Final Report

Reducing the Energy Use and Carbon Footprint of GB Potato Storage

Ref: R439

Reporting Period: September 2010 to March 2013

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1. SUMMARY

This final report covers a project commissioned to investigate how potato store energy consumption is affected by a range of store physical characteristics and operating conditions. The project also continued a period of long-term intensive energy monitoring for stores and contains a section regarding carbon footprinting of potato storage.

The store physical characteristics and operating conditions studied included:

- Air leakage - through doors, louvres, holes etc.
- Refrigeration system efficiency.
- Insulation - type and quantity.
- Air movement efficiency.
- Temperature uniformity within store.
- Humidification and adiabatic cooling.
- Store management and control.

Air Leakage

A method for testing buildings for air tightness (Appendix 3) was used to assess air leakage. The results can be expressed in a number of ways, including:

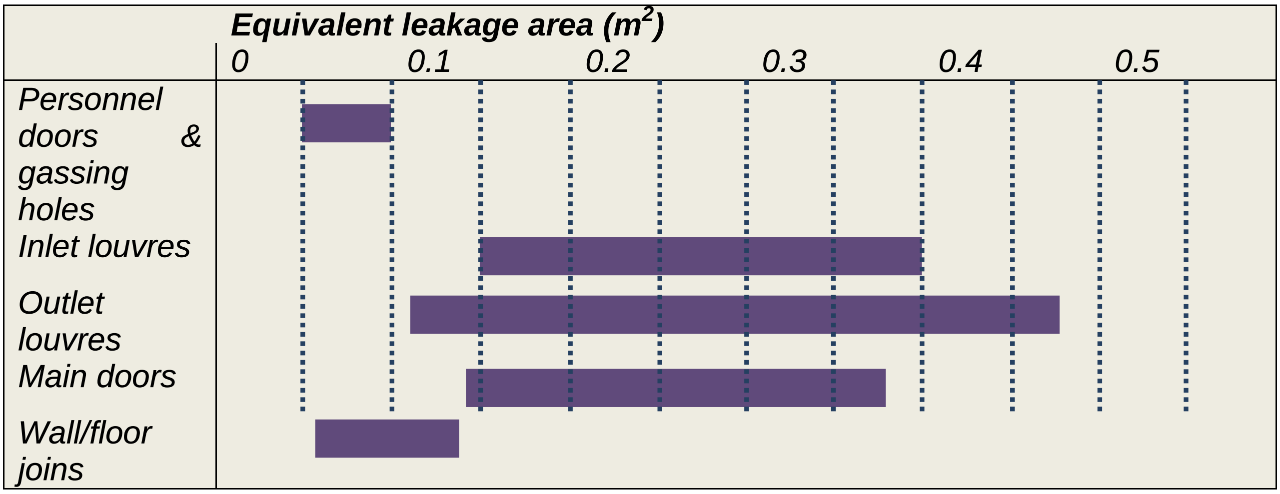
Equivalent leakage area – m^2

This is a useful way of helping a user to visualise leakiness. It expresses leakiness in terms of an equivalent size of a 'hole' in the store wall of which, by itself, would lead to the leakage measured.

The main areas of air leakage were found to be:

- Personnel doors.
- Louvres and louvre frames.
- Main doors.
- Store fabric (maintenance issues).

Figure A (below) shows the ranges of equivalent leakage area for each building component.



The results were used to calculate the energy loss from the stores as a result of air leakage. The calculations showed that air leakage can be responsible for up to 37 % of the store's total energy consumption (pre-pack) and 55 % (processing). If store improvements are made, these figures can be reduced to 4 % and 2 respectively, although it is important to note that for many stores, some form of controlled management of atmosphere will be needed. This will prevent unwanted and potentially damaging accumulation of carbon dioxide which can result in deleterious effects on fry colour (this is usually regulated through a fresh air flushing regime on the store controller) and, *in extremis,* may also be hazardous to health for personnel working within the store.

Refrigeration systems

Mechanical refrigeration cooling usually employs a direct gas expansion (DX) system which passes a refrigerant fluid round a pipe loop between the inside and outside of the building. The gas/liquid change of state provides low inside temperatures, whilst transferring heat energy to a higher temperature state outside.

As refrigeration systems are a form of heat pump – they use electrical energy to power the pumping of heat from a colder environment to a hotter one – their efficiency can be express in terms of the ratio of cooling power delivered to the electrical energy consumed by the system. The Coefficient of Performance (COP) is a dimensionless relationship of the electrical input to the cooling energy provided:

$$Coefficent\ Of\ Performance\ (COP) = \frac{kW_{coolingpower}}{kW_{electricalpower}}$$

The COP of a 'typical' DX refrigeration system used in pre-pack storage would be 2.5 to 3.5 whilst in processing storage the typical COP is between 3 and 4. (A COP of 3 means that three times as much cooling energy is delivered as electrical energy input, i.e. if a system provides 100 kWh of cooling energy at a COP of 3 then 30 kWh of electricity will have been consumed to deliver it.). Usually the lower the required cooling temperature, the worse the COP – hence the better performance of a processing store.

Refrigeration systems were tested to establish their efficiency and what could be done to improve them. The range of efficiencies as expressed in terms of COP was 1.6 - 4, i.e*. a variation of 2.5 times from best to worst*.

Some of the changes that could be made to improve efficiency are:

- State of the art system versus average system.
- Replacing condenser fans with modern EC fan types.
- Optimising condenser fan and thermostatic valve settings.
- Better maintenance and topping up refrigerant levels.

Examples of these changes, from specific case studies are provided below (images of the stores are provided in Appendix 5):

Case Study 1: 'State of the art' refrigeration system

This case study involved a store designed to cool produce to -2°C. The store was included in the project because it has many 'state of the art' features, which would tend to make the refrigeration system higher in efficiency than normal.

A test was carried out in April 2011 and the efficiency (COP) was measured at 3.87. This was achieved with a target store temperature of -2°C. (At a higher store temperature of 2 – 3°C, the COP might be expected to be nearer to 4.5). This is a good efficiency level.

The components of the system which made this system more efficient were:

- Variable speed drive compressors – allowing exact matching of cooling demand to performance.
- Variable speed condenser fans – ensuring the system operated in very stable conditions.
- Large condenser – ensuring heat could be removed quickly and efficiently.
- Dedicated sub cooling – ensuring the refrigerant was presented to the compressors at optimal conditions.
- Electronic expansion valves – ensuring correct utilisation of the evaporators for maximum stability and performance.

None of the technology installed on this store could be considered as being exotic or prohibitively complex or expensive. It is all readily-available for potato store refrigeration plant installations.

As an illustration of the benefit of this type of equipment, running cost figures are shown for a typical pre-pack store running at an average COP of 2.6 and one running at an average COP of 4.

	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes pre-pack storage in Store 5
COP 2.6	38.5	**£4,950**
COP 4	22.2	**£2,860**

Table A – Comparison of cooling costs at higher COP

Case Study 2: Condenser fan replacement

The refrigeration system on the store in this case study consists of an in-store evaporator in an air handling unit (overhead throw) with a remote external drive compressor and externally-mounted condensers. The original efficiency tests carried out in April 2011 concluded that the system had an efficiency COP of 2.66, which could be improved to 2.81 with the following improvements:

- Install VSD or EC (electronically commutated) fans to control condensing pressure.
- Alter TEV settings or install electronic expansion valves.

EC fans were provided by the manufacturer (EBM Papst) for us to trial. The installation was carried out in September 2011. A full retest was carried out on this day prior to and after the new EC fans were installed.The system efficiency was calculated in a slightly different way (the electricity consumption of the fans was included in the COP calculation) to ensure that the results were comparable.

The results achieved were:

- An increase in cooling duty of 8.5 kW (10 %).
- A slight electrical power increase of 0.8 kW.

- An increase in whole system efficiency of 10 %.
- COP prior to installation of 2.9 and COP after installation of 3.2.
- A much more stable cooling delivery.

The effect of the change of fans is a system inherently more stable and predictable in operation, with less potential for breakdowns and with an efficiency improvement of over 10 %. Table B below shows the effect on operating costs that this change will have.

	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes pre-pack storage in Store 5
COP 2.9	34.5	**£4,438**
COP 3.2	31.3	**£4,022**

Table B - Comparison of cooling costs with EC fans

The EC fans will cost £60 - £100 each and this installation would cost approximately £500-£750 fully installed.

Case Study 3: Condenser and TEV optimisation

The refrigeration in this case study is provided by a remote condenser/compressor unit (Friga-Bohn) with an in-store evaporator. Being a bulk store the evaporators sit at the top of the crop and air is pulled through them for redistribution via the central duct and lateral underfloor ducts.

During the first test, the refrigeration system was operating at part load and the condenser fans were found to be cycling from both fans off to one fan running, to both fans running and back again. This was leading to instability of cooling delivery and causing the unit as a whole to operate below maximum efficiency.

Two suggested condenser improvements were to:

1. Reduce the condensing temperature set point so that the fans cut in earlier; and
2. Remove the grilles from the base of the condenser pack to allow a better flow of air.

In addition, it was believed that the TEV settings were sub-optimal, as the store was designed to provide cooling for onion storage as well as potato storage.

The following table details the results and the expected efficiency increase for the suggested changes:

Capacity	Power input	Evaporating	Superheat	Condensing	Sub cooling	COP
kW	kW	°C	K	°C	K	x:1
101.3	**38.9**	**-5**	**15**	**44**	**8**	**2.60**
111.3	39.2	-3	12	42	7	2.84
117.6	38.8	-2	10	40	6	3.03
123.2	38.3	-1	8	38	5	3.22
132.9	**37.2**	**0**	**5**	**35**	**4**	**3.57**

Table C - Improvements to Store 7 system efficiency

A retest was carried out in September after the settings were changed. Unfortunately, the benefits of the change were not immediately obvious, as the system was operating at full load and the changes that were made only affect the efficiency at partial load. Additionally, the refrigerant charge was low and this affected the TEV operation which remained fully open throughout to compensate.

Table D below shows the effect on operating costs for 1,000 tonnes of processing storage with the suggested change. This change is a very low cost (sub £250) alteration, as it is only altering the settings on the system and does not require additional or replacement equipment.

	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes processing storage in Store 7
COP 2.6	13.9	**£412**
COP 3.57	13.3	**£395**

Table D - Savings achieved by improving COP on 1,000 tonnes processing storage

Case Study 4: Maintenance

The refrigeration system in this case study is typical of many refrigeration units found in box potato stores. As a packaged unit, it has two compressors with the condensers built into the box beneath the evaporator. The system was tested first in May 2011 and the COPs achieved at that visit were:

- Large compressor circuit - 1.57.
- Smaller compressor circuit - 1.67.
- Average - 1.62.

The system may have been said to have been 'showing its age' and total replacement was suggested. If it was to be kept, then remedial works were necessary to keep the system operational including repairing a refrigerant leak, and needing to recharge the system with refrigerant and top up with oil (during the test the compressors continually tripped out on low oil pressure).

The system was repaired and a retest was carried out in September 2011. The following COPs were measured:

- Large compressor circuit - 1.51.
- Smaller compressor circuit - 1.77.
- Average - 1.64.

The system performance improved for the smaller compressor but was worse for the larger compressor. Again, the system continually tripped out on low oil, suggesting that the repairs have not been successful. It has subsequently been recommended that there is a total replacement of the unit in order to achieve an average system COP of 3.3.

Table E below shows the anticipated difference in cost by replacing the refrigeration system on electricity use alone. The savings will be far greater than this, as there will be reduced maintenance and also the risk of cooling loss is mitigated, and hence the savings from maintaining crop quality will be great.

.	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes processing storage in Store 9
COP 1.6	22.6	**£1,193**
COP 3.3	11	**£580**

Table E – Savings achieved by replacing the refrigeration system in a 1,000 tonnes processing store

Although a payback on capital based on energy saving alone would be long for this store, the existing system could ultimately fail to deliver critical cooling and could jeopardise the quality of the crop in the store. Continuing heavy repair costs for this system also needs to be considered as it deteriorates further.

Insulation

Better insulation reduces the need for heating or cooling of a building by reducing heat transmission through the structure. Savings with modest improvements in insulation in box stores (adding 50 mm of spray foam to a store with 50 mm spray foam initially) can result in savings of 11.8 %. Increasing composite panel thickness to 120 mm from 80 mm resulted in a 6 % saving, while going from 100 mm to 150 mm Styrofoam board resulted in a 7.6 % saving. The same improvements in a bulk store resulted in 1.4 %, 1.9 % and 2.1 % savings, respectively.

Air Movement Efficiency

Box and bulk stores have very different internal ventilation and air movement requirements. In a bulk store, where air is ducted to where it is needed, air volume and pressure drops are key energy related drivers. In a box store air volume and air speed (which determines distance the air travels) are the key energy drivers. We found that for some box stores, while the volume of air delivered was meeting guidelines, air speeds and consequently distribution were not satisfactory. In some cases too low velocities lead to inadequate air mixing. In other stores volume delivered was far more than was necessary. On the whole, fan installations were sized appropriately for early crop conditions, but appeared to be over-ventilated for the remainder of the storage time. Variable speed fans are suggested as an energy saving addition.

Spatial temperature uniformity in potato box stores was evaluated and showed inconsistencies associated with air mixing. We also evaluated the use of air divider curtains which were shown to reduce air short circuiting and increase airflow to the pallet slots. However localised variations were still evident.

Humidification and adiabatic cooling

Humidification was assessed at two ambient stores and was shown to be effective but, like all other heat transfer processes, was inherently prone to some inefficiency. This means that the extent of any adiabatic cooling, whilst worthwhile in offering extended hours of ambient ventilation, will not necessarily deliver the full theoretical cooling which needs to be accounted for in quantifying potential benefits. Nevertheless, the value of adiabatic cooling as a potential means of achieving closer control of temperature (especially after loading) and reducing dependence on refrigeration was demonstrated.

Store management
A limited survey of store management practices showed adoption of improved monitoring and ventilation technology especially within existing stores. Ventilation changes have perhaps been in response to CIPC sprout suppressant use. However, it was also evident that some parts of the industry, notably the processed chipping sector, have failed to make improvements to stores as much as others.

Long-term intensive energy monitoring for stores
The ranges of energy consumptions for storage monitored in the 2010/11 and 2011/12 seasons are shown below.

	2010/11 season (kWh/tonne/day)		2011/12 season (kWh/tonne/day)	
	Highest	Lowest	Highest	Lowest
Pre-pack	0.21	0.43	0.35	0.51
Processing	0.1	0.2	0.11	0.34

These results are broadly in-line with previous years' numbers, and show that the set of stores in the project are representative of the storage types in the UK. The differences in energy consumption between the most and least efficient stores can be over two fold, with consequent differences in energy costs. Energy monitoring need not be expensive and simple analyses such as kWh/tonne/day can quickly highlight stores, or periods, when efficiencies fall.

Carbon footprinting of potato storage.
Carbon footprinting, as a way to identify the environmental impact of the storage process, has become more common in the potato industry. Carbon footprint figures generated by different organisations are not always consistent primarily because of different the boundaries as to what is or isn't included in the calculations between different studies. The publically-available carbon footprints give potato storage a range of 49.83 kgCO_2e/tonne to 32.68 kgCO_2e/tonne. In this project these footprints were assessed and independent footprints calculated based on best available knowledge.

The independent carbon footprints of potato storage for different storage types are:
1. Pre-pack, 3 °C, 7 months - 45.4 kgCO_2e/tonne.
2. Processing, 7.5 °C, 10 months - 39.2 kgCO_2e/tonne.
3. Processing, 10 °C, 6 months - 30.77 kgCO_2e/tonne.

Information has been provided within the report that would enable a store manager to calculate their own carbon footprint. In the context of the UK carbon emission reduction targets, it is anticipated that there will be increased demand for carbon footprint information as a way of demonstrating compliance with the reduction targets.

This project has identified and quantified cost-effective energy related savings which are available to most sites. However it's clear that the degree of savings and what needs to be done to achieve these are poorly understood

As part of the Potato Council's forthcoming *Storage 2020* communication initiative, a series of measures is being undertaken to raise awareness and effect change within industry:

- A one-stop, web-based signposting project launching in November 2013 to direct store owners and managers to the most relevant and up to date information on energy saving measures and store management best practice to allow stores to be run as cost-effectively as possible.
- An international conference on February 2014 to discuss opportunities to develop storage in Great Britain to meet current market needs and future challenges.
- A new nationwide store auditing service from spring 2014 to assess stores' effectiveness and provide guidance and recommendations on a store-by-store basis to improve performance.
- A major knowledge transfer day at Sutton Bridge CSR focusing on storage in July 2014.

1. INTRODUCTION

This project has examined energy use in commercial potato stores; specifically its variability across sites and seasons, and the component energy uses which are responsible for this.

The work has been prompted by the following issues.

1.1. Energy use variability

Potato Council's Project R401 – 'Reducing the cost of GB potato storage' (September 2007 - September 2010), which monitored the energy consumption of 32 potato stores over two seasons, concluded that the variation in the amount of energy used for potato storage by different stores is large.

The likely contributing factors to variations in store energy use are:

- Store management and control.
- Air leakage – through doors, louvres, holes, etc.
- Refrigeration system efficiency.
- Insulation – type and quantity.
- Air movement efficiency.
- Temperature uniformity within store.
- The use of Humidification and Adiabatic cooling.

We have carried out tests and done modelling on separate groups of pre-pack and processing stores, of different ages, types and construction to represent a broad cross-section of potato store designs.

1.2. Need to reduce carbon

Reducing energy use for storage is obviously important – not only for minimisation of costs, but also for environmental reasons. Energy use leads to the production of greenhouse gases and global warming, so its overuse is not desirable. The government is targeting a 26 % reduction in UK carbon emissions by 2020 over the base year of 1990[1].

Carbon footprinting of the storage process has become more common, but this is only realistic when proper evaluation of energy use is undertaken. With a 35 % difference between the smallest and largest published carbon footprint (32.68 kg/tonne to 49.83 kg/tonne) for storage, there is clearly some need to establish why there is a difference. It may be a realistic reflection of the true difference between store performance. However, it also is more likely to be as a result of variations in the way the carbon footprint has been calculated and the boundary conditions used. Part of this project covers a review of published footprinting work and a commentary on the reasons for the variations. An independent footprint has been included, based on results from the project.

[1] The UK's legally binding target under the Climate Change Act 2008 is to cut greenhouse gas emissions by 26 % by 2020 and 80 % by 2050 (1990 baseline).

1.3. Need to reduce costs

The graph in Figure 2.3.1 below shows how wholesale electricity prices have changed since the beginning of the project.

