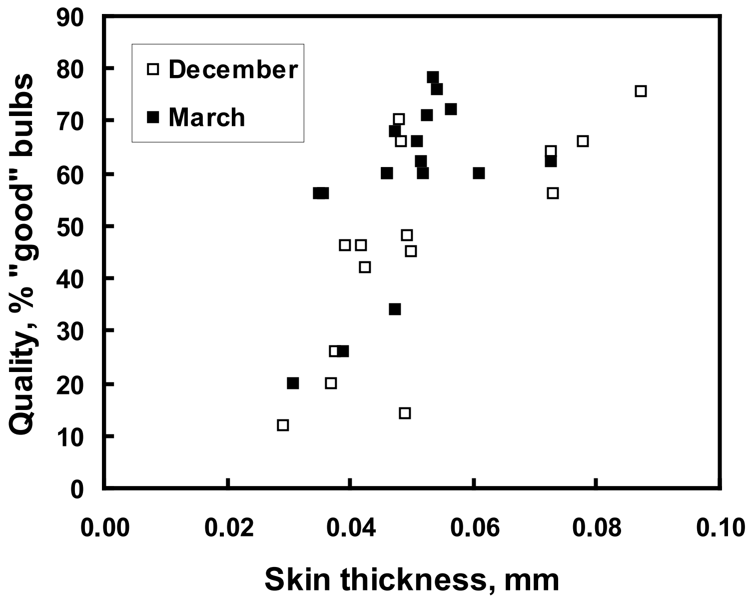

Figure 5. Relationships between skin quality of bulbs from field experiment 1997 and skin thickness. The points represent mean values for samples of each treatment plot taken from two occasions after storage.

Relationships between quality from commercial samples and skin strength, skin thickness and skin specific dry weight were very poor (r=–0.075, 0.069 and –0.01 respectively). This may have arisen because of the very large bulb to bulb variation that is observed in all our data. The consequence of this is that sampling will have an important bearing on how well the data relate. Measurements of quality for the commercial sources were made on different bulbs from those used to measure skin characteristics.

Objective 5: To quantify the permeability to oxygen, carbon dioxide and water of skins of different physical characteristics and thickness [Conclusions 17 and 18]

11. Studies of skin permeability to water vapour, oxygen and carbon dioxide

These measurements were done using equipment and methods developed at HRI specifically for onion skins (See Methods sections 11 and 12). Briefly, the principle used was diffusion exchange of gaseous molecules along a concentration gradient between a chamber, filled with an appropriate gas, and the atmosphere. The chamber was sealed such that gas could pass only through a window in which a sample of onion skin was fixed.

The ranges of onion skin permeability coefficients estimated for water vapour and for oxygen were very large. For water vapour, a forty-fold range of values from 0.00002 to 0.00088 cm s^{-1} was obtained. For oxygen, permeability coefficients were of a similar magnitude to those for water vapour and with an even larger variation in the range of rates (0 to 0.00215 cm s^{-1}). This included two values which were considerably greater than the remainder, so most (95%) of the estimates were between zero and 0.00036 cm s^{-1}. Measurements of permeability to carbon dioxide estimated values from zero to 0.0004 cm s^{-1}. This suggests that skin permeability to carbon dioxide and oxygen may be similar. Some skin samples were impermeable to the passage of oxygen and carbon dioxide. In contrast, some passage of water vapour was always detected. This may reflect that lighter mass of water vapour molecules (18) compared with oxygen (32) and carbon dioxide (44).

The only factor that had any significance was the position of the skin in the sequence on the bulb (Table 16). Inner skins were much less permeable to water vapour than outer skins.

Table 16. Effect of skin identity and location within skin on permeability to water vapour.

Sample history	Mean permeability coefficient cm s^{-1}
Skin identity	
Skin 1	1.93×10^{-4}
Skin 2	0.58×10^{-4}
lsd (p=0.05)	0.43×10^{-4}
Position within skin	
Top of bulb	1.52×10^{-4}
Equator of bulb	1.51×10^{-4}
Base of bulb	1.15×10^{-4}
lsd (p=0.05)	0.54×10^{-4}

lsds are provided for comparison of means immediately above in the same column.

Measurements of skins from field experiments in 1998 and 1999 revealed no effect of treatments on water vapour or oxygen permeability at all. Mean permeability coefficients for water vapour of treatment plots ranged from 0.00025 to 0.00037 (lsd p=0.05, 0.00024) in 1998 and from 0.00022 to 0.00033 (lsd p=0.05, 0.00014) in 1999. For oxygen, the range was 0.00004-0.00048 (lsd p=0.05, 0.00052)

There was no relationship with skin thickness for coefficients of water vapour or oxygen permeability (Figure 6).