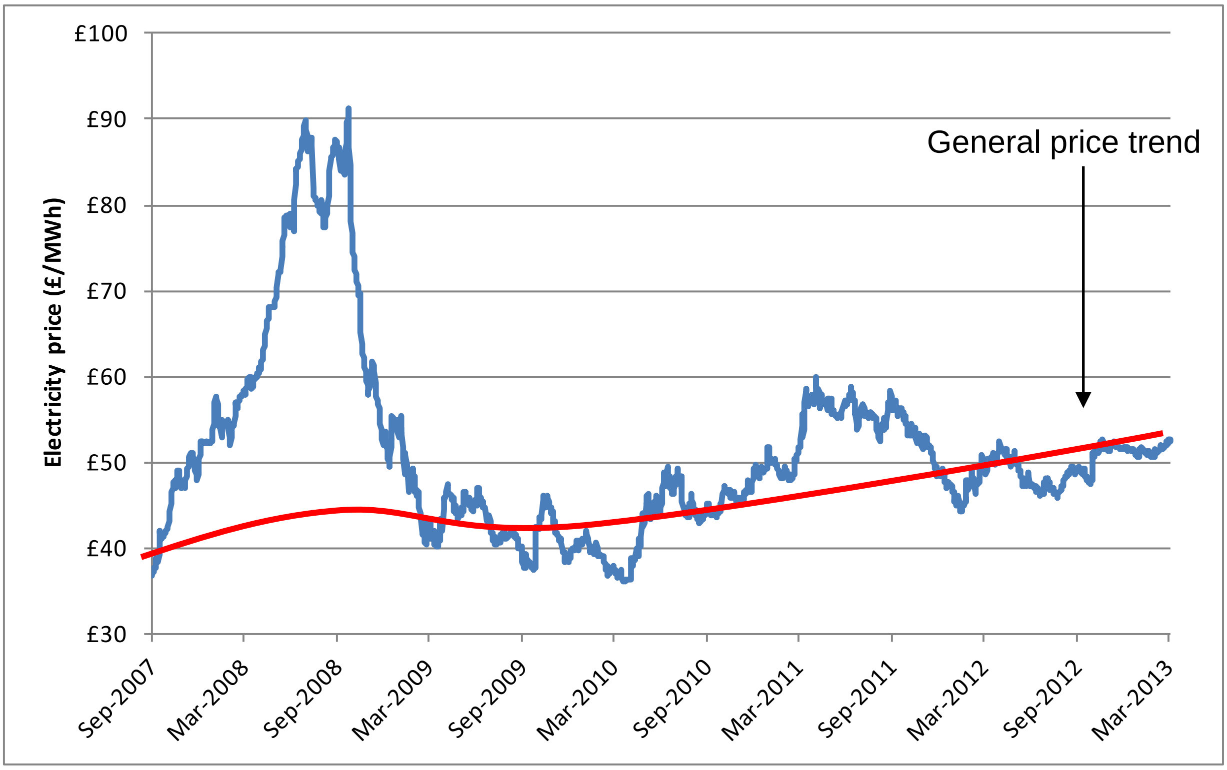


Figure 2.3.1 - Energy price changes (£/MWh)

The large blip in energy prices in 2008 was due largely to political pressures in the Middle East. Prices have remained in check in the last 12 months, which is a result of poor economic conditions in the UK and rest of the developed world. But even ignoring these, it's evident that the base price for wholesale electricity has increased from just over £35 per MWh in September 2007 to £52 per MWh in March 2013 (48 % increase).

A change in the economic climate and improving confidence in business and the stock market is likely to cause energy price increases. This is because energy is required for economic growth and as demand grows, energy supply becomes limited. Renewable energy production is, in the short term, driving prices higher through introduction of levies to cover the costs of FiTs (Feed-in Tariffs) and the Renewable Obligation (RO).

Table 2.3.1 gives typical prices charged in the commercial retail sector – rates which would have been available to potato producers (50,000 kWh represents the consumption of a typical 1,000 t pre-pack store).

Date	Contract energy cost (pence/kWh)	Annual cost of a 50,000 kWh site (£)	Cost difference from 2006 (£)
01/09/2006	8.25	4,125	0
01/09/2007	6.89	3,445	-680
01/09/2008	12.3	6,162	2,037
01/09/2009	8.99	4,495	370
01/09/2010	9.87	4,935	810
01/09/2011	10.35	5,175	1,050
01/09/2012	9.88	4,940	815

Table 2.3.1 - Typical energy prices and cost for a 50,000 kwh contract

2. EXPERIMENTAL SECTION

2.1. Physical store tests description

Work has been undertaken on 17 stores in this part of the project. Investigation in Year 1 (2010/2011) covered the following areas:

2.1.1. Intensive energy monitoring (9 stores)

The monitoring of electricity consumption of the store on a half-hour by half-hour basis over the whole of the storage period, alongside store and ambient temperature and the tonnage of crop stored. This activity extends the work which was undertaken in R410 to provide three seasons concurrent intensive energy monitoring.

2.1.2. Air leakage testing (8 stores)

We measured leakage of stores using a pressurisation and air-flow method at various levels of store sealing. It's suspected that substandard sealing of stores could be a significant cause of high energy use.

2.1.3. Refrigeration testing (10 stores)

We employed an advanced system to look at refrigeration efficiency. The system involved the monitoring of refrigeration gas/liquid pressures and temperatures and energy used by the compressor and condenser fans. Refrigeration is the largest consumer of energy in long-term storage, so the efficient operation of the refrigeration system is fundamental to achieving lowest running costs.

The following work was carried out in Year 2:

2.1.4. Insulation - type and quantity (8 stores)

We surveyed the insulation type and thickness and carried out a physical 'hot box' test to determine its effectiveness. Thermal imaging was used to ascertain any degradation and de-lamination. Good quality and appropriate levels of insulation is key to maintaining a consistent environment within the store and minimising energy use.

2.1.5. Air movement efficiency (8 stores)

The store fans' air delivery volume and pressures were measured against energy consumption. With many stores built and equipped to 'rules of thumb' criteria it is thought that different fan types and design of ducts can improve efficiency. The reduction in costs of variable speed fan drives offers a good opportunity to save energy with existing equipment but their use must not compromise store environment.

2.1.6. Temperature uniformity within store (2 stores)

We measured the temperature uniformity and return air speeds in two identical stores - one with an air curtain and one without - to ascertain if the conditions were improved with the curtain.

2.1.7. Humidification and adiabatic cooling (2 stores)

Humidification is increasing in popularity but remains a feature of a small minority of stores. As well as increasing humidity it offers the potential benefit of additional cooling through transfer of latent heat and so it can extend the availability of ambient cooling. A measure of the efficiency of this process is required.

2.1.8. Store management and control survey

The adoption of energy saving measures and other improvements to stores is an important part of maintaining their fitness for purpose in supplying high quality potatoes for today's markets. A survey of store managers was included to quantify uptake of these changes.

2.2. Schedule of stores tested

Table 3.2.1 below shows the stores tested and the type of tests carried out in this project.

Store name	Produce stored	Box or bulk	Capacity (tonnes)	Intensive monitoring energy and temperature	Refrigeration tests	Air leakage tests	Store management tests	Insulation	Air movement efficiency	Temperature uniformity	Humidification and adiabatic cooling
Store 1	Pre-pack	Box	1,200	☑	☑		☑				
Store 2	Pre-pack	Box	1,200	☑	☑	☑	☑	☑	☑		
Store 3	Pre-pack	Box	1,200	☑							
Store 4	Pre-pack	Box	800	☑	☑		☑	☑	☑		
Store 5	Pre-pack	Box	1,100	☑	☑	☑	☑	☑	☑		
Store 6	Processing	Bulk	2,800	☑							
Store 7	Processing	Bulk	2,800	☑	☑	☑	☑	☑	☑		☑
Store 8	Processing	Bulk	5,400	☑		☑	☑				
Store 9	Processing	Box	1,100	☑	☑	☑	☑	☑	☑		
Store 10	Other produce	Box	N/A[2]		☑						
Store 11	Pre-pack	Box	1,200		☑	☑	☑	☑	☑		
Store 12	Pre-pack	Box	1,200		☑			☑	☑		
Store 13	Other produce	Bulk	N/A[2]		☑						
Store 14	Pre-pack	Box	1,300			☑		☑	☑	☑	
Store 15	Processing	Bulk	2,600			☑					
Store 16	Pre-pack	Box	1,300							☑	
Store 17	Processing	Bulk	2,500								☑

Table 3.2.1 - Store investigations

2.3. Potato store simulation

As well as physical tests on real stores, a mathematical model was used to simulate the effect on energy use of the changes shown in Table 3.2.1.

We produced a simulation or 'model store'. This store is represented in equations within a Microsoft Excel spreadsheet.

This was extremely useful as it allowed the fixing of all variables which could affect energy use apart from the ones which were being evaluated. Physically, this would be

2 N/A - Not Available as these stores do not hold potatoes

impossible to do because of the huge variety of type, design and construction of potato stores and also the infinite permutations of weather conditions which are experienced. A simulator is the only way of making independent comparisons.

The simulation was validated by using energy data recorded in real stores.

The model store is based on a building containing 1,000 tonnes of crop, either in bulk or in boxes. The building stands alone and does not share any walls with other buildings or stores. Figure 3.3.1 is a visual representation of the model store for pre-pack produce and Figure 3.3.2 represents the processing model store.

Figure 3.3.1 - Pre-pack model store

Figure 3.3.2 - Processing model store

Table 3.3.1 shows the changeable parameters for the simulated stores.

Parameter	Pre-pack	Processing
Store capacity	1,000 tonnes	1,000 tonnes
Type of storage	Box	Bulk or box
Cooling system	Refrigerated only or refrigerated and ambient	Ambient only or ambient and refrigerated
Air leakage rates	Variable	Variable
Refrigeration efficiency	Variable	Variable
Insulation thickness	Variable	Variable

Table 3.3.1 - Model store parameters

2.4. Intensive energy monitoring

2.4.1. Materials and methods

We used intensive energy monitoring in nine stores; temperatures and crop content were also monitored. Stores were fitted with a remote data logger, which read the electricity consumption, the store temperature and the ambient temperature every half-hour. The data was collected in the same manner as in project R401. Appendix 1 reproduces the section about data collection from the 2008 interim project report.

2.4.2. Results

2.4.2.1. Outside temperature

The graph in Figure 3.4.1 below shows the difference in outside temperature for the two seasons 2010/11 and 2011/12 against, in each case, the average of the two preceding seasons. A negative value represents a colder period and a positive value represents a warmer period.

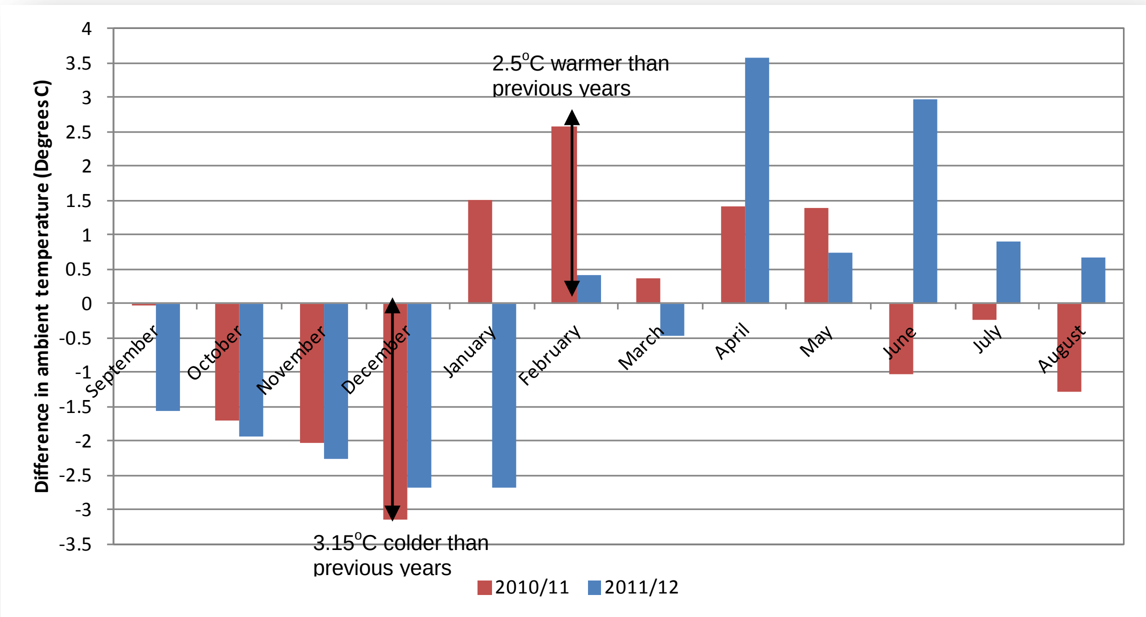


Figure 3.4.1 - Average monthly difference in outside temperature 2010/11 to average of previous two seasons

The graph shows a colder autumn, an early winter and a warmer spring.

From this one would expect that:

- Energy consumption for curing and pull-down would be less.
- Processing storage energy consumption in early winter would be more, as heat would be required.
- All stores would see an increase in energy throughout the spring.
- Long season storage should have reduced energy consumptions in June and July 2011.
- Long-season' energy consumptions would be higher in April – July 2012.

2.4.2.2. Rainfall

Apart from outside temperature the other main external influence to store energy consumption is the harvest condition of the potatoes – specifically how wet they are going into store. The wetter the crop the longer the fans must operate to dry them. A wet harvest generally means one with greater post-harvest energy consumption.

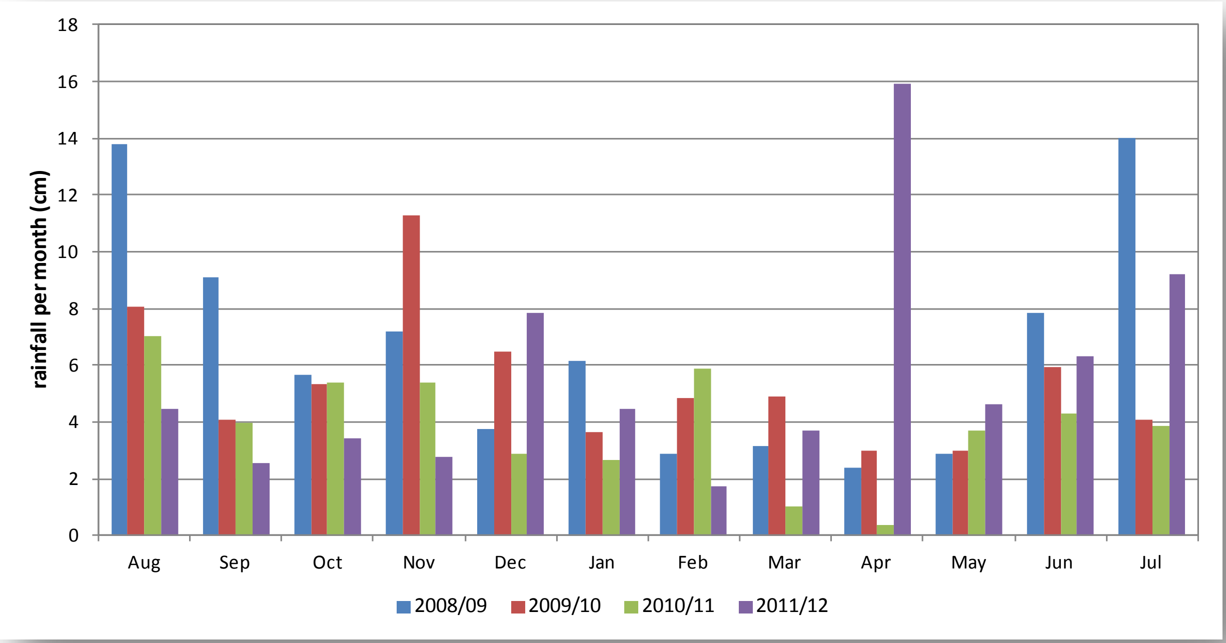


Figure 3.4.2 - Monthly rainfall for the past 4 years

Figure 3.4.2 above shows that 2010/11 season had average rainfall whilst the 2011/12 season had the driest harvest months of all years. This was borne out by the anecdotal evidence which shows this year had very little crop storage problems and that many people stored produce well into June quite easily.

2.4.2.3. Pre-pack storage

The graph in Figure 3.4.3 shows the energy consumption of the stores monitored during the 2010 to 2011 season expressed in kWh/tonne per day. The graph in Figure 3.4.4 shows the energy consumption of the stores monitored during the 2011 to 2012 season expressed in kWh/tonne per day.

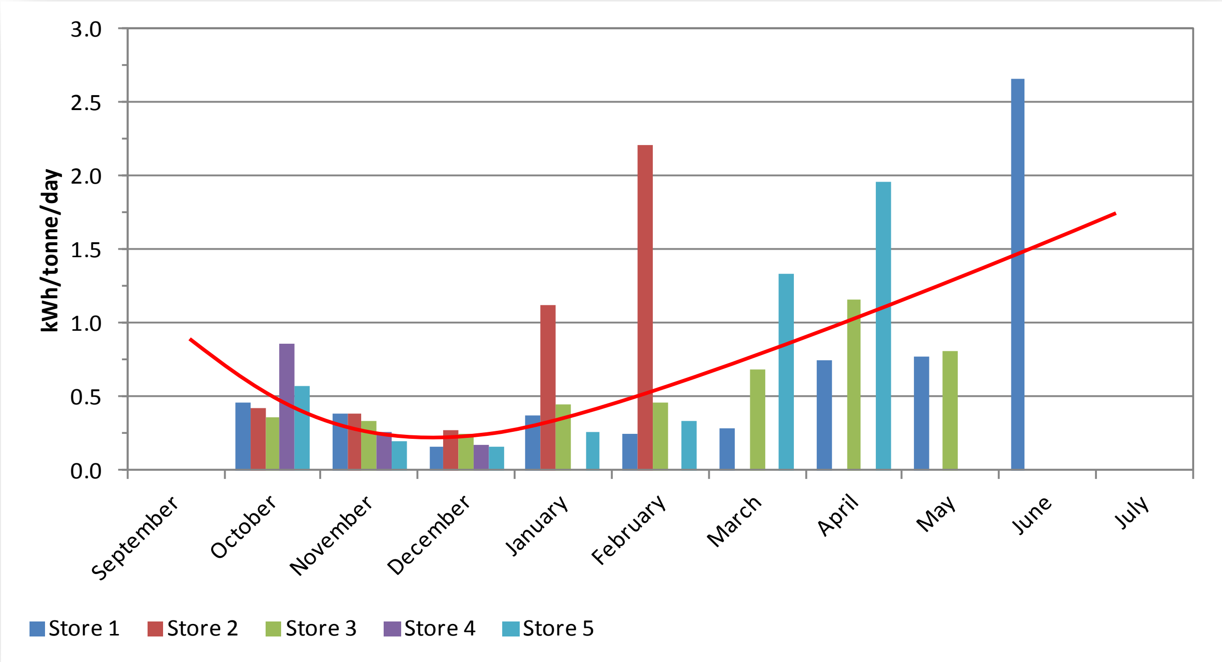


Figure 3.4.3 - Energy consumption of the pre-pack stores in kWh/tonne/day (2010/2011)

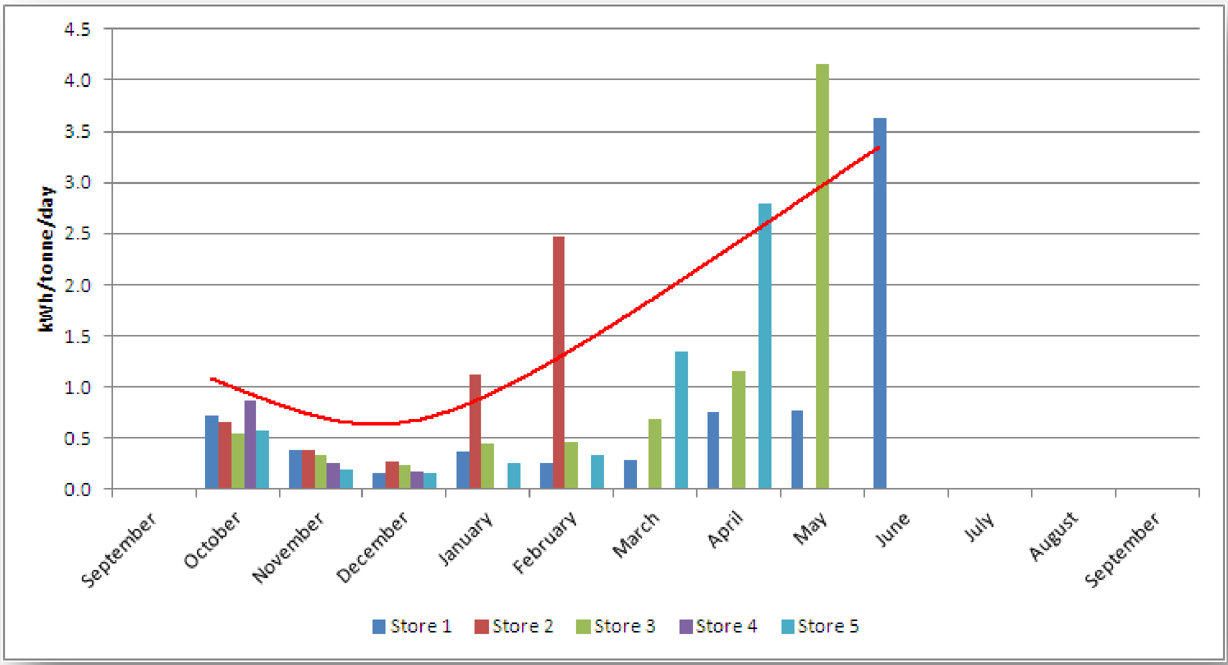


Figure 3.4.4 - Energy consumption of the pre-pack stores in kWh/tonne/day (2011/12)

Figure 3.4.5 shows the mean consumption per month of the pre-pack group.