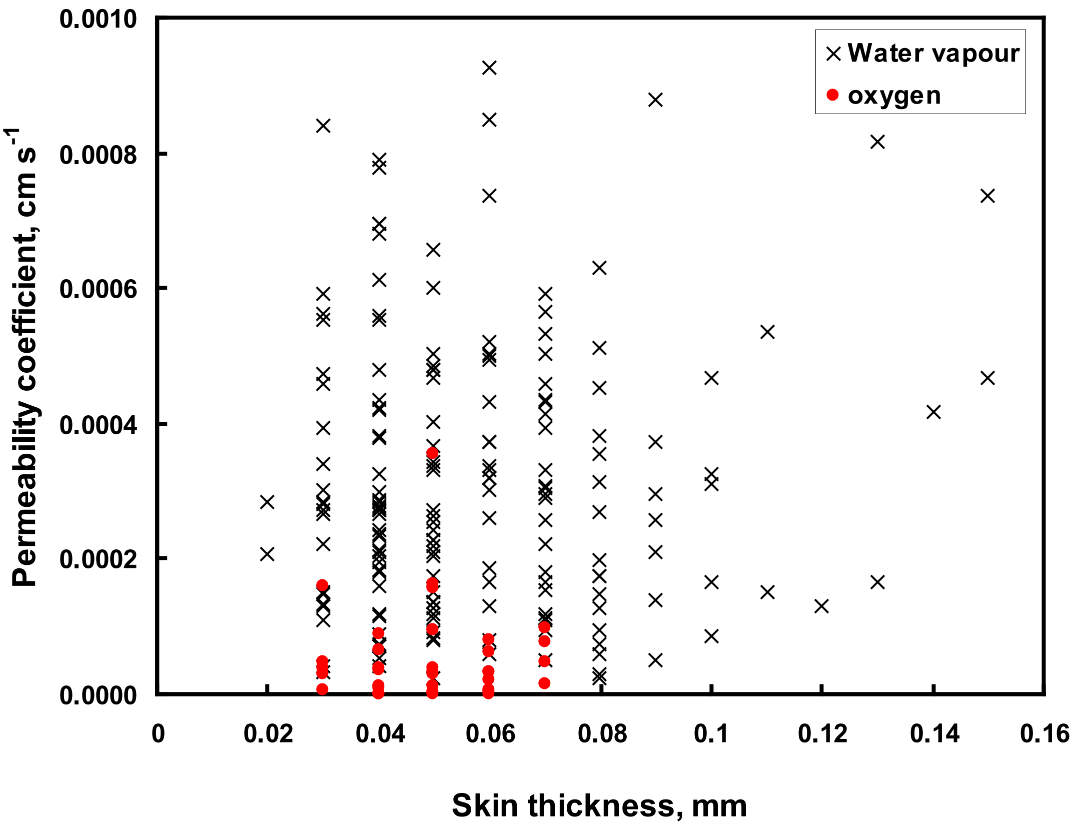

Figure 6. Permeability of skins to water vapour and oxygen in relation to skin thickness for bulbs from field experiments 1997/8 after storage for six months.

This absence of a relationship with skin thickness suggests that skins do not represent a simple uniform barrier to gaseous phase molecules. Rather, their physical structure may have a more important influence on their gas permeability properties. For example, variation in the degree of porosity or of the proportions of different chemical fractions may be independent of thickness and affect transfer across the skin.

Material and Methods

The core of data for all objectives was provided from three field experiments and a survey of commercial samples. These are described in section 1 and 2, below. The methods used to obtain the data are described in sections 3 to 13.

1. Field experiments at HRI Wellesbourne, 1997, 1998 and 1999
Investigations were based on plants and bulbs from field experiments at Wellesbourne. In 1997, skin development and resistance to damage was examined for four cultivars which we believed would provide contrasting performance. The experiments in 1998 and 1999 were designed to examine whether environmental factors such as variation in nitrogen fertiliser rate and water availability affect skin quality of two cultivars already known to differ in their skin thickness and susceptibility to damage. Essentially, the experiments in 1998 and 1999 were identical in design. The experiment in 1998 is described in detail. Differences that occurred in 1999 are recorded in a following section.

1.1. In 1997, seeds of cvs Crossbow, Durco, Hysam and Sherpa were sown on 20 March 1997 into a sandy loam soil of the Wick series and subsequently thinned to 45 plants m^{-2}. The experimental area had been dressed with 240 kg ha^{-1} of P and K in the previous autumn and with 120 kg ha^{-1} of N during early March. The crop was top dressed with 60 kg ha^{-1} N on 30 July, because heavy rain during June had caused leaching of N and appeared to have led to some nitrogen stress in the crop. Beds were 1.83 m wide and comprised 5 rows 36.6 cm apart. The experimental area was divided into four blocks each comprising four plots (one of each variety). A plot represented a single bed, 15 m in length. Guard plots surrounded the experiment and there were guard areas between plots within beds.

Maleic hydrazide was applied on 22 August and the crop was lifted on 11 September. Application of this sprout suppressant is standard commercial practice to inhibit sprouting in bulbs that are to be stored into the following year.
Bulbs were netted and stored in a forced airflow of 359 m^3 h^{-1} with the temperature initially at 28°C and relative humidity (RH) between 60 and 75%. After 4 days, the temperature was decreased to 25°C and the airflow re-circulated to maintain humidity. Temperature was successively decreased to 20, 15°C and 10°C on 22 October and 3 November and 24 November respectively. Ultimately a temperature of 5°C was achieved in early February 1998. Temperature and humidity were logged throughout storage. Curing and storage regimes vary within the industry depending on facilities available, marketing intentions and cost. The procedure used here for curing and early storage conforms to recommended good practice, although the final storage temperature of 5°C was higher than would be used commercially (-1°C). This represented a compromise based on facilities available at the time, but is unlikely to have had a major effect on the mechanical properties of the dead skins.

Samples of plants were monitored non-destructively during growth to identify which leaves gave rise to skins at harvest. Additionally, samples were taken for measurement of bulb size and development and leaf base thickness.

On two occasions during storage (24 November 1997 and 17 February 1998), samples were removed and assessed. Susceptibility of bulbs to damage was tested on 50 bulbs from each plot using the drum simulator (see Methods section 3). Skin number, thickness, water content and bulb size from all plots were measured on 10 bulbs per plot. This sample was split for measurement of skin strength and stiffness on each of five bulbs.

1.2. In 1998, seeds of cvs Crossbow and Hysam were sown into "304" peat-filled modules on 23 March and planted out into a sandy loam soil of the Wick series on 15 May at a density of 45 plants m^{-2}. Base dressings of either 20 or 40 kg ha^{-1} of N were applied to appropriate plots on 14 May and top dressings at the same rates on 22 June and 15 July. Phosphorus and potassium fertilisers were not applied, because soil analysis showed indices to be sufficiently high. Plugs were planted at 6 cm intervals in rows spaced 37 cm apart. There were 7 rows per plot. Only the inner 5 rows were used for samples, the outer rows acting as guards. The experimental area was divided into two blocks, each comprising eight plots that were 12 m long. The blocks were split in to sub-blocks of four plots. These were either sheltered from rainfall or unsheltered. Cultivar and nitrogen treatments were randomised within these sub-blocks.

Rainfall was prevented from falling on to the sheltered plots by the use of rain covers mounted on rails. These were automatically driven over the plots when rain fell and removed to parking areas when it stopped. Water status of the soil on each plot was monitored at weekly intervals with a neutron probe. Moisture release curves for these soils were characterised and a relationship between neutron probe readings and water content established. This enabled calculation of soil water potential.

Environmental conditions during crop growth were logged. Samples of ten marked plants on each plot were monitored non-destructively during growth to identify which leaves gave rise to skins at harvest. The progress of leaf appearance and death was also followed by observing these plants (Appendix 2 Figure 3). Occasionally, destructive samples of five plants per plot were removed for dissection to record the number of leaf primordia and to measure leaf weights and bulb diameter and weights when appropriate. The eighth leaf of five plants on each plot was identified and the leaf blade removed from leaf 7 when it was fully emerged. Measurements made on the skin formed from the seventh leaf base of these bulbs after storage for 3 months were compared with those on the equivalent skin of the non-destructively monitored plants.

Leaf collapse was estimated visually for entire plots, either by accumulative length of collapsed row or as approximate plant numbers, expressed as a proportion of the plot total. Because bulbs of the different treatments matured at different rates application of maleic hydrazide and the time at which bulbs were lifted was different for each plot. Samples of bulbs for storage were harvested on two occasions after the completion of leaf collapse: first, while the leaves were still green ("100%/100%") and the second after leaves had mostly senesced ("100%/25%"). On some plots, 100% collapse was never achieved. For these, leaf collapse was considered complete when the level reached a stable maximum.

Maleic hydrazide, used to suppress sprouting in store, was applied between 29 July and 19 August. First harvests (100%/100%) were made between 19 August and 1 September and the second harvests (100%/25%) between 14 and 18 September. Bulbs were netted and stored in a forced airflow of 359 m^3 h^{-1} with the temperature initially at 28°C and relative humidity (RH) between 60 and 75%. On two occasions during storage (4 to 19 December 1998 and 17 and 25 March 1999), samples of bulbs were taken from store. Assessment of skin damage susceptibility was made on 30 bulbs per plot for each harvest and storage occasion. Sample sizes for measurement of skin characteristics were the same as for the 1997 experiment.

1.3. In 1999*,* seeds were sown in modules on 24 March and planted out on 21 May. Base dressings of either 20 or 40 kg ha^{-1} of N were applied to appropriate plots on 20 May and Vydate was raked in to limit nematode attack, which had occurred in a small way in 1998. Top dressings of nitrogen fertiliser were applied at the base rate on 24 June. The second top dressing was not applied, because growth had been very slow after planting. This probably resulted from a combination of delayed planting (due to bad weather), serious nematode attack in spite of precautions and heavy rain in the weeks following planting which led to nitrogen leaching. The top dressing on June 24 should have relieved this, but growth continued to be poor. By the time the second top dressing was due, the leaf development had ceased and the plants were well into bulbing. Samples for monitoring growth and development were taken as in 1998 (Appendix 2 Figure 3). Additionally, samples of tissue for anatomical investigation were removed from the bases of leaf seven of five plants for each of eight plots (both varieties plus both watering treatments for low nitrogen treatment).
Because of poor growth and yield (Appendix 3 Table 1), samples were finally harvested on only one occasion: when leaves had mostly senesced. Leaf collapse was not complete on any plot, principally because the weight of foliage was small. Maleic hydrazide was applied between 23 and 27 August. Bulbs were lifted on 3 September when all leaves had senesced and stored as described for previous experiments.
Samples were removed from store and skin characteristics measured on 6-9 December 1999 and 13-14 March 2000). Sample numbers were as for the 1997 experiment. Insufficient bulbs of an appropriate size were available for drum testing of quality.