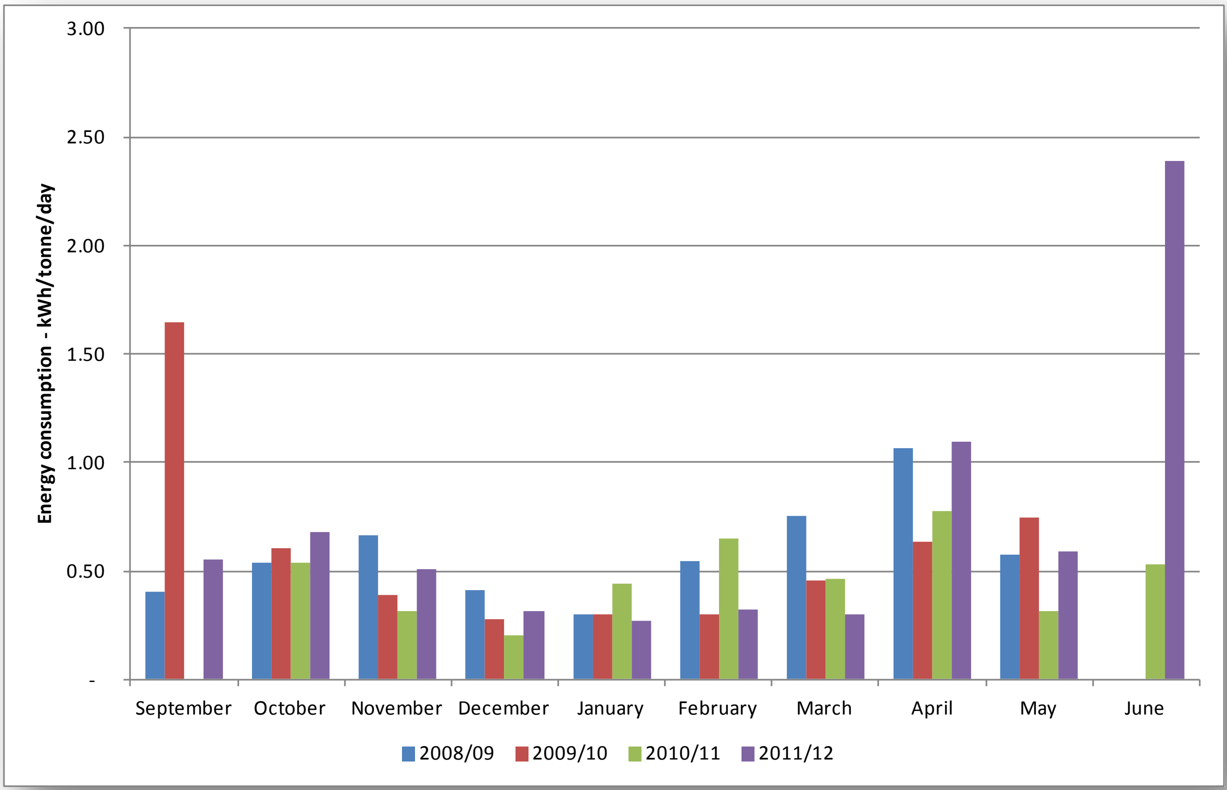


Figure 3.4.5 - Comparison of energy consumption achieved in the monitored years for the pre-pack stores

For the 2010/11 season, the stores used less energy in the months leading to January, more energy in January and February and then there was little difference in the following months. This is reasonably consistent with what would be suggested by the effect of ambient temperatures – January and February were comparatively mild months in 2010 and 2011.

Generally, the 2011/12 is consistent with past performance after ambient temperature effects are accounted for. The stores used more energy in the early season and less energy in January, February and March. Data looks a little erratic thereafter due to potatoes being taken out of different stores at different times.

Table 3.4.1 shows the energy consumptions in the 2011 to 2012 season compared to energy consumptions from other monitored years. Stores 1, 2 and 3 were not intensively monitored in the previous project, so there is no historic data available.

Store Name	Store 1		Store 2		Store 3		Store 4			Store 5		
Season	**2010/11**	**2011/12**	**2010/11**	**2011/12**	**2010/11**	**2011/12**	**2007-10 Average**	**2010/11**	**2011/12**	**2007-10 Average**	**2010/11**	**2011/12**
Storage length (days)	254	212	137	272	207	210	153	92	151	174	203	228
Target temperature (°C)	2.5 - 3	2.5 - 3	2.5 - 3	2.5 - 3	2.5 - 3	2.5 - 3	3	2.5	3	3	2.5	3
Ambient cooling available	✓	✓	✓	✓	✓	✓	*X*	*X*	*X*	*X*	*X*	*X*
Refrigeration available	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Electricity consumption (kWh)	111,988	102,959	54,884	130,385	91,499	107,528	37,071	8,624	49,784	54,273	59,043	80,860
CO_2 equivalent (t)	60.1	55.3	29.5	68.8	49.1	57.7	20.2	4.6	26.6	29.6	31.7	43.4
Store quantity (tonnes)	1,393	1,109	931	969	1,217	1,138	797	333	810	1,298	1,382	1,315
Average daily energy consumption (kWh/tonne/day)	**0.32**	**0.44**	**0.43**	**0.49**	**0.36**	**0.45**	**0.38**	**0.28**	**0.41**	**0.25**	**0.21**	**0.41**
CO_2 equivalent (kg/tonne)	*0.17*	*0.23*	*0.23*	*0.26*	*0.20*	*0.25*	*0.21*	*0.15*	*0.22*	*0.13*	*0.11*	*0.21*
Full store SEC[2] per day (kWh/tonne/day)	**0.28**	**0.39**	**0.35**	**0.47**	**0.31**	**0.43**	**0.51**	**0.46**	**0.51**	**0.37**	**0.20**	**0.35**
CO_2 equivalent (kg/tonne)	*0.15*	*0.21*	*0.19*	*0.25*	*0.17*	*0.24*	*0.27*	*0.25*	*0.28*	*0.20*	*0.11*	*0.19*
Cumulative SEC (kWh/tonne)	**184.3**	**99.9**	**130.1**	**153.1**	**137.1**	**97.5**	**115.5**	**39.9**	**66.2**	**65.7**	**146.7**	**78.8**
CO_2 equivalent (kg/tonne)	*98.9*	*53.7*	*69.9*	*82.2*	*73.6*	*52.4*	*62.0*	*21.4*	*35.5*	*35.8*	*78.8*	*42.3*
Entire season SEC (kWh/tonne)	**80.4**	**92.8**	**58.9**	**134.6**	**75.1**	**94.5**	**46.5**	**25.9**	**61.5**	**42.5**	**42.7**	**61.5**
CO_2 equivalent (kg/tonne)	*43.2*	*49.9*	*31.7*	*72.3*	*40.4*	*50.7*	*25.3*	*13.9*	*33.0*	*23.2*	*22.9*	*33.0*

Table 3.4.1 - Pre-pack seasonal performance versus historic information

2.4.2.4. Processing

The graph in Figure 3.4.6 shows the energy consumption of the stores during the 2010 to 2011 season expressed in kWh/tonne per day.

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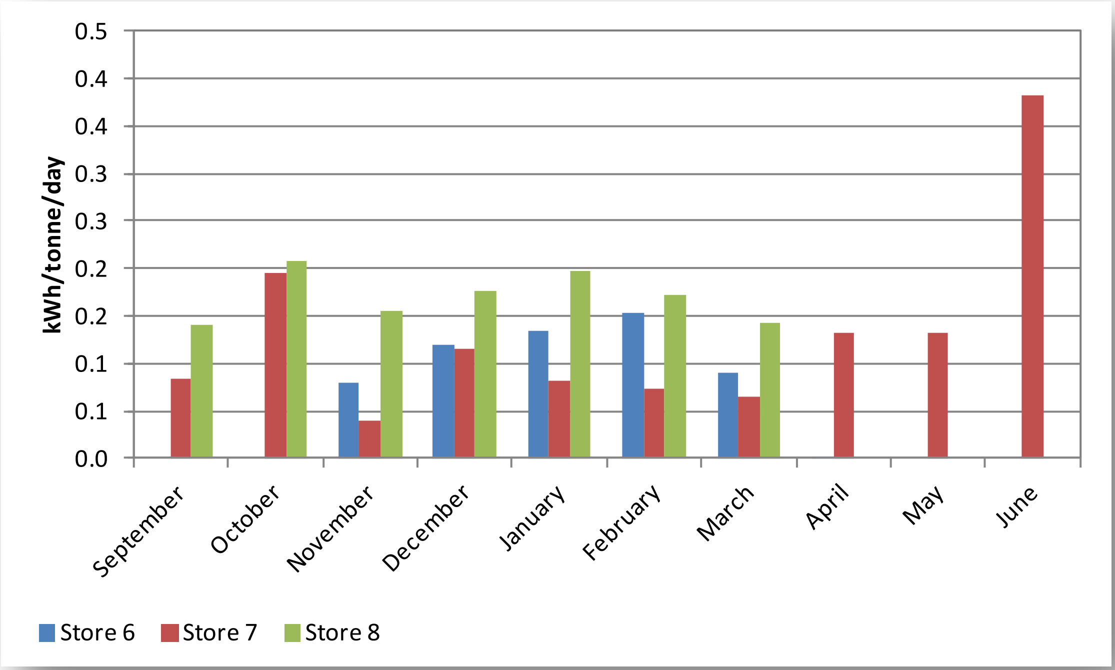


Figure 3.4.6 - Energy consumption of the processing stores. (2010 /11 season - kwh/tonne/day)

The tonnage data from Store 9 was insufficient to allow these numbers to be calculated and hence is omitted from the analysis above.

The graph in Figure 3.4.7 shows the energy consumption of the stores during the 2011 to 2012 season expressed in kWh/tonne per day.

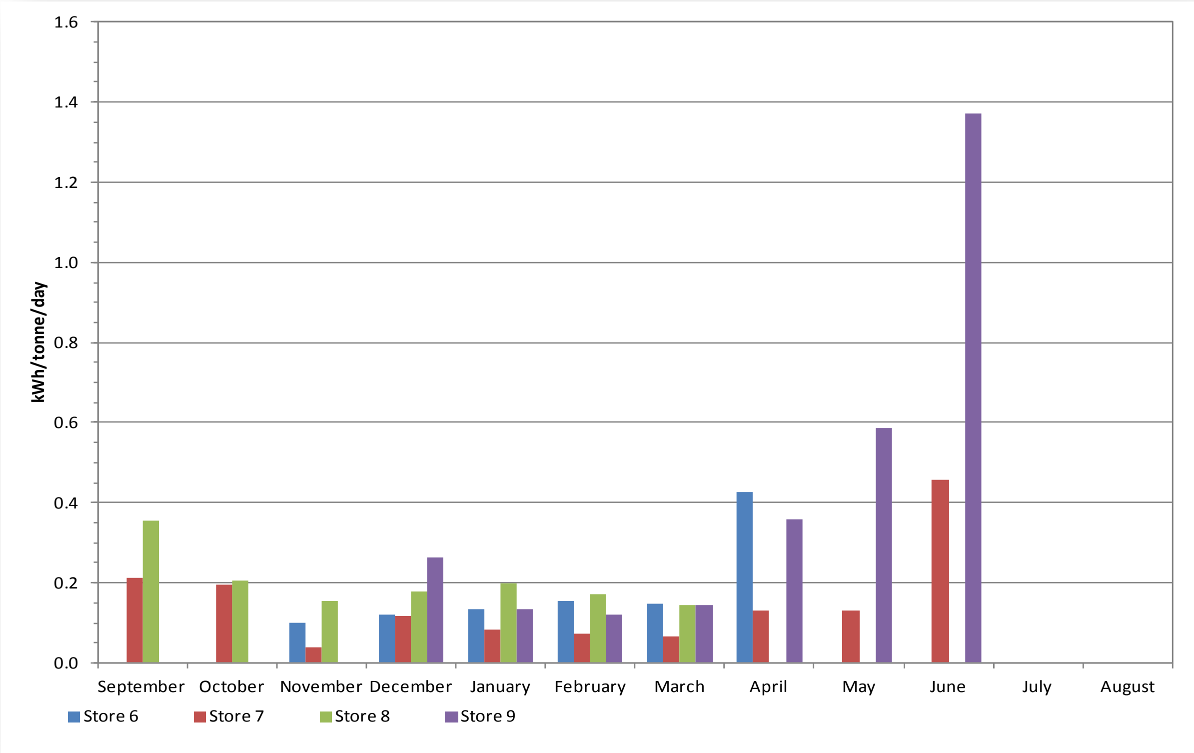


Figure 3.4.7 - Energy consumption of the processing stores (2011 /12 season - kwh/tonne/day)

Figure 3.4.8 compares the average energy consumptions of these stores in the 2010-2011 storage season, to the averages of the processing group for the previous two seasons (project R401).

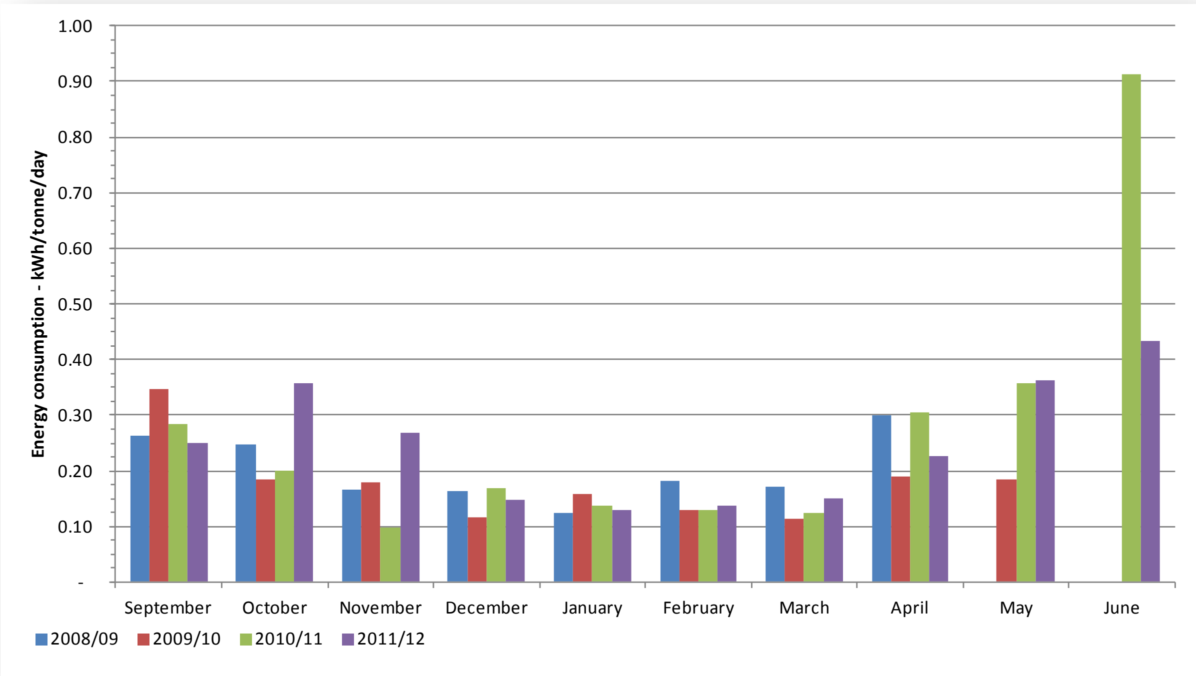


Figure 3.4.8 - Comparison of energy consumption achieved in previous years for the processing stores

This group of stores shows very consistent performance over the four seasons. There is greater consistency largely as a result of less energy use than pre-pack storage. Interestingly the good harvest conditions in 2011 and the subsequent good quality of produce in the stores led to higher energy consumptions later on in the season as the storage season was longer.

Table 3.4.2 shows the energy consumptions in the 2010 to 2011 season compared to energy consumptions from other monitored years. Store 9 was not intensively monitored in the previous project, so there is no historic data available. Insufficient information on storage tonnages prevented some measures being evaluated.

Store Name	Store 6			Store 7			Store 8			Store 9	
Season	2007-10 Average	2010/11	2011/12	2007-10 Average	2010/11	2011/12	2007-10 Average	2010/11	2011/12	2010/11	2011/12
Storage length (days)	177	177	186	275	280	222	194	194	280	212	267
Target temperature (°C)	10.6	11.0	11.0	8.3	8.0	8.0	12.0	9.0 – 10.0	10.0	10.0	10.0
Ambient cooling available	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Refrigeration available	X	X	X	✓	✓	✓	X	X	X	✓	✓
Electricity consumption (kWh)	60,348	51,279	47,137	89,082	90,104	62,883	105,574	108,192	128,991	39,732	112,328
CO_2 equivalent (t)	32.9	27.5	25.3	48.5	48.4	33.8	57.2	58.1	69.3	21.3	60.2
Store quantity (tonnes)	2,620	2,900	2,860	2,820	2,900	2,860	5,118	4,732	5,253	935	1,275
Average daily energy consumption (kWh/tonne/day)	0.16	0.10	0.09	0.11	0.11	0.10	0.12	0.12	0.09	0.20	0.33
CO_2 equivalent (kg/tonne)	0.09	0.05	0.04	0.06	0.06	0.05	0.14	0.06	0.04	0.11	0.18
Full store SEC per day (kWh/tonne/day)	0.15	0.14	0.11	0.13	0.11	0.14	0.15	0.17	0.24	N/A	0.34
CO_2 equivalent (kg/tonne)	0.08	0.07	0.05	0.07	0.06	0.07	0.08	0.09	0.13	N/A	0.18
Cumulative SEC (kWh/tonne)	35.2	17.5	24.0	46.8	39.6	30.1	46.3	36.2	25.4	N/A	88.6
CO_2 equivalent (kg/tonne)	19.3	9.4	12.9	25.9	21.3	16.2	25.2	19.4	13.6	N/A	47.5
Entire season SEC (kWh/tonne)	24.1	17.7	16.5	31.7	31.1	22.0	23.0	22.9	24.6	42.5	88.1
CO_2 equivalent (kg/tonne)	13.2	9.5	8.8	17.3	16.7	11.8	12.5	12.3	13.2	22.8	47.3

Table 3.4.2 - Processing seasonal results versus historic information

2.5. Store air leakage

2.5.1. Background

One of the contributory factors to potato store energy consumption is air leakage. This is defined as the ***unregulated air exchange*** between inside the store and outside, not to be confused with ***controlled exchange of air through fans and louvres*** for the purposes of maintaining correct storage conditions.