2. Survey of skin quality in commercial sources of bulbs
The purpose of this survey was to determine the extent to which variation in cultivation history contributed to differences in onion skin quality under commercial circumstances.
In 1998 and 1999, bulbs of two cultivars were obtained from eight commercial sites based on two centres. One of these sourced its bulbs from predominantly sandy soils, while the other obtained them from peat based soils. A record of some of the background variables for each crop was also obtained. In 1998, all samples were dried and cured at the same site, but this was not achieved in 1999. In both years, all samples were ambient-stored in bins at the same location. In the first year of study, samples of 40 bulbs were removed from the bins on 24 November 1998 and 7 April 1999. For the second year sampling was on 13 December 1999 and 3 April 2000. These were subjected to damage using the drum simulator (see Methods section 3) on the following day and assessed for quality after 24 hours at 5°C by HRI scientists and later by industry representatives. Skin quality was also recorded by industry assessors, for samples of 20 bulbs from a load that had passed through a topping machine. These tests were done on dates close to those for drum testing. Skin strength (as burst pressure) and thickness of the outermost complete skin was measured on a sub-sample of 10 bulbs.
Quality assessment at HRI was done as described under "Damage susceptibility" below. Quality assessment by the industry was essentially descriptive of the numbers of skins, the severity of skin splitting and the number of bulbs affected. Quality scores were based on these descriptions. Quality scores related fairly closely with the

proportion of bulbs regarded as "acceptable" (basically showing little damage). For analysis of relationships between quality and crop history, this proportion was used.

3. Damage susceptibility (Drum-rolling test)

Machine handling was simulated by rotating samples of 30 to 50 bulbs at approximately 18 rpm for 2 minutes in a large polypropylene drum (64 cm in diameter and 84 cm long), mounted horizontally on a motorized drive unit. The interior of the drum was fitted with plastic drainpipes to inflict impacts on the bulbs as they rolled over the uneven surface. The design and manufacture of the drum (Appendix 4 Figure 4) was done at HRI Wellesbourne in collaboration with the Instrumentation Group.

Bulb skin quality was assessed with reference to damage using the following scale (Appendix 4 Figure 5):

5 - two firm skins, no splits
4 – two firm skins, minor splitting (no more than 2 over < 10% of surface)
3 - Two firm skins, no gaping of splits, but more than one or two minor splits
2 - Two firm skins, wider splits of less than 20mm width over most of surface
1 - Flesh showing through a single split/cracked outer skin

In this study, skin quality reflected only the degree of splitting and cracking damage.

4. Skin resistance to multi-directional force (Burst pressure)

This method measures the strength of skin material irrespective of its orientation. Samples of onion skin, 13.8 mm in diameter, were removed from the equatorial region of bulbs using a cork borer and held across an orifice (6.8 mm diameter) by compression between two "O" rings. Strength was measured by increasing the pressure at a constant rate on one side of the skin using a cylinder of compressed air. A transducer interfaced to a computer, recorded changes in pressure. Peak pressure was taken as the pressure at which skin failure occurred. Measurements were made in ambient room conditions (usually around 20°C and 50%RH). The equipment used for this measurement (Appendix 4 Figure 6) was designed and manufactured at HRI Wellesbourne in collaboration with the Instrumentation Group. When cutting disks from skins that are still attached to bulbs, successive skins in the "plug" sometimes bond very tightly and are difficult to separate. It is important to examine each disk closely to ensure it comprises only one skin. Removal of skins from the bulb prior to disk cutting is slower, but makes skin separation more certain.

5. Skin stiffness

Samples of skin (2 mm wide by 35 mm long) were cut from the equatorial region of bulbs. These were mounted on cards, across a 20 mm cut-out using clear adhesive tape to attach the ends of the sample. The supporting cards and the adhered ends were then placed in the pneumatic grips of an Instron materials-testing instrument (Appendix 4 Figure 7). The sidebars of the cardboard support were then cut allowing the skin to be stretched by the machine at a rate of 1 mm min^{-1}. The slope of load/area of cross-section of the skin against extension was estimated as skin stiffness. Tension was increased until the sample failed, also providing an estimate of unidirectional failure stress (strength) and failure strain. These latter properties were measured only for onion skins in the humidification experiments and from the field experiment in 1999.

6. Skin thickness
Skin thickness was measured by digital electronic calipers with a sensitivity of 0.01 mm. An average of several measurements of each sample was always made, avoiding major vascular bundles. These were therefore estimates of inter-veinal tissue thickness.

7. Skin moisture content
This was determined by weighing a sample of skin immediately after removal from a bulb and then re-weighing after drying for at least 48 hours at 90°C.

8. Skin specific dry mass
This was estimated from the dry weight of disks used in burst pressure testing (see Methods section 4 for details of sampling and size). Because these are cut to a known and constant diameter, their dry weights represent the amount of biological matter present for a known area. A simple division of disk dry weight by disk area provides specific skin weight. However, in practice only disk weight needs to be used if disks are always cut to the same diameter. Disks were weighed on a balance capable of discriminating to 5 decimal places of a gram. A 4-place balance would provide sufficient sensitivity. By increasing the "known" area of skin sampled, further loss of accuracy could be minimised.

9. Numbers of skins
In this report, skins have been identified by numbering sequentially in ascending order from the outside. For the purposes of detecting effects of skin identity, this is adequate. However, characteristics of skins may depend on the context in which they find themselves. So skin 2 in a two-skinned bulb may have quite different properties from skin 2 of three- or four-skinned bulbs. Further analysis in which bulbs with similar numbers of skin are examined separately will be necessary to properly estimate mean values for skin properties.

10. Anatomical studies
Samples (as described under field experiment 1999) were taken from equivalent positions in the bases of the eighth leaf, opposite the pore, and approximately halfway between the base plate and the green part of the leaf. These were frozen over liquid nitrogen and then stored at -20°C. The frozen samples were mounted on a cryostat, embedded in Tissue-Tek and sectioned. The resulting sections were mounted on stubs, sputter-coated with gold and viewed in a scanning electron microscope. Numbers of cells comprising the width of the leaf were counted and their average dimension across the leaf width estimated.

11. Permeability of skins to water vapour
Estimation of diffusion of water vapour through onion skins was based on the measurement of weight loss of a water-filled system from which water could escape only by evaporating through a "window" of onion skin (Appendix 4 Figure 8). Polypropylene vials (43 x 10mm) were filled to within 1mm of the top with pure water. The cap of the vial was specially modified by 7.2 mm diameter hole and an O-ring that provided a seal between the cap and the skin. The underside of the skin

rested on the top of the tube. It was important that the O-ring was not placed between the skin and the tube top. Sealing was much less effective when configured this way. The weight of the tube was measured using a balance that was accurate to 0.00001 of a gram.
Skin permeability was estimated, usually at ambient room conditions, using 48 tubes placed in a turbulent air stream to eliminate boundary layer effects. Weight loss was recorded over a five-hour period and skin permeability coefficients calculated from the rate of evaporation, area of cross section and difference in water content of the atmosphere inside and outside the tube. Extensive preliminary investigation established that time courses were linear if about an hour was allowed for equilibration after tube closure with the skin. Leakage rates of the tubes were negligible when tested with disks of thick polypropylene inserted in place of skins. When setting up 48 tubes for a single run, skin disks were cut on the previous day and sealed into caps with holes. Each vial was filled with 2.5 ml of water at this time and closed with an entire cap to prevent evaporation. It is important that the level of water in the tubes is maintained at the same distance from the top.

12. Permeability of skins to oxygen and carbon dioxide
Estimation of diffusion of oxygen through onion skins was based on the measurement of changes in oxygen concentration in a chamber specially-designed and constructed at HRI in collaboration with the Instrumentation Group (Appendix 4 Figure 9). An oxygen concentration difference between ambient atmosphere and the internal atmosphere of the chamber was achieved by filling the chamber with nitrogen. Oxygen concentration in samples of the internal atmosphere were measured by gas chromatography using a molecular sieve column. A linear calibration from 0 to 25% oxygen was achieved with a series of standard gases. Most measurements were below 5%. Concentrations could be discriminated to better than 0.1%. The chambers comprised an aluminium cylinder with internal dimensions of approximately 100mm length and 51mm diameter. Samples of skins are sealed into a 15mm diameter orifice between two plates that form the top of the chamber. Set in the lower plate is a neoprene washer that forms a gas tight seal between the skin and plate. Tops and bases were tightly screwed together and sealed with O rings. Inlet and outlet ports with valves enabled filling of the chamber. A gas tight septum was set in the chamber wall to permit sampling of the contents with a syringe and needle. The chambers were tested under pressure for gas tightness and obvious leaks were sealed. In normal use, there was no gross pressure difference between the chamber and atmosphere. Base leakage rates were established with aluminium disks placed in the location for the skins. Ten similar chambers were used to compare permeability of skins to oxygen in a single run. Samples of 1ml were taken from the chamber at regular intervals for up to 24 hours and immediately replaced by 1ml of nitrogen. Linear time courses were obtained over this period. Atmospheric gas was also sampled and its oxygen concentration measured. Permeability coefficients were calculated in the same way as for water vapour exchange.
Permeability to carbon dioxide was estimated using the same approach, but was done separately by filling the chambers with carbon dioxide and following the decrease in concentration from close to 100% for about 40 hours. Simultaneous measurement of oxygen and carbon dioxide in the same samples was impractical, because using nitrogen inside the chamber resulted in a small concentration difference between the chamber and atmosphere and thus a slow increase to a low final concentration inside

the chamber. Measurement of carbon dioxide was done using gas chromatography and a Poropak column calibrated with known concentrations.

13. Statistical analysis
Three methods have been employed to analyse the data.

Damage assessments scored bulbs into five classes (see description above). These were examined by analysis of variance of mean scores and by binomial regression analysis of individual and accumulated score categories. Mean scores can provide a useful indication of quality, but they can be misleading. For example a mean sample score of 3 results from equal scores of 4 & 2, 5 & 1 or all 3s. Clearly samples with such differing composition are not the same. In binomial regression analysis, the incidence of a particular category is estimated. The effects of factors on this are analysed by examining changes in deviance resulting from successively fitting suitable statistical models. Graphical examination of the data showed a strong negative correlation between the numbers in classes 5 and 1, but little relationship with numbers in any of the other classes. This suggests that bulbs tend to be either “acceptable” or “unacceptable”. It was decided that those bulbs in classes 3 and above should be “grouped as broadly “acceptable”. The effect of factors on the frequency of bulbs in individual classes and a variety of groups was examined. Results from the grouping of scoring classes 5, 4 and 3 are presented.

Skin characteristics were analysed using three methods: i) analysis of variance of means per bulb, ii) variance-components model fitting by residual maximum likelihood (“REML”) for separating effects of different skins and iii) multiple linear regression for examining relationships.
Analysis of variance of bulb means is relatively simple and can provide an initial indication of effects of factors. It is limited in its application, because different bulbs have different numbers of skins. Analysis of variance does not cope with “unbalanced” data such as this. Also the bulb means are biased by contributions from skins of potentially different type. For example, if low nitrogen treatment had resulted in bulbs with predominantly two skins and high nitrogen in bulbs with four skins, the resulting mean skin thickness for high nitrogen would be markedly influenced by the presence of the two additional “inner” skins. Analysis was restricted to the first three skins, because of the low numbers of fourth and fifth skins. Inclusion of the latter skins resulted in estimation of some very “odd” mean values.