Uncontrolled air exchange in a potato store is not desirable because it can lead to sub-optimum crop storage conditions and an increase in energy use.

This is because:

1. When conditions are cold, more cold air enters the store than is required and heating may be needed to maintain temperature. This, in turn, leads to a decrease in humidity and consequential crop weight loss.
2. When conditions are warm, more warmer air enters the store than is required, leading to a requirement for extra cooling, often by refrigeration. Additionally there is now a risk of condensation on the crop.

The first effect is seen mostly in processing potato storage. The second is more common in pre-pack potato storage.

Air leakage can occur from many places within a potato store. The most common areas are:

- Around main doors.
- Around personnel doors.
- Around louvres and louvre blades.
- Eaves and junctions between store walls, floors and roof.
- Gassing and other holes.
- Between cladding materials.

Reducing air leakage by sealing these areas will help reduce the stores energy consumption and maintain the correct conditions for storage.

Another benefit of reducing air leakage is that it helps to prevent wastage of the sprout suppressant CIPC or Ethylene[3].

2.5.2. Test method

2.5.2.1. Regulations

The air tightness of regulated buildings is regulated under the Building Regulation Requirements Part L 2010 (England and Wales). The standards are applicable to new buildings and alterations to existing buildings. Potato stores are covered by this regulation because they are agricultural buildings with high energy demand.

Part L states reasonable air permeability for non-domestic buildings less than 10 $m^3/h/m^2$ at a building differential air pressure of 50 Pa. This value applies to a whole range of building types from commercial office space to industrial factories. Most

[3] CIPC is now subject to strict regulation in application of 36 g per tonne for pre-pack produce and 63.75 g per tonne for processing storage.

potato stores should achieve values well below this because their design includes less opening voids – like doors and windows – and therefore they tend to be better sealed.

2.5.2.2. ATTMA method

The method of testing buildings for air tightness is outlined in Air Tightness Testing and Measurement Association's (ATTMA) publication – Air permeability measurement 2006. The introduction to this is reproduced in Appendix 3.

Briefly this requires that:

- Any 'air conditioning' plant is isolated and sealed off.
- Variable flow fans are installed in a suitable location (a doorway is most common) to pressurise the building. A trailer fan is used for larger leakier buildings where necessary.
- The fans pressurise the building in steps of 10 Pa by increasing their speed and hence the airflow rates.
- Measurements are taken of the flow of air into the building required to maintain these pressures.
- The measurements are assimilated and calculated to give the test result.

Figure 3.5.1 - Small door mounted fan

Figure 3.5.2 - Large trailer fan

We carried out air leakage testing using this method. As we were interested in the incremental importance of each element of the building sealing, we extended the tests by:

- Sealing any parts of the building we wished to test for air leakage.
- Carrying out a test.
- Removing temporary sealing from each item in turn and testing again.

This gave a set of results for each store - usually 5 or 6 which gave incremental permeability figures for each level of sealing.

2.5.2.3. Smoke tests

In addition to the volumetric and pressure measurement, smoke tests were performed. This involved both filling the store with smoke and placing the building under pressure to see where it leaked, or placing the building under pressure and targeting the smoke at likely leaky areas.

The results of these tests were captured on video which, although not possible to reproduce in this report, identified many of the worst performing places and indicated qualitatively the extent of the problem.

2.5.2.4. Comparison of metrics

Air leakage results can be expressed in a number of ways, all of which have some validity. Some are easier to explain and visualise by the layman – others provide more robust results which can be used to compare other stores and sites. All leakage rates are for differential pressures of 50 Pa.

Permeability – $m^3/h/m^2$

This is the standard unit used in Building Regulations and ATTMA (Air Tightness Testing and Measurement Association). It is the leakage of air in cubic metres per hour (m^3/hour) divided by the surface area of the building envelope (area of roof, walls and floor). This allows comparison to be made of different sizes of building and benchmarking against the standards given in the Building Regulations.

Air leakage – m^3/hour

This is simply the amount of air leaking from the building in m^3/hour. It does not scale well when applied to buildings of different size.

Air changes - per hour

This is a ratio between the air leakage in m^3/hour to the volume of air within the building in m^3. This method of expressing the air leakage is easy to visualise.

Equivalent leakage area – m^2

This is a useful way of helping a user to visualise leakiness. It expresses leakiness in terms of an equivalent size of a ‘hole’ in the store wall of xxm^2 which, by itself, would lead to the leakage measured.

2.5.2.5. Photographs of temporary sealing

Temporary sealing the stores involved the use of copious quantities of lightweight plastic sheeting and duct tape. The stores were sealed internally where possible and if necessary externally by tape along outside joints. Sealing the building internally was very effective as sealing materials were held tight against the leak areas by the internal building pressure ensuring a good temporary seal.

The following set of photographs shows how the temporary sealing was applied.

Figure 3.5.3 - Main door sealed inside

Figure 3.5.4 - Main door sealed from outside

Figure 3.5.5 - Louvre sealed from inside

Figure 3.5.6 - Louvre sealed from outside

Figure 3.5.7 - Personnel door sealed from inside

Figure 3.5.8 - Personnel door sealed outside

2.5.3. Results

Appendix 4 contains a sample report produced by the air leakage test company. More than 60 or these were produced. Tables 3.5.1 and 3.5.2 below show the main results.

Store #	Permeability ($m^3/h/m^2$)		Air changes (#/hr)		Effective leakage area (m^2)	
	Before sealing	After sealing	Before sealing	After sealing	Before sealing	After sealing
Store 2	5.63	3.52	2.17	1.35	0.53	0.33
Store 5	5.6	1.03	2.1	0.39	0.55	0.1
Store 7	2.62	1.73	0.92	0.56	0.42	0.25
Store 8	10.42	4.28	2.26	0.93	1.5	0.62
Store 9	8.68	5	3.39	1.95	0.79	0.45
Store 11	3.88	1.68	1.7	0.74	0.33	0.14
Store 14	4.75	4.26	1.8	1.62	0.41	0.37
Store 15	44.35	14.97	10.76	3.63	5.5	1.9

Table 3.5.1 - Results from leak testing the potato stores

Figure 3.5.9 below shows the permeability before and after sealing the stores in graphical format which highlights the huge differences between the stores.

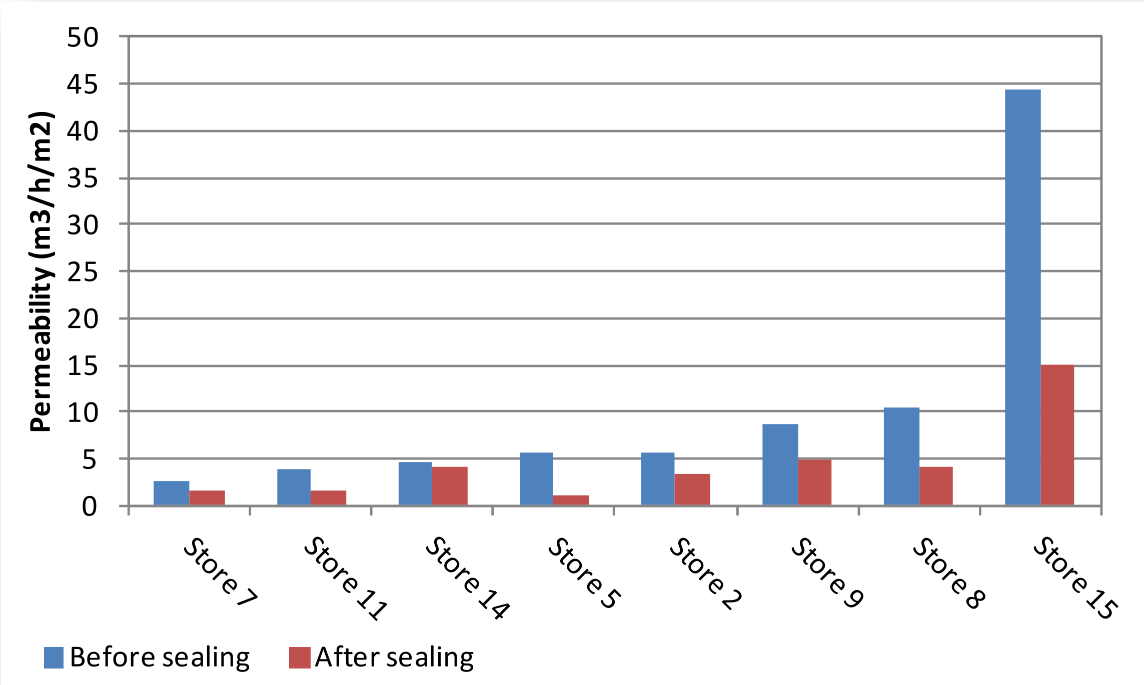


Figure 3.5.9 - Permeability of the stores before and after sealing the stores at 50 Pa

All the values are expressed at a building-outside differential pressure of 50 Pa. The scale of changes between complete sealing and no sealing is, in most cases, quite dramatic.

Table 3.5.2 below shows the potential air leakage reduction through sealing (i.e. the arithmetic result of the 'no temporary sealing' level minus the level achieved by temporary sealing).

Store #	Permeability ($m^3/h/m^2$)	Air changes (#/hr)	Equivalent leakage area (m^2)	% improvement
Store 2	2.11	0.82	0.2	37%
Store 5	4.57	1.71	0.45	82%
Store 7	0.89	0.36	0.17	34%
Store 8	6.14	1.33	0.88	59%
Store 9	3.68	1.44	0.34	42%
Store 11	2.2	0.96	0.19	57%
Store 14	0.49	0.18	0.04	10%
Store 15	29.38	7.13	3.6	66%
Average				**48.4%**

Table 3.5.2 - Possible improvements in air leakage for each store

Clearly store conditions varied enormously from a 1980s ambient store (Store 15) with sliding doors, through to modern purpose built facilities (Stores 7,11, 5 and 2), which one would hope would be built to high standards of construction.

Store 15 achieves the worst result, with an equivalent leakage area of 3.6 m^2. This is largely because of the main doors (sliding and in very poor condition) and the louvres which in some cases were missing blades. A good example of an average store which still shows room for improvement was Store 9. This store had a side wall that was beginning to part from the floor and hence most of the improvements in this store could be achieved through repair of this.

The main areas of air leakage were found to be:

- Personnel doors.
- Louvres and louvre frames.
- Main doors.
- Store fabric (maintenance issues).

Figure 3.5.10 below shows the ranges of equivalent leakage area for each building component.

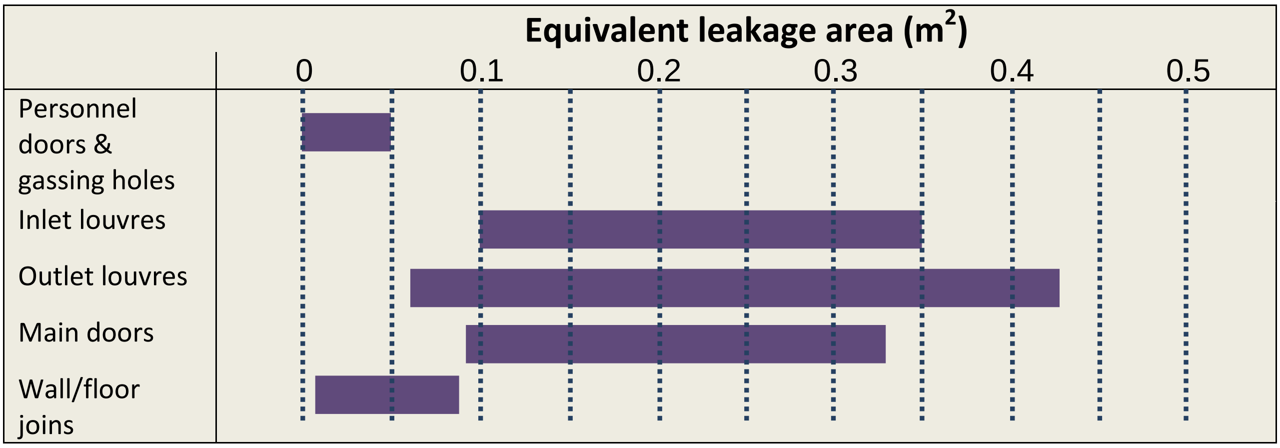


Figure 3.5.10 - Range of equivalent leakage area per factor

Clearly louvres and main doors are the biggest problem for most stores. Luckily they are probably the easiest to deal with, as they represent bounded areas which can be maintained.

2.5.4. Energy losses from air leakage

The determination of energy loss from the stores as a result of air leakage can be established in two ways. We can:

- Use an industry standard calculation to scale the air leakage results at 50 Pa to real world air leakage rates and then calculate the heating or cooling energy needed to maintain the storage conditions.
- Measure the differential pressures in the building over a period of time and use the air leakage curves to determine the leakage at each point, and then calculate the energy required for heating or cooling as above.

The first method has been used to calculate the following results:

Store #	Increase in electricity consumption (kWh)		Percentage energy lost	Cost £
	Heating	Cooling		
Store 5	-[4]	3,331	5.46%	£484
Store 14	-[4]	3,861	3.63%	£516
Store 11	-[4]	1,937	N/A[5]	£286
Store 2	-[4]	2,557	5.17%	£394
Store 8	25,132	-[6]	22.29%	£2,908
Store 7	3,848	3,521	4.74%	£811
Store 9	10,635	1,733	26.68%	£1,360

Table 3.5.3 - Energy losses as a result of air leakage

Table 3.5.3 shows the effect of air leakage on store energy consumption. In the worst cases, air leakage contributes to 3.74 % of energy consumption for processing storage and 5.46 % for pre-pack storage. Store 15 has been omitted from the data set because it is a short-term ambient store and the effects of air leakage on energy consumption are very small.

The results reflect the stores' physical condition and storage lengths/temperatures – Store 9 has a wall that has parted from the floor and, as a result, has a high air leakage.

The model store was used to assess the difference in performance between a store with all the worst air leakage factors and one with all the best. The table below shows these results.

		Model Pre-pack (3 °C)	Model Processing (7.5 °C)	Model Processing (10 °C)
Electricity needed for air leakage (worst case)	kWh for heating	4,564	19,974	41,001
	kWh for cooling	17,126	18,953	3,568
Electricity needed for air leakage (best case)	kWh for heating	523	2,291	4,702
	kWh for cooling	1,964	2,173	409
Percentage energy saved		33.3 %	49.2 %	17.0 %

Table 3.5.4 - Energy lost in best and worst case air leakage from the model stores

Table 3.5.4 shows that there is significant energy saving achievable by reducing air leakage - 33 % for pre-pack and up to 50 % for processing.

[4] There is no provision for heating with these stores.
[5] This cannot be calculated, as the total electricity consumption of the store is not known.
[6] This store does not have provision for mechanical cooling.

2.6. Refrigeration system tests

2.6.1. Background and theory

Cooling potato stores is achieved with either ambient air or mechanical refrigeration. Ambient air cooling works by blowing cooler outside air into the store. The effectiveness and efficiency of this type of cooling is dependent on the differential between external and internal temperatures and the fan efficiency.

Mechanical refrigeration cooling usually employs a direct gas expansion (DX) system which passes a refrigerant fluid round a pipe loop between the inside and outside of the building. The gas/liquid change of state provides low inside temperatures, whilst transferring heat energy to a higher temperature state outside.

The diagram below shows how the typical refrigeration system is configured.

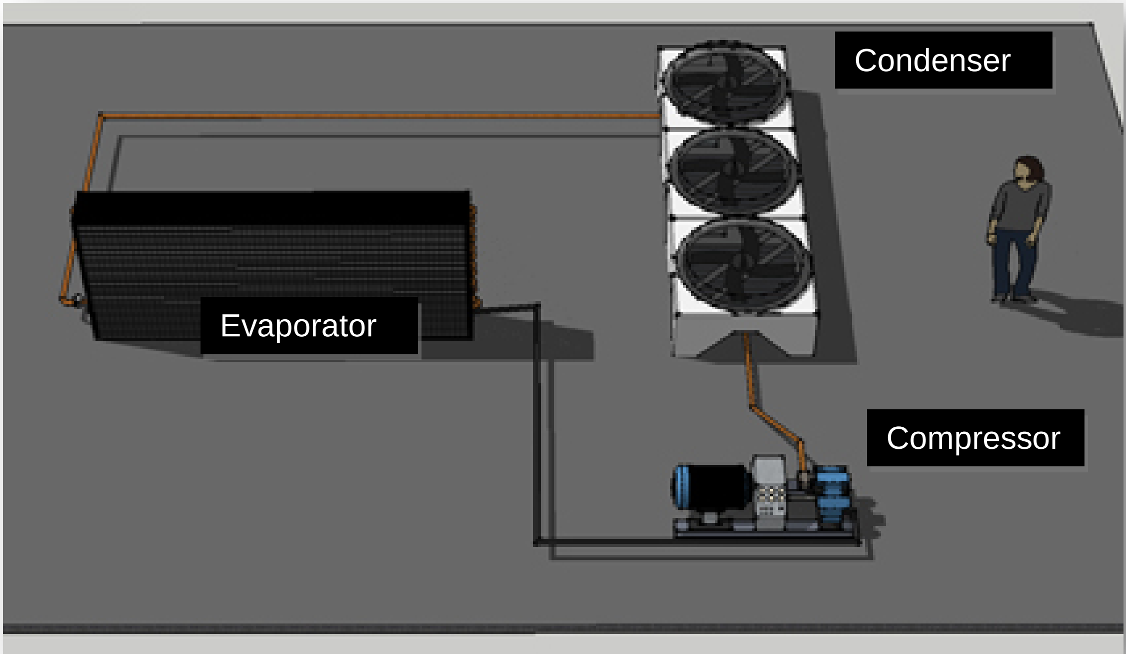


Figure 3.6.1 - Components of potato store refrigeration system

The evaporator coils reside in the air handling unit. Fans draw air through the cold coils and blow the air across or through the crop to provide cooling.

As refrigeration systems are a form of heat pump – that is they use electrical energy to power the pumping of heat from a colder environment to a hotter one – their efficiency can be express in terms of the ratio of cooling power delivered to the electrical energy consumed by the system. We call this ratio the Coefficient of Performance (COP). COP is a dimensionless relationship of the electrical input to the cooling energy provided:

$$Coefficent\ Of\ Performance\ (COP) = \frac{kW_{coolingpower}}{kW_{electricalpower}}$$

The COP of a ‘typical’ DX refrigeration system used in pre-pack storage would be 2.5 to 3.5 whilst in processing storage the typical COP is between 3 and 4. (A COP of 3 means that three times as much cooling energy is delivered as electrical energy input, i.e. if a system provides 100 kWh of cooling energy at a COP of 3 then 30 kWh of electricity will have been consumed to deliver it.). Usually the lower the required cooling temperature, the worse the COP – hence the better performance of a processing store.

The efficiency of refrigeration systems are not fixed and will vary with:

- System type and design – refrigerant gas, compressor type, etc.
- Operational parameters and control settings.
- Cooling temperature.
- Ambient temperature.
- Cleanliness of system.
- Refrigerant quantity.
- Lubricant quantity.

A reduction in COP can be temporary; for example if the ambient temperature increases then the COP will fall, or permanent; if the refrigerant leaks out then the efficiency will be compromised until such time as it is replenished.

Seasonal average efficiency will be very different from an on-the-spot measurement; largely as a result of fluctuating outside temperatures (poor efficiency in hot weather and better in colder periods) and changes in storage temperatures (lower efficiencies when the crop is required to be cooler).