Analysis with REML, overcomes this unbalanced structure and enables comparison of the different skins. To apply REML it is necessary to examine a number of statistical models that included factors in the experiments. The significance of terms in these models was determined initially by examination of Wald tests. The importance of these terms was then gauged by successively dropping them from the chosen model and testing changes in deviance against a chi-squared table. Only significant terms resulting from this procedure were retained. Mean values for significant treatments were then estimated from the resulting model. The importance of the relationships between skin characteristics and their relevance to the effects of factors (such as nitrogen, variety harvest etc) was assessed by including covariates in fixed treatment models.

Relationships between quality and skin characteristics were determined by multiple regression analysis of factors on parameters of these relationships. The significance of effects of factors was assessed by successively dropping factors from statistical models and examining changes in deviance as above.

The probability level for determining the presence of significant differences was taken as p=0.05 (5%). Where possible, least significant differences at p=0.05 are presented to enable direct comparison of means. Means that are significantly different must be separated by at least this value. Otherwise, statistical variation is presented as 95% confidence limits for individual means.

Glossary

Relative humidity Amount of water vapour present in air expressed as a percentage of the amount of water that would be present if the air were entirely saturated.

Stiffness Resistance of material to being stretched, compressed or bent can be described as stiffness. It is usually estimated as the load (or force) per unit area of cross section of a material that is required to deform the material by unit *strain*. It represents the slope or *modulus* of this relationship. Materials with a large modulus are stiff, those with a small modulus are more elastic.

Strain Deformation or displacement of a material under load, relative to its total length.

Stress Load or force applied per unit area of cross section of a material.

Strength Load (force) required to fracture a material expressed per unit area of cross section; referred to as *stress.* (Note that where skin "strength" refers to burst pressure it has not been adjusted for thickness.)

Tensile strength *Strength* determined by pulling a material until it fails (also referred to as *failure stress*).

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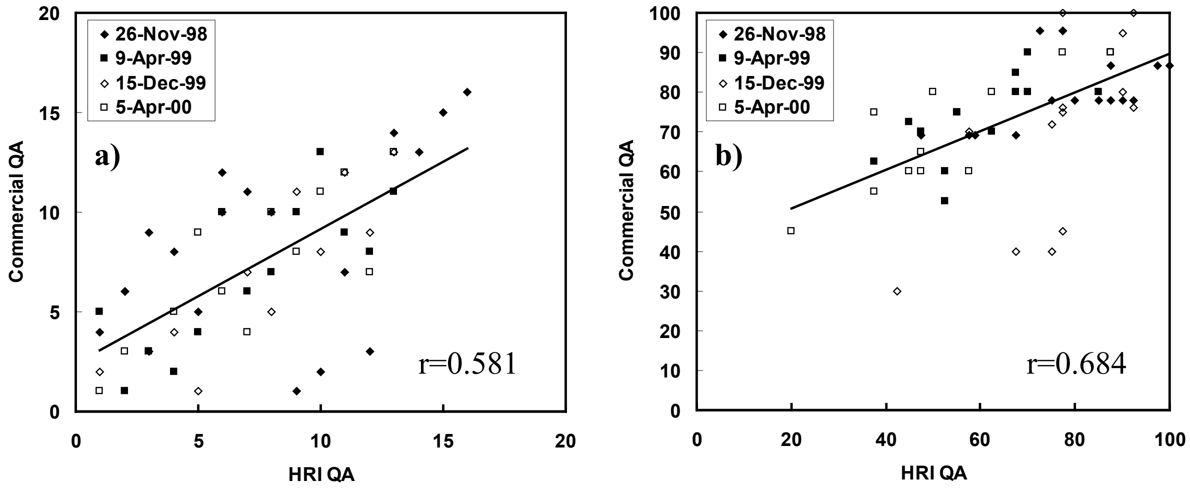
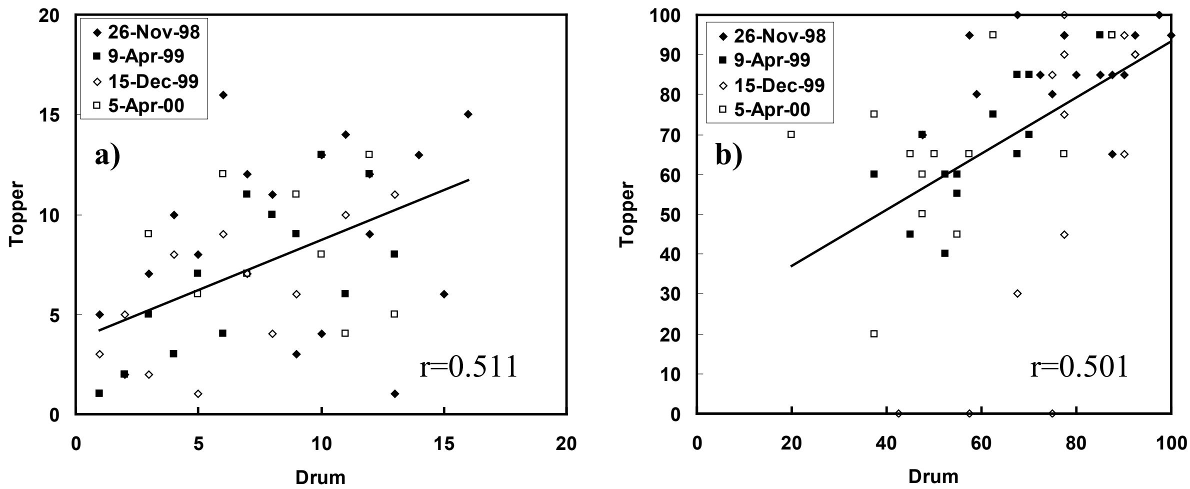
APPENDIX 1.