2.6.2. Refrigeration system standards

The Energy Performance of Buildings Directive (EPBD), January 2003, requires that all air conditioning systems greater than 12 kW cooling output to be inspected for safety and performance by January 2011 and thereafter every five years.

The Institute of Refrigeration Technical Bulletin 31 contains information regarding the inspections, what they include and their purpose. A small extract is reproduced below:

> ***Who can carry out the inspections?***
> *All inspections **must** be done by an accredited air conditioning assessor. They will provide a written report giving advice and guidance on how to improve the energy efficiency of the system as soon as practicable after the inspection.*
>
> ***What does the inspection report include?***
> - *The current efficiency of equipment and suggestions for improvement including, where appropriate, its replacement.*
> - *A list of any faults identified (e.g. condition of air filters) during the inspection and suggested actions.*
> - *The adequacy of the equipment maintenance and suggestions for improvement.*
> - *The adequacy of the installed controls and control settings and suggestions for improvement.*
> - *The current size of the installed system in relation to the cooling load.*
> - *Suggestions for improving the system's energy efficiency, or, where appropriate minimizing or avoiding the need for air conditioning.*

Additionally, the Fluorinated Greenhouse Gases (F-gas) Regulations 2009 (FGG Regulations 2009) state how refrigeration systems containing these gases should be maintained and inspected to reduce their greenhouse gas emissions. The Defra-produced information sheet – *Information Sheet RAC 3 – Key Obligations (F-gas support)*, contains the following table:

Section	Obligation	Applicability to RAC Systems (for systems using F-gas refrigerants)
4.1	Take steps to prevent F-gas leakage and repair detected leakage as soon as possible.	All stationary systems
4.2	Regularly check for leakage, see Table 2 for details.	Stationary systems 3 kg or more (or if hermetic and labelled 6 kg or more)
4.3	Fit automatic leak detection system.	Stationary systems above 300 kg[7]
4.4	Keep certain records about refrigeration plant that uses F-gases.	Stationary systems 3 kg or more
4.5	Recover F-gases during plant servicing and maintenance, and at end of plant life.	All stationary systems
4.6	Use appropriately qualified personnel to carry out installation, servicing and maintenance, and leakage checking. Have company certification if employing personnel to undertake installation, maintenance or servicing of RAC systems. Further obligations for companies employing these personnel or wishing to take delivery of containers of F-gas.	All stationary systems
4.7	Label new equipment adjacent to service point/information & in instruction manuals.	All stationary systems
4.8	Placing on the market of non-refillable containers used to service equipment is banned from July 2007, except for those shown to be manufactured before that time.	All systems

Table 3.6.1 - Summary of EC F-gas Regulation Obligations for RAC Systems

Both the F-gas regulations and the EPBD regulations place importance on ensuring the equipment is as efficient and well maintained as possible. These regulations are applicable to potato storage and most of their requirements can be achieved by ensuring the systems are well maintained and annually checked for leaks, energy efficiency and correct operation. Additionally an F-gas log book for each system should be kept and the plant labelled correctly with refrigerant type, quantity, cooling capacity, etc.

2.6.3. Test method

A series of tests on the stores in the project was undertaken to measure their efficiency and to identify what could be done to improve them. A limited number of

[7]Unlikely to apply to many potato stores.

improvements of common faults were made on the spot and the systems re-tested to see how the efficiency had improved.

A specialist piece of monitoring equipment called a ClimaCheck was used to determine the efficiency of the systems and to suggest where improvements were possible. The ClimaCheck simultaneously measures refrigerant temperatures and pressures and the electrical input to the compressor and fans.

Using its proprietary software, the ClimaCheck calculates the energy flows of the system into and out of the evaporator, condenser and compressor. It can determine the efficiency of the refrigeration and also highlight areas where improvements can be made.

Figure 3.6.2 - ClimaCheck monitoring system

Measurements are taken and logged at pre-determined intervals (one minute) during the operation of the refrigeration equipment. A graph and a screenshot of the ClimaCheck output are given in Figure 3.6.3 on the following page.

Date	Time	SecC Evap in (°C)	SecC Evap out (°C)	Ref Low press. (Bar(g))	Ref Evap Midpoint (°C)	Ref Comp in (°C)	Super heat (K)	SecW Cond in (°C)	SecW Cond out (°C)	Ref High press. (Bar(g))	Ref Cond Mid point (°C)	Ref Exp. Valve in (°C)	Sub cool total (K)	Ref Comp out (°C)	Comp Isen. eff** (%)	Pow er input Comp. (kW)	COP Cool	Cap. Cool (kW)	COP Heat
2011-04-06	**13:25:00**	10.9	7.8	3.95	-6.0	9.1	14.9	19.5	29.1	18.11	42.0	33.9	8.0	74.3	60.2	39.7	2.62	103.9	3.55
2011-04-06	**13:24:00**	10.8	7.9	4.05	-5.4	9.0	14.2	22.1	29.1	19.08	44.1	33.6	10.3	75.4	61.0	40.6	2.61	106.0	3.54
2011-04-06	**13:23:00**	10.6	7.8	4.08	-5.3	9.2	14.3	19.7	29.3	18.34	42.5	34.5	7.9	74.4	59.5	40.4	2.60	105.1	3.53
2011-04-06	**13:22:00**	10.6	7.9	3.84	-6.7	9.0	15.5	19.4	28.8	17.81	41.4	33.2	8.0	74.6	60.0	39.2	2.61	102.3	3.54
2011-04-06	**13:21:00**	10.6	7.8	4.15	-4.8	9.1	13.7	20.2	29.4	18.54	42.9	34.8	8.0	74.9	58.3	40.8	2.55	104.2	3.48
2011-04-06	**13:20:00**	10.6	7.9	4.01	-5.7	9.1	14.6	19.3	28.9	18.16	42.1	34.1	7.9	74.3	59.7	40.0	2.61	104.4	3.54
2011-04-06	**13:19:00**	10.6	7.8	3.83	-6.8	9.0	15.6	19.5	28.7	18.12	42.0	33.1	8.8	74.5	61.6	39.2	2.65	103.7	3.58
2011-04-06	**13:18:00**	10.6	7.8	4.15	-4.9	9.1	13.8	20.4	29.3	18.55	43.0	34.1	8.7	75.4	57.7	40.9	2.54	104.1	3.47
2011-04-06	**13:17:00**	10.6	7.8	4.02	-5.6	9.1	14.5	19.7	29.2	18.24	42.3	34.2	7.9	74.4	59.7	40.3	2.60	104.9	3.53
2011-04-06	**13:16:00**	10.6	7.7	3.84	-6.7	9.1	15.6	19.3	28.7	18.06	41.9	33.1	8.6	74.4	61.4	39.4	2.65	104.5	3.58
2011-04-06	**13:15:00**	10.6	8.0	4.07	-5.3	9.1	14.2	21.1	29.1	18.57	43.0	33.9	9.0	75.6	58.6	40.7	2.55	103.9	3.48
2011-04-06	**13:14:00**	10.6	8.0	4.14	-4.9	9.1	13.8	20.0	29.2	18.43	42.7	35.0	7.5	74.7	58.3	40.7	2.55	103.9	3.48
2011-04-06	**13:13:00**	10.6	7.9	4.02	-5.6	9.1	14.5	19.1	28.7	18.11	42.0	34.2	7.6	74.3	59.2	40.1	2.60	104.0	3.53
2011-04-06	**13:12:00**	10.6	8.0	3.88	-6.5	9.1	15.4	19.3	28.8	17.87	41.5	33.2	8.1	74.3	60.3	39.6	2.63	104.3	3.56
2011-04-06	**13:11:00**	10.6	8.0	4.03	-5.6	9.1	14.4	21.9	28.9	19.02	44.0	33.5	10.3	75.3	61.3	40.2	2.63	105.7	3.56
2011-04-06	**13:10:00**	10.6	7.8	4.14	-4.9	9.1	13.8	20.1	28.8	18.38	42.6	33.9	8.6	75.1	57.6	40.5	2.56	103.7	3.49
2011-04-06	**13:09:00**	10.6	7.9	3.95	-6.0	9.1	14.9	20.3	29.8	18.15	42.1	33.6	8.4	74.7	59.8	39.6	2.61	103.2	3.54
2011-04-06	**13:08:00**	10.6	7.7	4.06	-5.4	9.1	14.3	21.9	29.3	18.64	43.2	33.6	9.4	75.6	59.0	40.3	2.57	103.4	3.50
2011-04-06	**13:07:00**	10.6	7.7	4.14	-4.9	9.1	13.8	20.3	29.0	18.42	42.7	34.1	8.4	75.3	57.4	41.0	2.54	104.3	3.47
2011-04-06	**13:06:00**	10.6	8.0	4.09	-5.2	9.1	14.1	19.9	28.8	18.29	42.4	34.8	7.4	74.6	58.6	40.7	2.56	104.4	3.49
2011-04-06	**13:05:00**	10.6	8.0	4.05	-5.5	9.1	14.4	19.3	28.7	18.14	42.1	34.5	7.4	74.4	58.9	40.5	2.58	104.4	3.51
2011-04-06	**13:04:00**	10.6	7.8	3.94	-6.1	9.1	15.0	19.1	28.5	17.92	41.6	33.5	7.9	74.3	59.6	40.1	2.62	104.9	3.55
2011-04-06	**13:03:00**	10.6	7.7	3.90	-6.4	9.1	15.2	20.6	28.5	18.87	43.7	33.0	10.5	74.5	64.0	40.0	2.71	108.4	3.64

Figure 3.6.3 - Screenshot of data streams measured and calculated by ClimaCheck

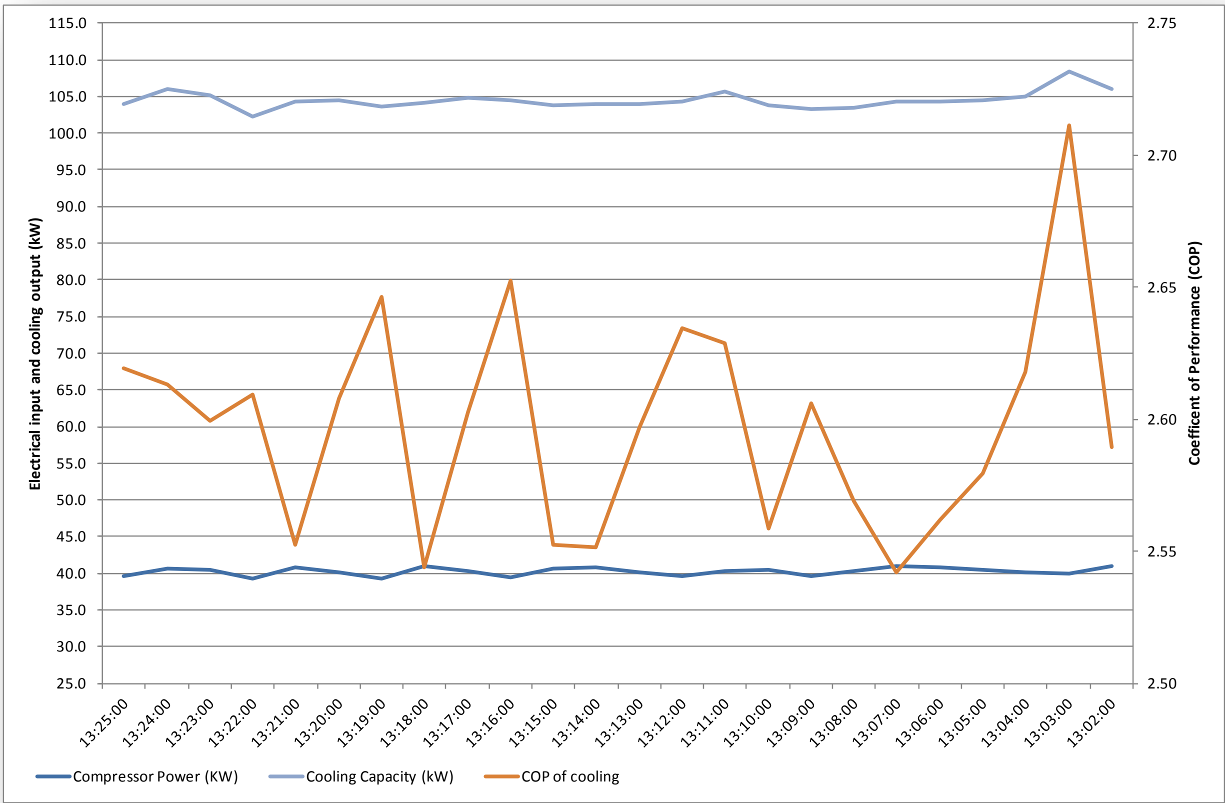


Figure 3.6.4 - One of the graphs provided by the ClimaCheck

Figure 3.6.5 - ClimaCheck monitoring

Figure 3.6.6 - Compressor wired for ClimaCheck monitoring

Figure 3.6.7 - Condenser set undergoing monitoring

Figure 3.6.8 - Monitoring in store

2.6.4. Results

Table 3.6.2 on the following page shows the results of the initial round of refrigeration system testing.

Store #	Description	Target produce temp	General issues	COP[8]	Suggested upgrades to improve performance	Potential COP if upgraded
2	• Packaged unit with VSD[9] compressor	3	• Compromised airflow to evaporators due to store suction wall	2.91	• Sub cooling • Adjustment to expansion valves • EC[10] or VSD[11] condenser fans • Improve airflow to evaporators	3.76
4	• Portable' fridge unit with internal compressor and integrated condenser • Old system	3	• Condenser too small • Recirculation of air into condenser • Maladjusted TEV[12]	2.42	• Alter TEV settings • Install larger Condenser • Stop recirculation of air • Improve general airflow • Site compressor outside of unit	4.75 (basically - install a new system)
5	• External drive • Compressor and external condenser pack with air conditioning fan technology	3	• Unstable condensing pressure control • Too high superheat	2.66	• Install VSD or EC fans to control condensing pressure • Alter TEV settings or install electronic expansion valves	2.81
7	• Packaged compressor and condenser (external)	8	• Restricted airflow to condensers • Badly-staged condenser fans	2.61	• Adjust TEV or fit electronic valves • Improve condenser fan control • Fit EC or VSD condenser fans • Fit VSD compressor	3.57
9	• Packaged unit • Old and poorly maintained	10	• Low on refrigerant • Low on oil • R22[13] replacement • Leaky seals	1.94	• New unit	3.94

[8] Coefficient of Performance.
[9] Variable Speed Drive - a technology that can control the compressor to match cooling demand to compressor operation.
[10] Electrically Commutated - this is a new fan technology that is inherently variable speed and more efficient than AC fans.
[11] Variable Speed Drive - for condenser fans this controls the fan speed based on condensing pressure and can be retrofitted to most AC fans.
[12] Thermostatic Expansion Valve.
[13] Older type of refrigerant - no longer made and recycled refrigerant only available for existing systems.

10	• State of the art, sub cooling • Heat recovery • VSD compressors • Electronic expansion valves	-2	• None	3.87	• Ground sink cooling for season performance • Increased heat recovery • Possibly install scroll compressors	4.7
11 and 12	• Similar to Store 5	3	• One fan broken on condenser • Iced evaporator	2.94	• Smaller staged compressors • VSD or EC condenser fans • Defrost evaporators	3.29
13	• Packaged compressor and condenser 6 compressors with VSD on lead • Staged condenser fans (8)	2	• Highly compromised airflow into and around unit • Maladjusted EV and condensing pressure control • Defrost incomplete at end of cycle	2.51	• Adjust expansion valve • Adjust condensing pressure control • Fit sub cooling • Reconfigure system for better airflow • Alter condenser fan behaviour or fit VSD/EC fans	3.29

Table 3.6.2 - Summary of results from the initial round of refrigeration system tests

2.6.5. Practical improvements for store refrigeration efficiency

The results show that there is big potential to improve the efficiency of some refrigeration systems. The following checklist shows the improvements that can be made to increase refrigeration system efficiency.

Improvement	Type of improvement	Likely efficiency improvement	Cost level
Check for correct level of refrigerant and oil	Maintenance	5 – 50 %	Very low (£0-£250)
Reduce recirculation of air into condenser	Maintenance	25 %	Low (£250 - £500)
Ensure correct TEV settings	Maintenance/set point adjustment	10 %	Very low (£0-£250)
Optimise condenser pressure control	Maintenance/set point adjustment	10 %	Low (£250 - £500)
Replace condensing fans with VSD or EC types	Technology replacement	25 %	Medium (£500 - £1,000)
Install electronic expansion valves	Technology replacement	10 %	Medium (£500 - £1,000)
Optimise condenser size	Technology replacement	10 – 30 %	Medium to high (£1,000 - £2,500)
Install scroll compressors or VSD control	Technology replacement	10-20 %	Medium to high (£1,000 - £2,500
Install sub cooling	Additional technology	25 %	High (£2,500 +)
Fit heat recovery	Additional technology	20 %	High (£2,500 +)
Total system replacement and redesign	System replacement	50-60 %	High (£2,500 +)

Table 3.6.3 - Practical improvements for store refrigeration efficiency

2.7. Insulation - type and quantity

Probably the largest contributor to store temperature rise is heat conduction from the external environment passing through the building structure – wall, floors and roof. Rate of heat transmission is determined from the U-value (thermal transmittance) of the building components. The U-value of a construction is dependent on the thickness, area and thermal conductivity of the building materials.

Calculation of U-values is relatively easy. However, in practice, because of variability in the nature of materials, its thickness, and its degradation through age, the actual U-value of a structure might be somewhat different to that given by a theoretical calculation.

The objective of this part of the work was to take a sample of buildings and try to determine how the theoretical U-value might differ from the actual, and why this should be, thereby informing growers how they might compensate for this.

2.7.1. Insulation theory and background

Thermal conductivity (k) is a property of a material, and is measured in watts per metre, per degree Kelvin (W/mK). It indicates the rate at which heat passes through a particular material. Thermal conductivity is often represented by the symbol lambda (λ), the values of which for a number of materials can be found in the building regulations and CIBSE Guide A. For instance, glass has a thermal conductivity of 1.05 W/mK, while fibreglass has a thermal conductivity of 0.04 W/mK, meaning that glass conducts heat over 25 times more effectively than fibreglass.

The first step when quantifying the thermal properties of a structure is to calculate the thermal resistance of each material used in its make-up. Given a material's thickness (m), a simple value for thermal resistance can be calculated by dividing the thickness of the given material by its thermal conductivity (values for thermal conductivity of some common building materials can be found in CIBSE Guide A):

$$R = l/\lambda$$

So, for 50 mm thick fibreglass, the thermal resistance would be:

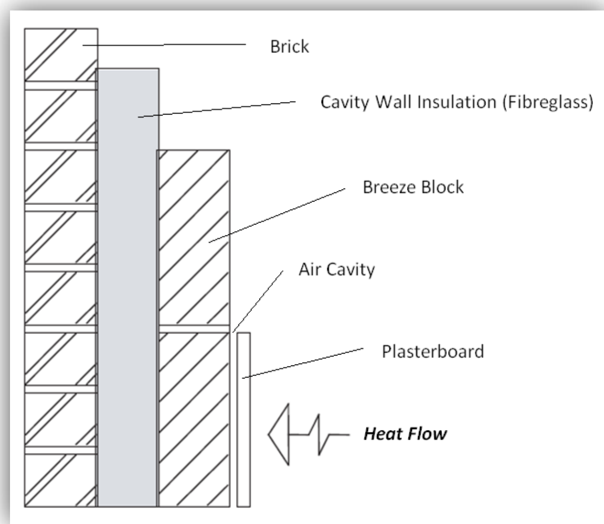
$$R = \frac{0.05}{0.04} = 1.25\ (m^2K/W)$$

Given the R-values, the U-value of a structure can be calculated. It is calculated from the inverse of the sum of the R-values of the structure. The lower this value is, the greater the material's resistance to heat flow.

$$U\ value = \frac{1}{R}\ (W/m^2K)$$

So, for 50 mm thick fibreglass, the thermal resistance would be:

$$U\ value = \frac{1}{1.25} = 0.8\ (W/m^2K)$$



Therefore, for any particular wall, roof structure, or building made of several different materials, it is possible to come up with an overall U-value to indicate the heat loss of the structure. This can be done through assessment of the building materials and their thicknesses and aggregating the R-values of each.

For example, in the case below, for a wall, consisting of brickwork, cavity insulation, block work, an air cavity and plasterboard, all of the constituent parts can be amalgamated to produce a single U-value.

By considering all building components an aggregate U-value for the whole building can be calculated.

Material	Thickness (mm)	Thermal conductivity (W/mK)	Thermal resistance or R-value (W/m^2K)
Brickwork	102	0.8	0.13
Cavity insulation	50	0.04	1.25
Aggregate blockwork	100	0.15	0.67
Air cavity	10	0.024	0.42
Plasterboard	12.5	0.17	0.07
Total U-value (W/m^2K)		**1/2.54 = 0.39**	

Table 3.7.1 - U-value calculation

U-value standards for all new buildings from the Building Regulations 2010 Part L1b are shown in Table 3.7.2. These represent the minimum requirement. While these values may not be applicable to already existing potato stores, it is now formally part of the building regulations to achieve these values. In reality, much lower values would be required in order to achieve the Building Regulations ‘Target CO_2 Emissions Rating’ as outlined in the regulations.

A high U-value for a potato store is not desirable as it can lead to sub-optimum crop storage conditions, in terms of lower humidity, greater temperature stratification and an increase in energy use for heating and cooling.

Table 2 **Limiting fabric parameters**	
Roof	0.20 $W/m^2.K$
Wall	0.30 $W/m^2.K$
Floor	0.25 $W/m^2.K$
Party wall	0.20 $W/m^2.K$
Windows, roof windows, glazed rooflights, curtain walling and pedestrian doors	2.00 $W/m^2.K$
Air permeability	10.00 $m^3/h.m^2$ at 50 Pa

Table 3.7.2 - U-value standards for new buildings

2.7.1.1. Application of U-value in potato storage

Each structural element in a potato store will have its own U-value associated with it. Most of the surface area of a store is taken up by walls and a roof which can be checked for insulation thickness and type, and a U-value simply determined. In stores there is also a large floor area, main doors, personnel doors and louvers which also have to be taken into consideration.

It is possible to model the whole store mathematically to determine its aggregate U-value. To do this all structural components would need to be considered. It's common however to consider the U-value of the walls, roof and floor as being the largest contributors to the net U-value. In this project we have sought to determine by physical test how the store U-values might differ from the basic calculation method.

2.7.1.2. Different store insulation types

Three different types of insulating material were found in the group of stores tested.

2.7.1.2.1. Spray foam

Figure 3.7.1 - Spray foam insulation

This can be applied to most surfaces, and in many cases, is sprayed directly onto the fibre-cement sheeting or the cladding material. As it covers the whole building envelope (bar the floor and any mechanical ventilation) it helps to mitigate the effects of any thermal bridging for instance through the structural steel. It also seals small gaps in the structure which would lead to air infiltration. Typical U-values are between

0.15 and 1.00 W/m^{2}K with thicknesses of 160 down to 25 mm respectively.

2.7.1.2.2. Sheet insulation material

Extruded or expanded polystyrene board is attached on to the portal frame by rails and purlins. Adhesive is commonly used to ensure a good seal between the boards. Joints should be taped. U-values range from 0.44 to 0.22 W/m^{2}K for 50 to 100 mm thickness respectively. A similar setup is used for Styrofoam type board (the blue boarding in the picture). This has a tongue and grooved joint to prevent air leakage between panels.

Figure 3.7.2 - Styrofoam board insulation

2.7.1.2.3. Composite panels

These are sheet insulation panels faced with a cladding material which protects the insulation and allows for easy cleaning. Again they are attached onto sheeting rails and purlins, between structural steel frame I-beams. Unlike sheet insulation panels they can be fitted externally to the structure of the portal frame building to give a "sealed" box-type construction as shown below, to form a complete wall. This type of construction also goes some way to mitigate the effects of thermal bridging, although things like bolts, connecting the outer cladding, will still conduct heat into or out of the building.

Figure 3.7.3 - Composite panel insulation

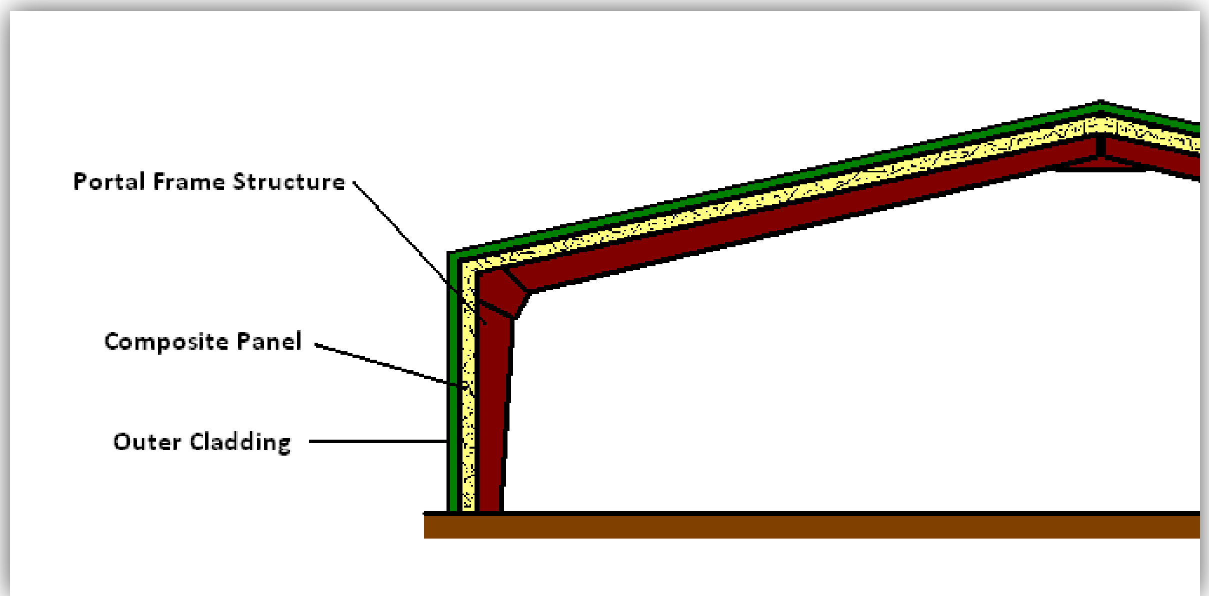


Figure 3.7.4 - Ideal sealed box structure

One issue with composite panels is the way that they interlock. Small air gaps can occur as a result of contraction and expansion of the panels. This is not the case with spray foam as it forms from one homogenous layer, although is not without its own structural problems with age. Best practice seems to be to adhere each panel contact area to each other, followed by sealing the joins with insulating tape. U-values for composite panels are in the range of 0.46 to 0.16 W/m2K for 40 to 120 mm thick panels.

2.7.2. Test method

We attempted to calculate the overall U-value of the buildings using a method based upon the ASTM's (*American Society for Testing and Materials) hot* box test for composite materials and structures (ASTM C1363 – 11). In practice this method measures heat flow through a material with known material dimensions and surface temperatures in lab conditions. Scaling this to a whole building necessitates measuring internal and external temperatures whilst applying a given amount of heat and then making allowances for heat loss through ventilation leakage.

After a number of days, this gave a set of results for each store. Degree-day analysis and accounting for air leakage caused by the wind enabled a structural U-value to be determined for the building. Night time periods were used in the calculations to ensure maximum temperature differences between inside and out and also to negate the effect of solar gain.

2.7.2.1. Experimental arrangement

Figure 3.7.5 shows the the experimental setup. Remote temperature sensors (denoted by Xs) were set up within the store. One ambient sensor was used. Four, 2 kW electric heaters provided the heat and the main fan was left running to give additional heat and to make sure the store temperature was even. The electricity used by the heaters and the fans was monitored to give a half hourly electicity consumption.

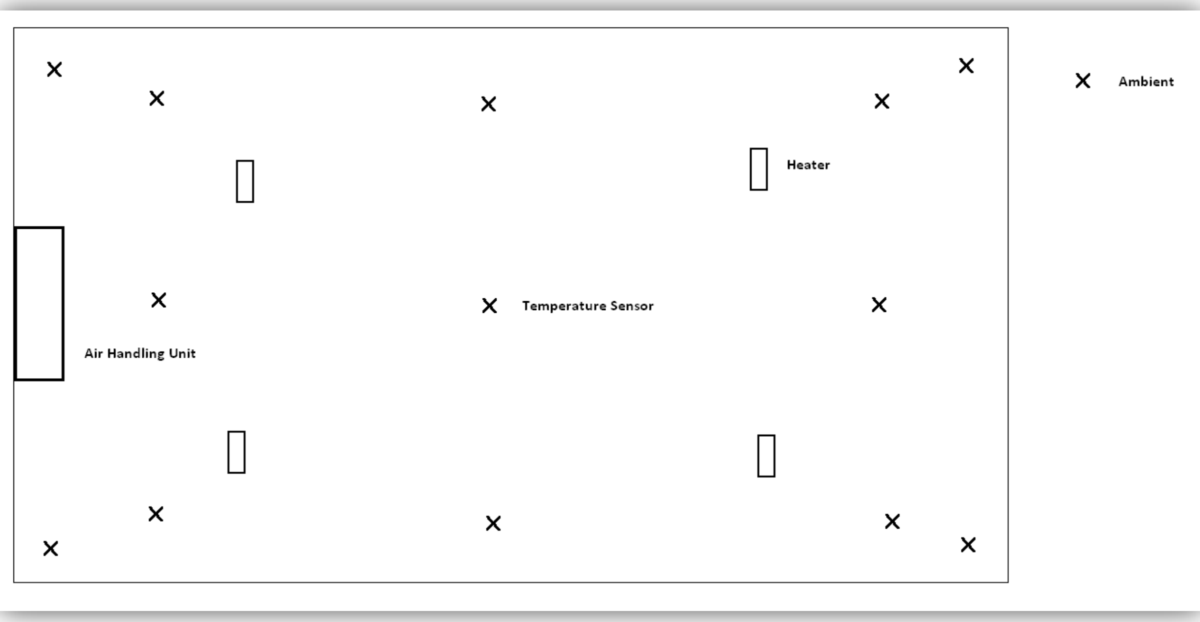


Figure 3.7.5 - Test arrangement

Wind speed and direction was recorded, either from an anemometer set up in proximity to the store, or downloaded from a local weather station.

The photos below show the setting up of various pieces of equipment, including temperature loggers, anemometers, electricity profile loggers and heaters. The energy consumption of the heaters and the fans, internal and ambient temperatures were measured throughout.

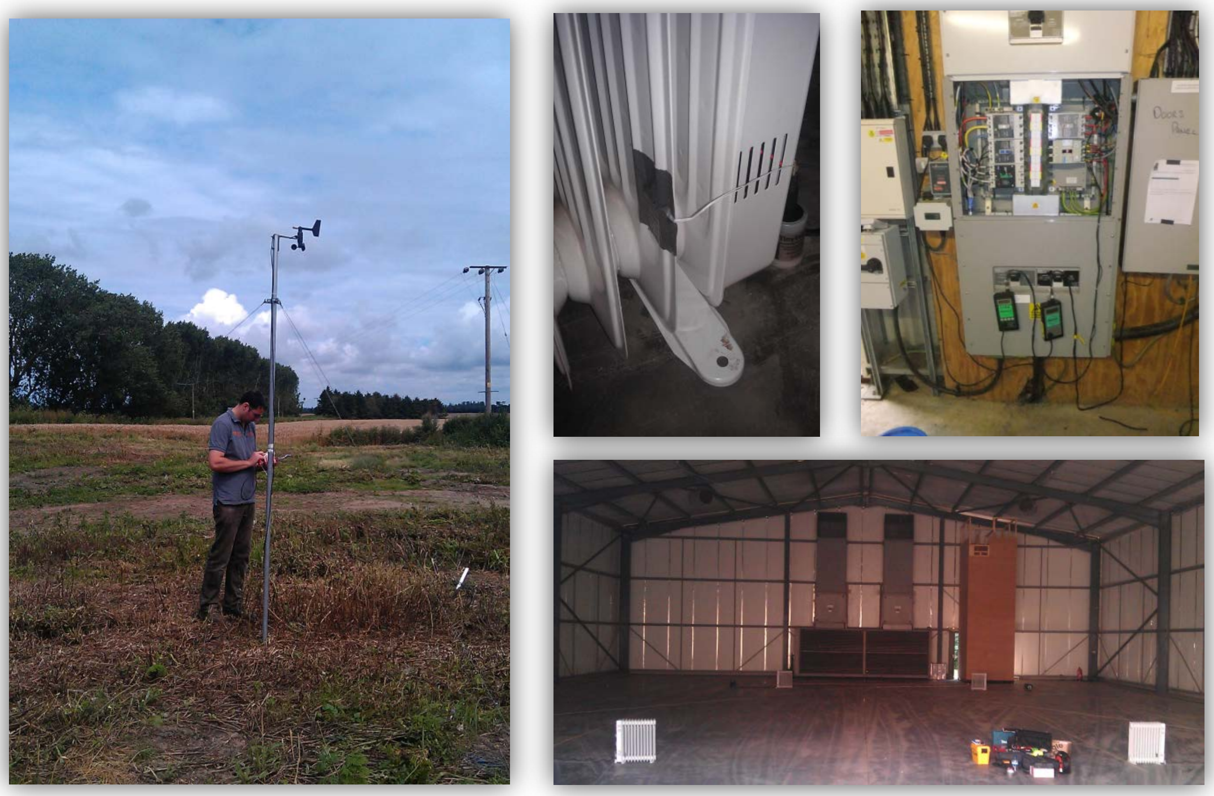


Figure 3.7.6 - Photos of installation for measuring U-values

2.7.3. Results

The measurements recorded between 23:00 and 07:00 for each night of the experiment were used in a heat balance calculation to yield the experimental U-value.

The table below shows the main results:

Store	U-value from tests	U-value of wall insulation	U-value of roof insulation	Type of Insulation
Store 2	0.71	0.25	0.2	Composite panel
Store 4	0.63	0.36	0.27	Spray foam over composite panel
Store 5	1.17	0.56	0.56	Styrofoam board
Store 7	0.35	0.25	0.2	Composite panel
Store 9	0.83	0.25	0.2	Composite panel
Store 11	0.84	0.25	0.2	Composite panel
Store 12	1.25	0.53	0.28	Spray foam
Store 14	1.16	0.56	0.56	Styrofoam board

Table 3.7.3 - Insulation test results

The results in the table above show a large variation between stores and also between the expected U-values based on the store construction and insulation level. There are two possible reasons for this:

1. Insulation in the stores is ineffective and uninsulated areas such as doors and louvers have more of an effect than previously thought.
2. The experimental procedure did not work in the way intended.

Of the two reasons the second is most likely. The influence of uninsulated areas is small because they are such a small proportion of the surface area of the store.

The data analysis shows that U-value fluctuations tracked ambient temperature for the most of the stores. This suggests that the thermal inertia of the building elements were having an overriding effect on the calculated results.

We achieved air temperatures in-store of 25°C and more heat would have given us greater in-store air temperature. We were unwilling to take the air temperature higher than 25°C as the air was being recirculated through the refrigeration evaporator coils and such high temperatures could have caused problems.

We conclude that the hot box test was not ideal for these circumstances and did not scale well. The best method for determining insulation effectiveness is assessment of type and thickness followed by a thermal imaging survey to identify weak points.

2.7.4. Effect of increasing insulation levels – model store

In order to compare the effect of increasing insulation thickness we used the model store. The tables below show the effect of increasing insulation levels for each store type and for each insulation type.

Insulation type	kWh cooling requirement	Insulation thickness	Saving
Composite panel	161,586	80 mm	
	151,915	120 mm	**6.0%**
Spray foam	173,147	50 m (with 100 mm on roof)	
	152,696	100 mm (with 150 mm on roof)	**11.8%**
Styrofoam	151,915	100 mm	
	140,374	150 mm	**7.6%**

Table 3.7.4 - Modelled box store savings from increased insulation levels

Insulation type	kWh cooling requirement	Insulation thickness	Saving
Composite panel	158,452	80 mm	**1.9%**
	155,377	120 mm	
Spray foam	157,960	50 m (with 100mm on roof)	
	155,826	100 mm (with 150mm on roof)	**1.4%**
Styrofoam	155,377	100 mm	**2.1%**
	152,139	150 mm	

Table 3.7.5 - Modelled bulk store savings from increased insulation levels

2.7.5. The role of thermal imaging

In addition to the hot box tests, thermal imaging was used to identify areas of higher heat transmission in the structure. No major areas for concern were identified. However experience of thermal imaging on other sites has regularly shown large differences between the integrity of insulation. Major issues have been de-lamination of spray foam insulation and thermal bridging. The following two images show these problems in stores assessed outside this project.

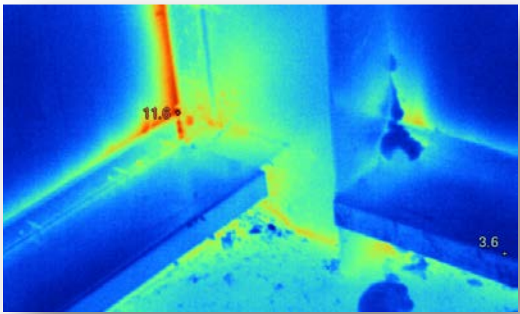


Figure 3.7.7 - Thermal bridging

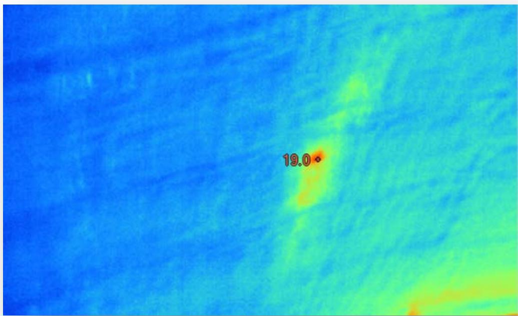


Figure 3.7.8 - Delamination of spray foam

2.8. Air movement efficiency

Potato stores are ventilated for a number of reasons:

- Dry the crop.
- Cool the crop.
- Keep temperatures stable and even.
- Avoid condensation in the crop.

Any ventilation system should be able to achieve all these objectives and maintain good conditions throughout the storage period. Systems tend to be designed for the peak requirement of flow and pressure so, given, the variation in temperatures, pressures and airflows required during a typical season, will at many times be operating inefficiently.

Ventilation accounts for between 30 % (refrigerated stores) and 90 % (ambient only stores) of the energy used during storage.
Most of the energy that goes into providing ventilation is absorbed by the fan impellor to move air, although there are some frictional losses in the motor and bearings.

2.8.1. Background and theory

Fan energy use is proportional to the **volume of air** and the **total pressure** developed by the fan. Total fan pressure is made up of two components, **velocity pressure** and **static pressure**.

Velocity pressure is directly associated with the speed of air leaving the fan. Speed is important where a fan is required to throw air a long distance without significant mixing.