A significant degree of consistency in assessment was achieved between commercial and scientific staff operating at different times in different places on the same samples (Appendix Figure 1). There was also a significant, though poor, correlation between quality of bulbs after having been subjected to “topper” treatment compared with quality after drum treatment (Appendix Figure 2). Using “ranking” (Appendix Figures 1b) and 2b)) rather than a quantitative values for assessment (Appendix Figures 1a) and 2a)) offered no consistent improvement.

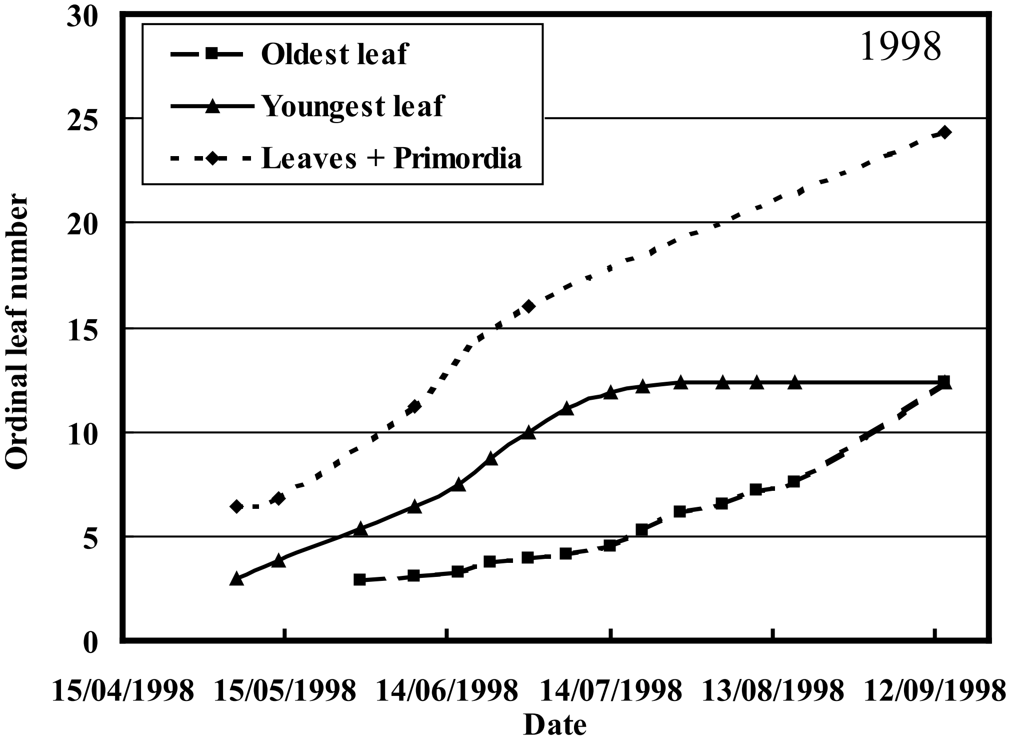


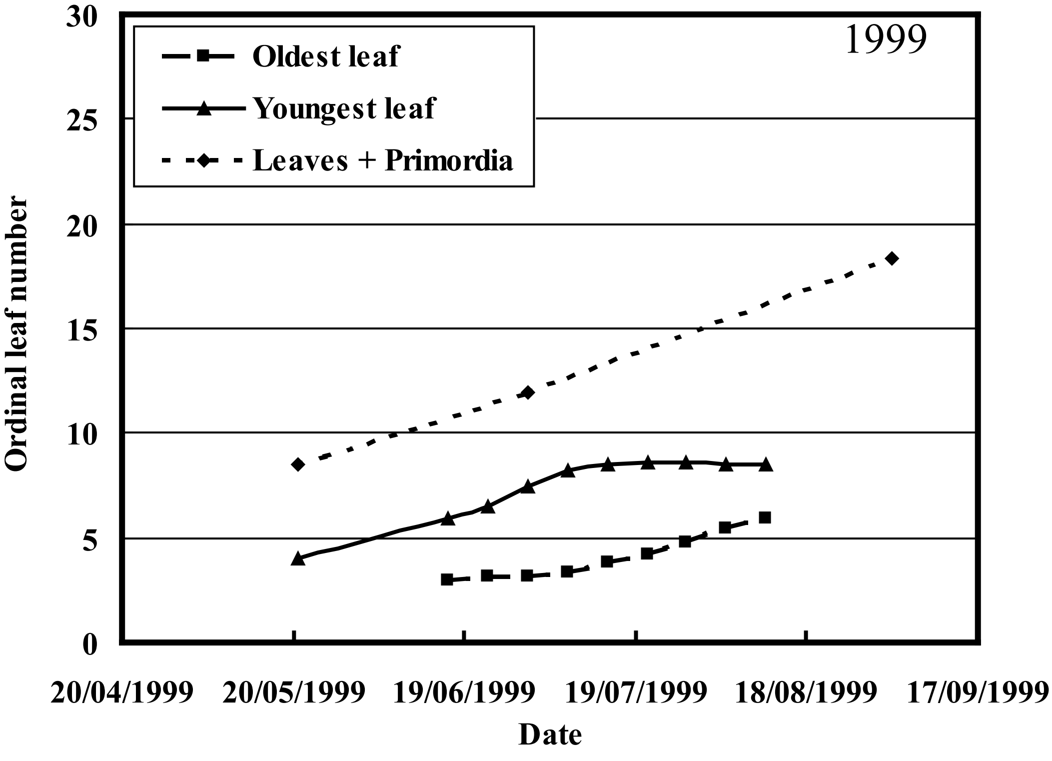
Appendix Figure 1. Relationship between quality assessment done commercially and that done by HRI staff for samples subjected to drum damage simulation test. a) rank position based on proportion of acceptable bulbs, b) proportion of acceptable bulbs. Correlation coefficients, r, are significant at p<0.05.