Static pressure is required to overcome the resistance to the airflow imposed by intake and outlet louvres, ducts, refrigeration coils, filters, guards and the crop itself.
Total pressure remains constant in a system so, as velocity pressure decreases, static pressure increases. The key to low energy use and good performance is therefore to keep air volumes, air speeds and pressures as low as possible while still meeting the primary objectives of ventilation.

It's worth noting a few more important characteristics of fans. These come from what are called the **'Fan Laws'**; basic physical laws which pertain to all fans.

These are:

1. **Air Flow** is directly proportional to fan speed – halve the speed and you halve the flow.
2. **Pressure** development is proportional to the square of the fan speed – halve the speed and you quarter the pressure development.
3. **Power** required is proportional to the **cube** of the fans speed – halve the speed and you reduce the power requirement by 87 %.

The relevance here is that although, in the past fans have been regarded **as fixed speed devices**, with the advancement and reduction in capital cost of electronic variable speed drives (inverter drives); it's now possible to regard fans as **variable speed**.

2.8.1.1. Air flow

Potato stores are typically built and set up in the UK to general rules of thumb that go back to when potatoes were first stored in enclosed buildings. The figures are largely empirical. UK recommendations are different to other countries.

System	Airflow rate (m^3/s/1,000t)
USA and Scandinavia	7 for drying, 3.5 for wound healing
UK	20 moving to 40
Netherlands	40; in the past 20

Table 3.8.1 - Airflow rates used around the world

The figure of 20 m^3/s/1,000t is commonly used to size the fan used in the system (in the UK). This figure seems to be well suited to our climate based upon historical operation, but is based upon the requirements of the crop during pull down – i.e. the period of time when the flow rate needs to be at its highest to dry and remove field heat from the crop, not typical operation requirements. There is a gradual move to the higher rate of 40 m^3/s/1000 t airflow in the UK, meaning the airflow removes heat more rapidly, with less weight loss.

2.8.1.2. Pressure

Pressure is developed by the fan in order to overcome the resistance to airflow of the louvers, ducts and the crop. As crop condition will vary from year to year, maximum fan pressure needs to be such that it will overcome additional pressures from dirt and moisture.

In box stores the static pressure requirement is small but higher velocity pressure is required to ensure that the throw of the fan unit will be enough for the conditioned air to reach the end of the store, before being pulled back through the crop

2.8.1.3. Power requirement

The store designer decides the air volume and pressure development requirement of the fan to meet in the most extreme operating conditions. He uses this to pick an appropriate model from a manufacturer's range using a fan design curve (see Appendix 5 for an example). This means that, for all but the most extreme conditions, the volume flow, pressure development and hence power consumption of the fan is greater than strictly necessary. In practice, over-sizing is tempered by the operation of the control system - the store control system simply tailors the operation of the fan to provide the required airflow. The downside of this approach is that, when the fan is operating it does not operate at its optimum efficiency, either in terms of volume or pressure. Of course, any excess energy consumption just adds to the cooling requirement for the store.

2.8.2. Test method

The tests sought to calculate the air delivery (volume and velocity) from the set of stores. This was done by measuring pressures (both static and velocity) at relevant points in the system using a digital, calibrated, differential pressure manometer.

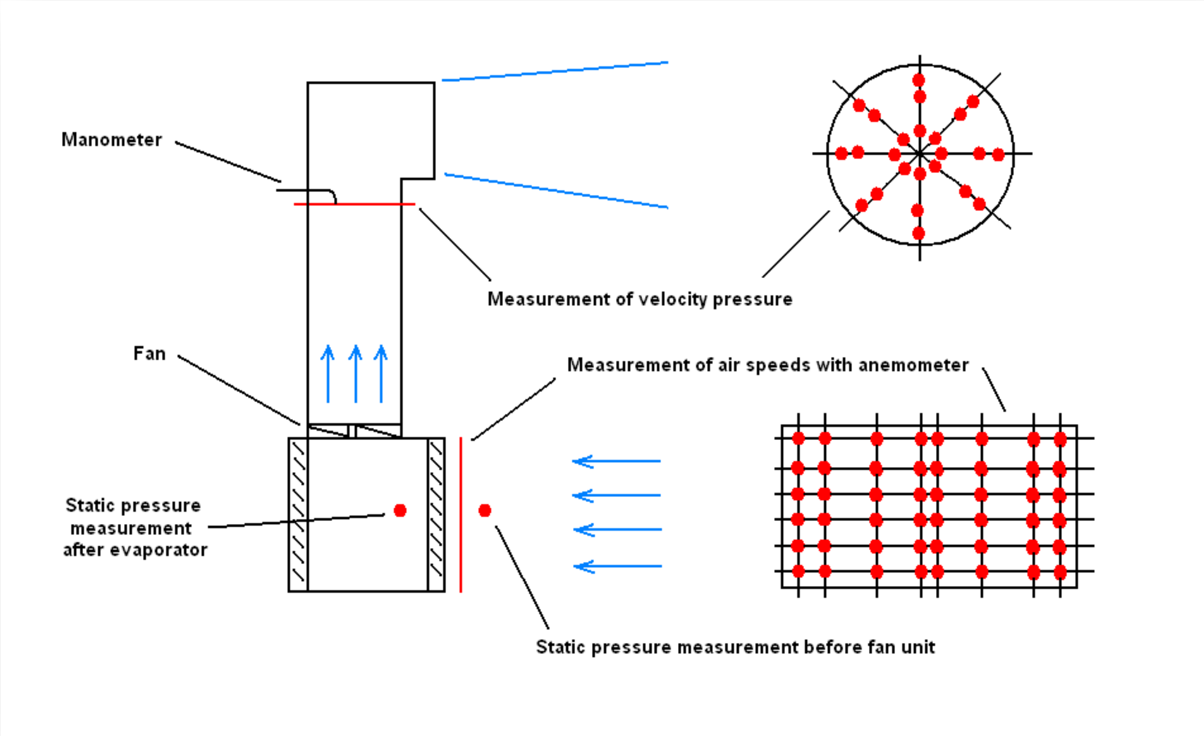


Figure 3.8.1 - Pressure measurement method

For some systems the volume of air drawn by the fans was also measured by using a vane anemometer over to the evaporator/intake grille and multiplying the recorded airspeeds by the surface area of the intake. These results were correlated with the pressure measurements to double check the readings.

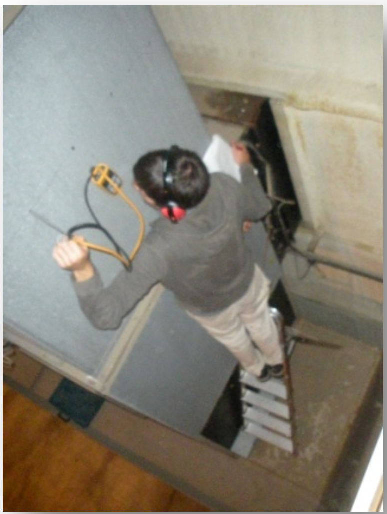


Figure 3.8.2 - Measuring pressures in ducts

2.8.3. Results

2.8.3.1. Box stores

Apart from Store 2 the box stores measured are overhead throw non-ducted design as shown in Figure 3.8.3.

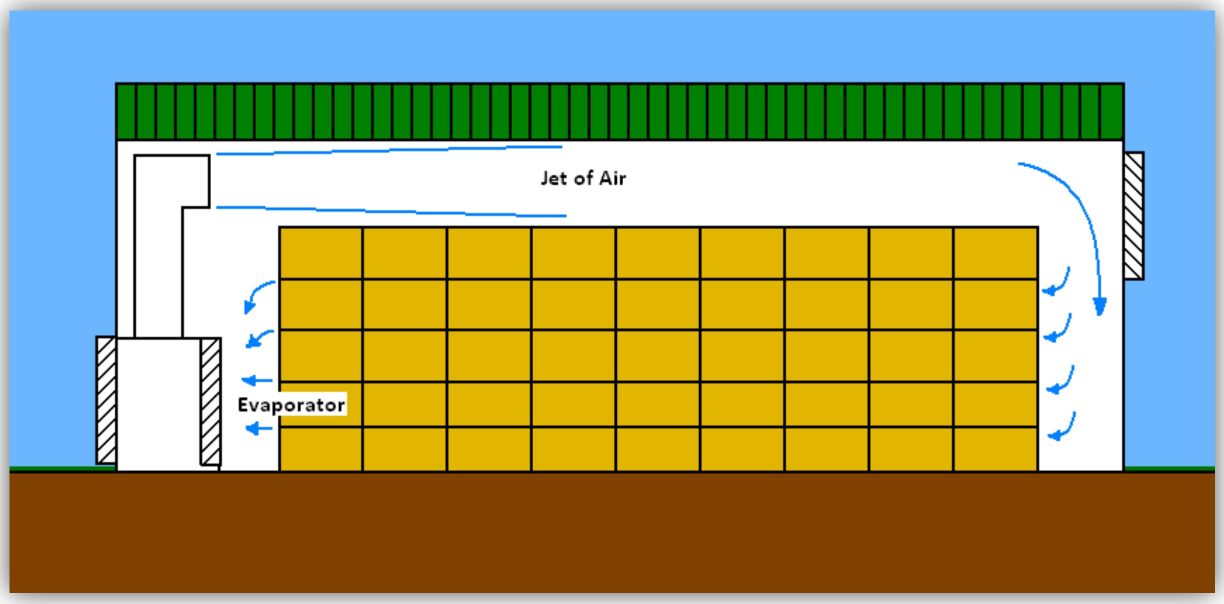


Figure 3.8.3 - Box store setup

With a non-ducted system, good air distribution relies on the velocity of the air to allow it to reach the far corners of the store. Although such systems do not have to overcome the pressures imposed by long ducting systems, they have to generate enough velocity pressure to project the air to its intended destination. This is done in the form of a jet of air.

If the velocity is too low, then the volume of air will not reach all the way to the back of the store, which may lead to big temperature differences across the crop, and risks of condensation, disease and rotting. Where the velocity is too high unnecessary energy consumption is taking place. Provided the correct air volume is being delivered, there may be an opportunity for reducing energy demand.

Centreline air velocity from the duct at the back of a store (Vt) should be between 3.5 and 5.0 m/s in order to prevent conditioned air falling onto the surface of the crop. Below 0.25 m/s, the jet of air dissipates and starts to lose its effectiveness. The length of throw is calculated as the distance taken for the air velocity to fall below this value.

The following table contains the main results of the air movement tests. The final column shows the calculated distance that the fan throws the air beyond the end of the store – i.e. if the air just reaches the store end wall this value would be 0. A negative value implies the air jet dissipates before reaching the end of the store and a positive value indicates that the air could be thrown further should the wall be removed.

Site	Power (kW)	Volume of air delivered ($m^3/s/1000t$)	Fan throw beyond store end wall
Store 2	17.13	20.425	n/a
Store 4	6.05	17.438	7.00
Store 5	12.18	30.673	3.41
Store 9	14.13	18.873	-11.30
Store 11	12.62	27.458	2.61
Store 12	15.15	26.592	-8.73
Store 14	14.13	17.697	1.73

Table 3.8.2 - Results of fan measurements in box stores

The table shows that there is a significant variation in volumes of air delivered and throws of the air. All the stores provided a reasonable volume of air (accepting measurement inaccuracies and current good practice) but none of them provided the higher volumes that are becoming the UK standard.

Interestingly the throw of air in two cases is less than the length of store; these stores will need to use additional air movement fans to ensure air is moved around the potatoes properly.

The potential for reducing fan speeds and hence energy is demonstrated by Figure 3.8.4 below.

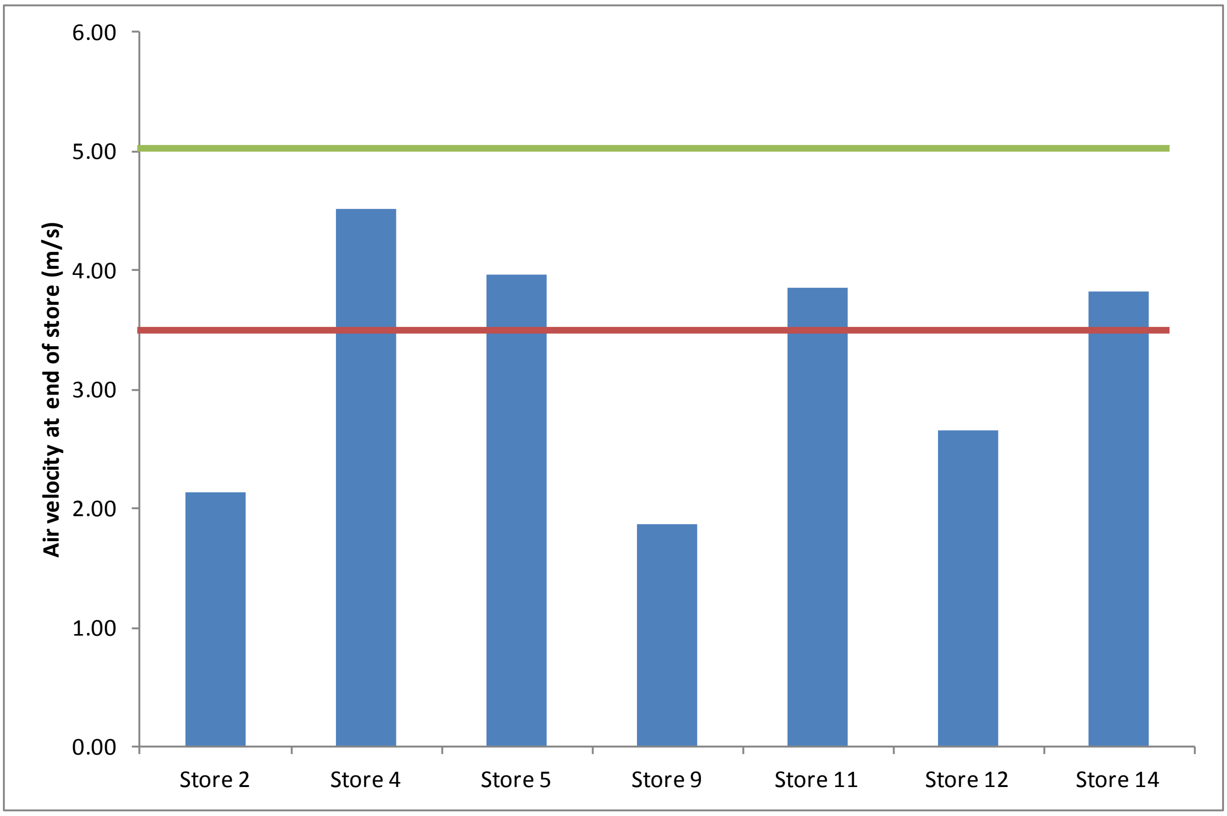


Figure 3.8.4 - Comparison of air velocities at the end of the stores

Where the air velocity is greater than 3.5 m/s at the end of the store, there is potential to reduce the fan speed to obtain better efficiency whilst maintaining good air distribution. This applied to four of the seven stores. Reducing fan speeds should only be done following calculation at the intended reduced speed to ensure that the volume of air delivered is still appropriate for good storage conditions.

For instance, Store 5 was delivering 33.74 m^3/s (significantly above the guideline 24 for the tonnage), and with a throw of 29 m (4 m more than the length of the store). It was possible to reduce the airflow to 30 m^3/s (11 % reduction) while still obtaining the necessary throw. Reducing the speed by this much represents an energy saving of approximately 28 %.

The same was the case with Store 11 which was delivering 31.91 m^3/s (target = 22) and at 28 m throw (3 m more than the store). This could also be reduced to 30 m^3/s maintaining throw, reducing fan speed by about 6 %, and saving about 14 % energy. If the fans were slowed down further still, to produce the desired volume of air the velocity would become insufficient to reach the end of the store. Theoretically this could still be achieved with good crop storage conditions if smaller, lower power air movement fans were installed to ensure air was distributed appropriately. We would not recommend doing this unless detailed air distribution analysis is carried out. This remains an area for further work.

2.8.3.2. *Bulk stores*

Store 7 was the only bulk store measured from the set of four processing stores, as the other stores were unsuitable. Store 7 is fairly representative of the bulk stores in UK potato storage and is shown diagrammatically in Figure 3.8.5 below.

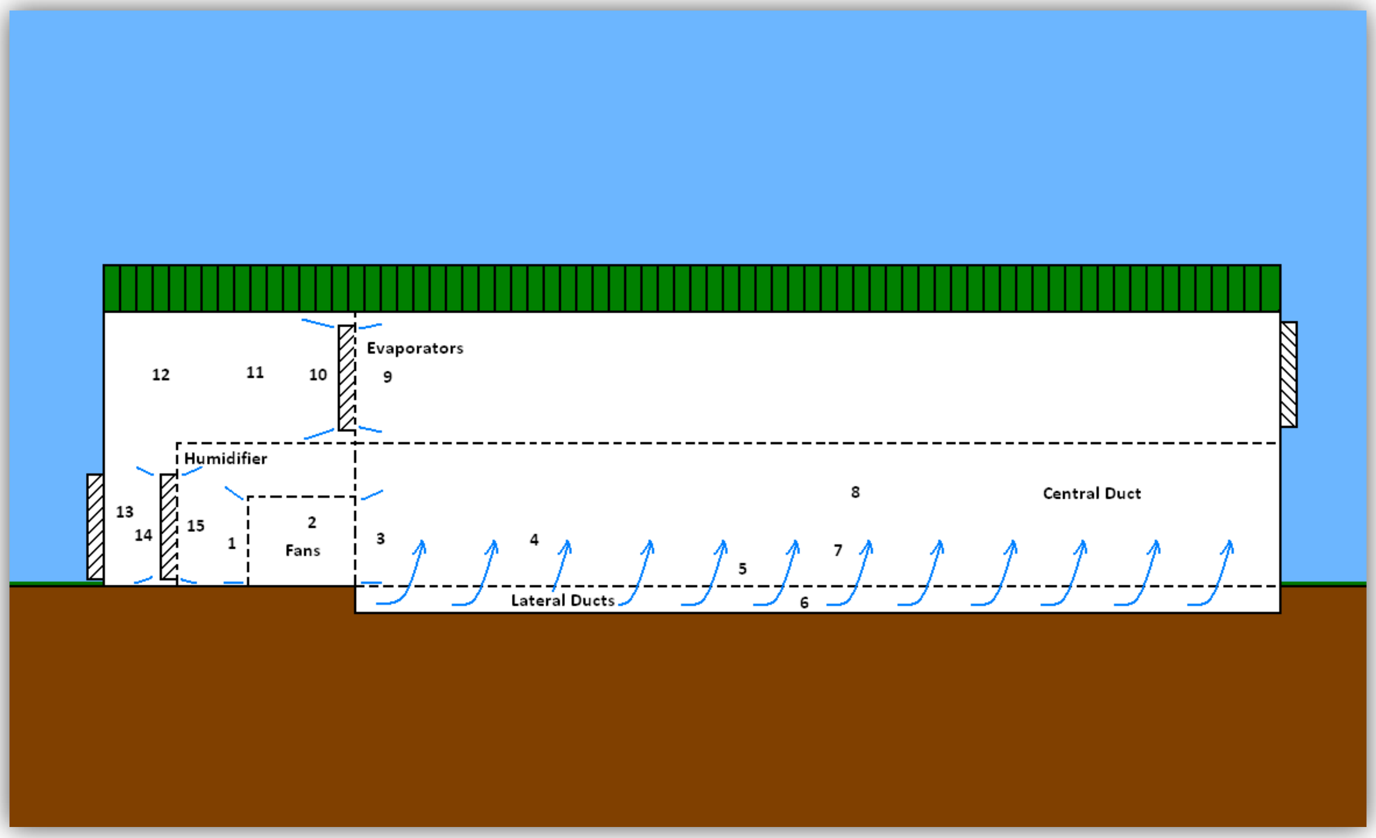


Figure 3.8.5 - Bulk store setup

For efficient operation air delivered must be appropriate and the back pressure minimised. The choice of louvres, ducts, guards, coils and other components affects the design pressure and selection of the most efficient fan. Thereafter, once a fan is installed, changes in pressure requirement affect efficiency slightly, but have a more significant effect on volume air throughput. This can affect the cooling/drying performance of the store.