Appendix Figure 2. Relationship between bulbs subjected to topper and assessed commercially and bulbs subjected to drum damage and assessed by HRI staff a) rank position based on proportion of acceptable bulbs, b) proportion of acceptable bulbs. Correlation coefficients, r, are significant at p<0.05..

APPENDIX 2.
Leaf formation and emergence in 1998 were more rapid and attained greater numbers than in 1999.





Appendix Figure 3. Development, appearance and loss of leaves of onions from experimental crops during 1998 and 1999.

APPENDIX 3.

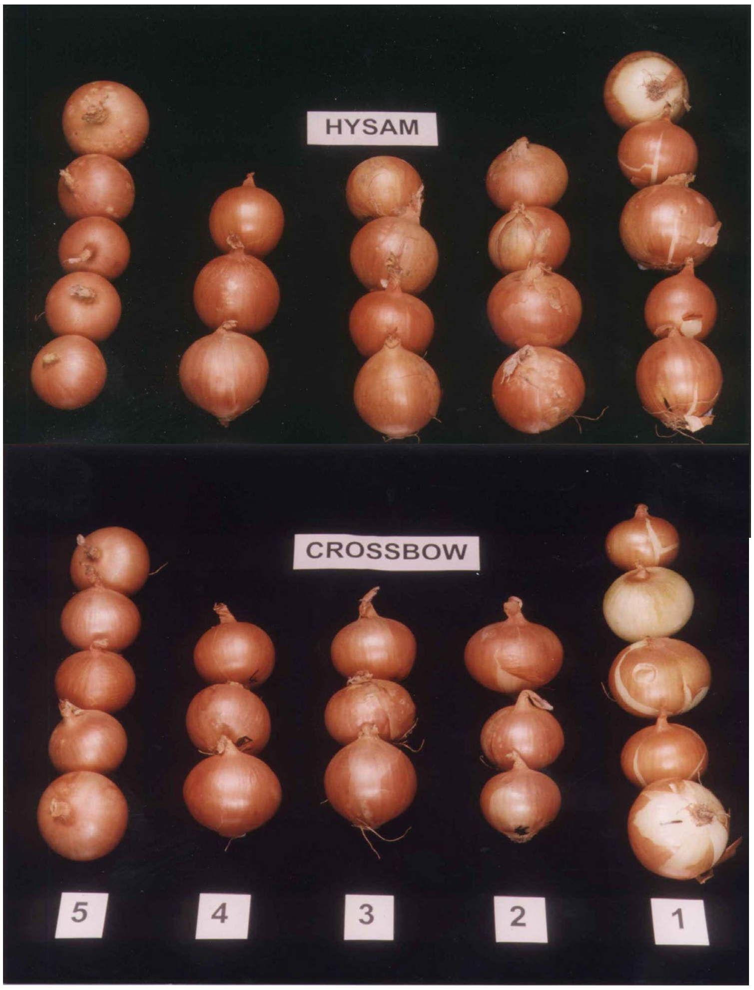
Bulb yields achieved from experimental plots illustrate that the environmental factors had significant effects on the crops (Appendix Table 1). It is important to confirm that some effect occurred because these same factors need not necessarily have influenced quality. The absence of any effects on quality may simply have been due to ineffective treatment. As can be seen from the main body of results, the effects of environmental factors on quality was generally quite small, while yield differences were large. For the two cultivars, yield was the same, but their bulb quality and skin characteristics differed greatly.

Appendix Table 1. Yields of bulbs from experiments 1998 and 1999.

Treatment	Yield, tonnes ha^{-1} 1998	1999
Cultivar		
Crossbow	56.1	16.2
Hysam	56.6	18.4
lsd, p=0.05	6.44	1.71
Water availability		
Sheltered	45.7	14.8
Unsheltered	67.1	19.9
lsd, p=0.05	8.90	3.91
Nitrogen		
Lower rate	51.7	15.3
higher rate	61.1	19.3
lsd, p=0.05	6.44	1.71

APPENDIX 4. ILLUSTRATIONS OF METHODS

Appendix Figure 4. Motor drive unit and drum used to simulate conditions suffered by onions during commercial handling.



Appendix Figure 5. Quality assessment of damaged bulbs

APPENDIX 4. ILLUSTRATIONS OF METHODS [Continued]

Appendix Figure 6. Onion skin blaster. Chamber for measuring the pressure at which onion skins fracture when subjected to multi-directional stress from gas pressure.

Appendix Figure 7. Onion skin stiffness. Sample of skin has been removed from bulb and secured into cardboard template before being stretched to failure in grips of materials testing instrument.

APPENDIX 4. ILLUSTRATIONS OF METHODS [Continued]

Appendix Figure 8. Onion skin permeability testing. Tubes for monitoring the passage of water vapour through skin sealed into the cap by measuring loss of weight of the water-filled tube.

Appendix Figure 9. Onion skin permeability testing. Chamber for monitoring changes in oxygen and carbon dioxide concentration resulting from passage of gas across skin sealed in to top.