Pressure drops occur at restrictions, louvers, evaporators, through ducts and where the air changes in direction.

The table below shows the results of the pressure calculation for the bulk store tested.

System element	Free area	Flow (m3/s)	Duct length (m)	Pressure drop (Pa)	% of system resistance
Sudden contraction	2.25	30		21.87	7.96 %
Guard	2.25	30		14.21	5.17 %
Sudden expansion	2.25	30		109.33	39.78 %
Duct resistance	6.75	30	33.40	16.70	6.08 %
Resistance through outlet to lateral		30		22.14	8.06 %
Lateral duct resistance		30	12.65	6.33	2.30 %
Sudden expansion from lateral		30		9.84	3.58 %
Resistance through floor and potatoes		30		61.85	22.51 %
Contraction through evaporator	16.00	30		0.43	0.16 %
Evaporator	16.00	30		7.22	2.63 %
Expansion from evaporator	16.00	30		2.16	0.79 %
90° bend	64.00	30		0.07	0.02 %
90° bend	64.00	30		0.07	0.02 %
Contraction through humidifier	16.00	30		0.43	0.16 %
Expansion through humidifier	16.00	30		2.16	0.79 %
Total				**274.81 Pa**	**100 %**

Table 3.8.3 - Calculation of pressure drop through the system at Store 7

As the table above suggests there are many factors that influence the pressure drop incurred in a system. This can be simplified to 3 main areas:

1. Main and lateral ducts including inlet and outlet of the fan.
2. Crop.
3. Refrigeration coils and humidification pad.

The simplified diagram Figure 3.8.6, shows the results in this format for Store 7.

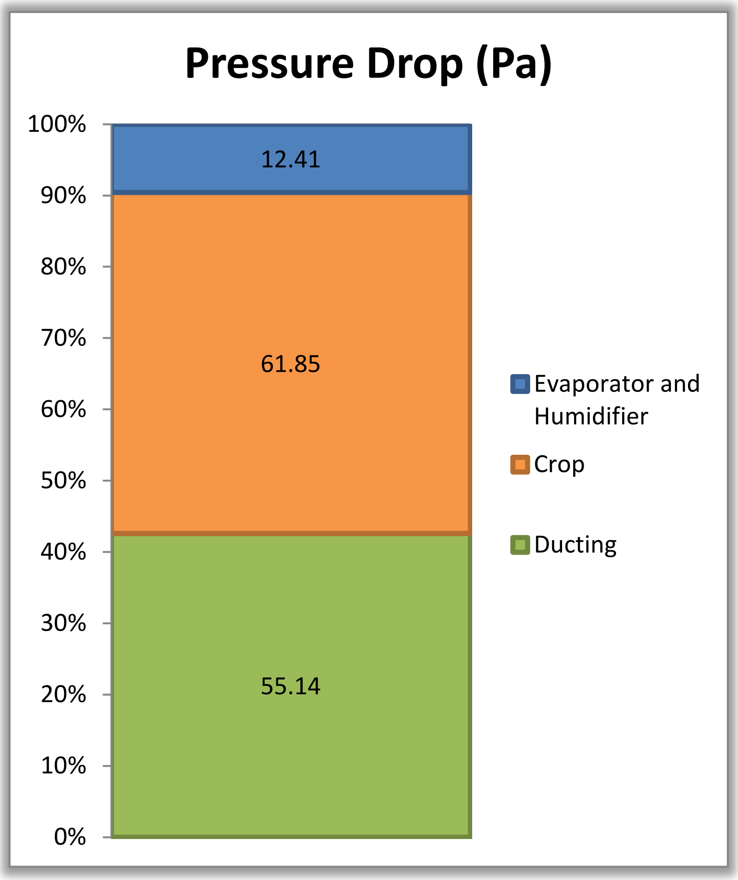


Figure 3.8.6 - Simplified pressure drop calculation results

Good design of ducting is therefore important to reduce pressure drop. Similarly, good loading and clean crop helps to ensure evenness of air delivery and efficiency of the system.

2.8.3.3. Variable speed drives

Bulk store fans are sized for worst case conditions. In many cases sizing takes into account dual purpose (grain drying for example).

Variable speed drives can play an especially important role in enabling efficient operation in all conditions for bulk stores. As air is ducted to its destination, maintaining air velocity is not an issue. This gives more scope for fan speed variation as evenness of air delivery is not generally affected. Figure 3.8.7 shows the effect of reducing fan speed on airflow, pressure and power drawn (and hence energy consumption) by a fan subjected to reduction in speed with a variable speed drive.

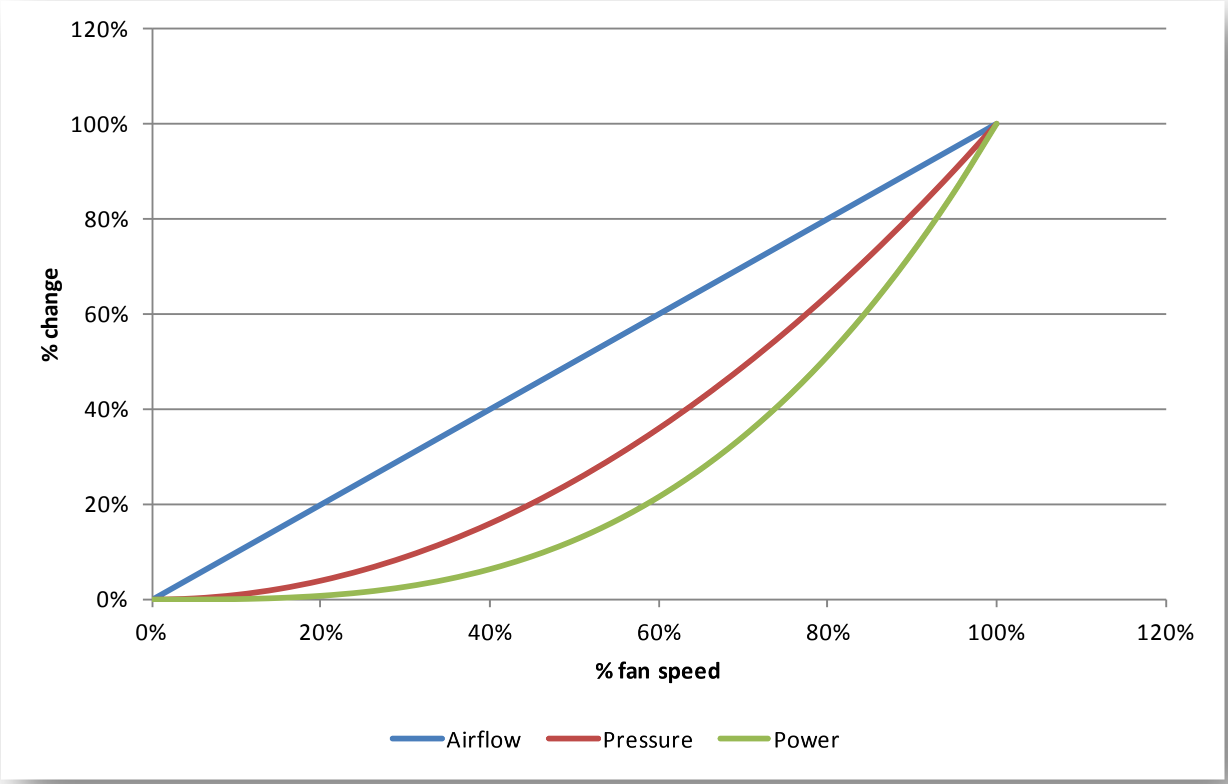


Figure 3.8.7 - Effect of reducing fan speed on airflow, pressure and power

Fan Speed	Airflow	Pressure	Power
0%	0.%	0.00%	0.00%
30%	30%	9.00%	2.70%
40%	40%	16.00%	6.40%
50%	50%	25.00%	12.50%
60%	60%	36.00%	21.60%
70%	70%	49.00%	34.30%
75%	75%	56.25%	42.19%
80%	80%	64.00%	51.20%
85%	85%	72.25%	61.41%
90%	90%	81.00%	72.90%
95%	95%	90.25%	85.74%
100%	100%	100.00%	100.00%

Table 3.8.4 - Effect of reducing fan speed on airflow, pressure and power

Worked example of effect of variable speed drive

Take a store, which has a fan rated to deliver 5 m^3/s of air (7 kW), and over a particular day requires the delivery of 216,000 m^3. This air can either be delivered at full fan output over 50 % of the day - the traditional on/off approach, or at reduced fan output over the whole of the day – variable output approach. The operational profile of the traditional approach might look like this.

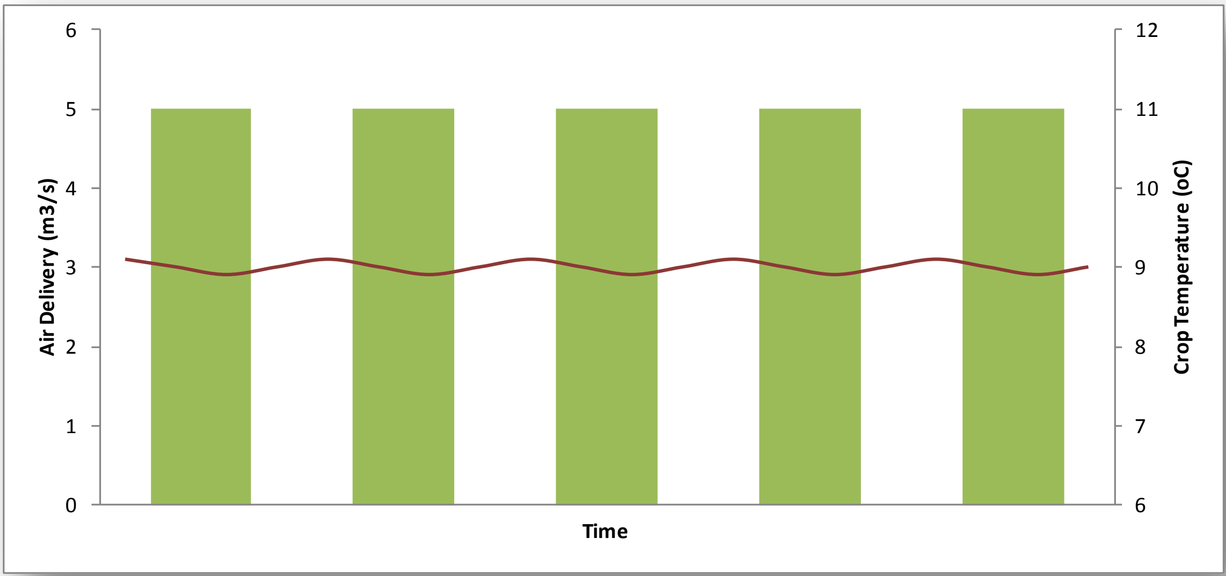


Figure 3.8.8 - Airflow delivery pre VSD

In the above situation the energy input requirement of the system would be the rating of the fan x operating hours:

12 h x 7 kW = 84 kWh

Alternatively the same quantity of air could be delivered by operating the fan constantly at half speed.

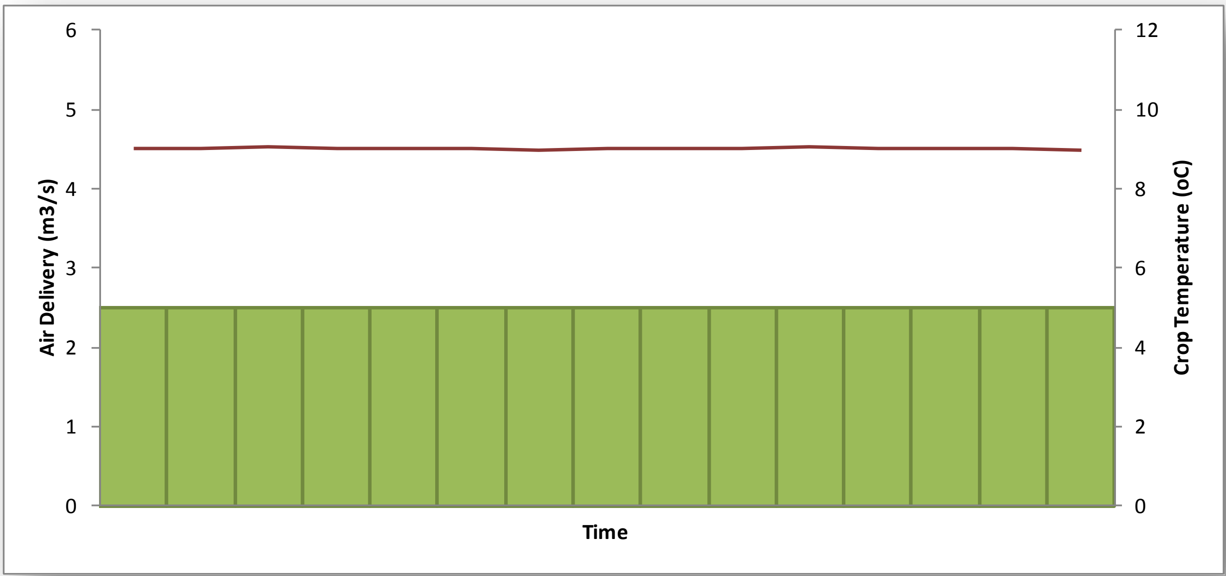


Figure 3.8.9 - Airflow delivery after VSD

In this case the energy use would be:

$$24 \text{ h} \times 7 \text{ kW} \times (1/2)^3 = 21 \text{ kWh}$$

In other word a 75 % reduction in energy use.

This simple example shows the energy saving potential from speed control. Other non-energy benefits of using VSD fans and operating them continuously include fewer problems with condensation on walls and ceilings during cold weather.

Clearly, care has to be taken to ensure that air distribution is not compromised by this approach. However, it's evident that the rewards in terms of reduced energy cost would justify some experimentation even if extra equipment (such as roof fans) had to be employed to achieve good air mixing.

The effects of a variable speed drive on the whole season energy use can be significant. Under initial operation (the first month or two) it is likely that no saving will be seen as the fan should be sized to dry the crop at near to maximum operational speed. The benefits come at the point where the crop is dry, and a constant airflow can be delivered with a proportionally greater reduced power input, rather than intermittent blasts of airflow at significant power input.

2.9. Temperature uniformity within store

2.9.1. Background

Condensation is a big potential problem in potato storage as its occurrence can lead to skin disease and bacterial rotting. The storage environment is naturally humid - typically, over 90 % relative humidity.

At high humidity small differentials in temperature will lead to condensation events either within the mass of the crop or on structural components. For example, at 10°C and 95 % RH, a 1.14°C temperature fall will cause the air to reach its dew point. Maintaining a uniform temperature throughout a store is, therefore, extremely important.

In positively ventilated stores, i.e. stores where air is forced under pressure or by suction through the potatoes, the condensation risk is usually the lowest. However, in stores which did not have positive ventilation, such as overhead throw box stores, steps need to be taken to address this condensation risk.

Beyond full conversion of the store to a letterbox or suction system, these measures are primarily focused on eliminating short-circuits and ensuring that as much air as possible is routed evenly through the pallet slot under each box. This will maximise the scope for cooling throughout the store.

One way in which this has been addressed over the last decade, is through the installation of an air divider or separator, as shown below. A similar effect can also be achieved through installation of a plenum chamber.

Figure 3.9.1 - Air divider curtain fitted in store

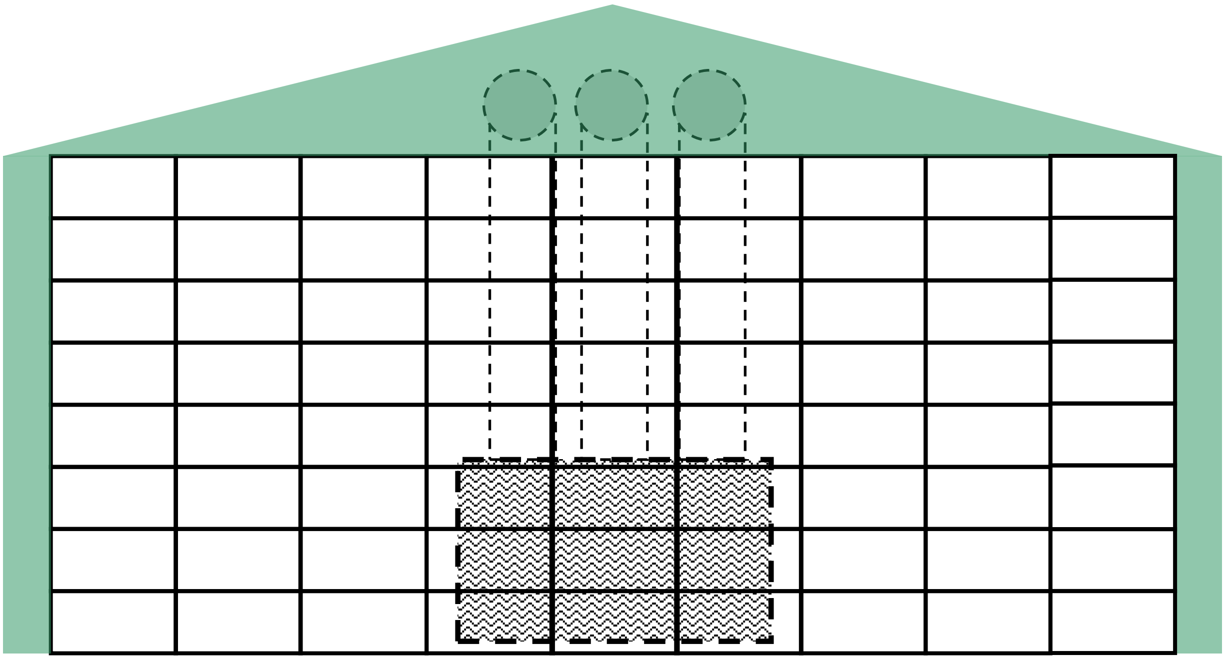


Figure 3.9.2 - Sectional view of a box store with an air curtain fitted

Whilst undoubtedly improving a store through the elimination of short-circuits, as all the delivered air has to return to the farm via the pallet slots, there has been no data gathered on the systems' impact on temperature uniformity.

In this work, an attempt was made to quantify the effectiveness of an air divider by intensive logging of temperatures and airflow across a store fitted with the system. The results were then compared with similar measurements carried out in a conventional store which had no such device in place (control).

2.9.2. Materials & methods

Temperature and air flow profiles of two purpose built box potato stores (Test Stores 14 & 16) were compared. The assessments took place over two time periods in different seasons. Both stores were physically and dimensionally similar, as were their air handling and refrigeration capacities.

Each store had a capacity of approximately 1160 tonnes in one tonne boxes. Each store featured an overhead throw direct expansion refrigeration system for cooling of the crop to a temperature of around 3.5°C. Additionally there was a cross flow ambient air extraction system available for use if prevailing ambient conditions were suitable. Store control was via a computerised Cornerstone system.

Store 14 was fitted with an air divider curtain, Store 16 was not. Figure 3.9.1 below shows the box stacking pattern in each store.

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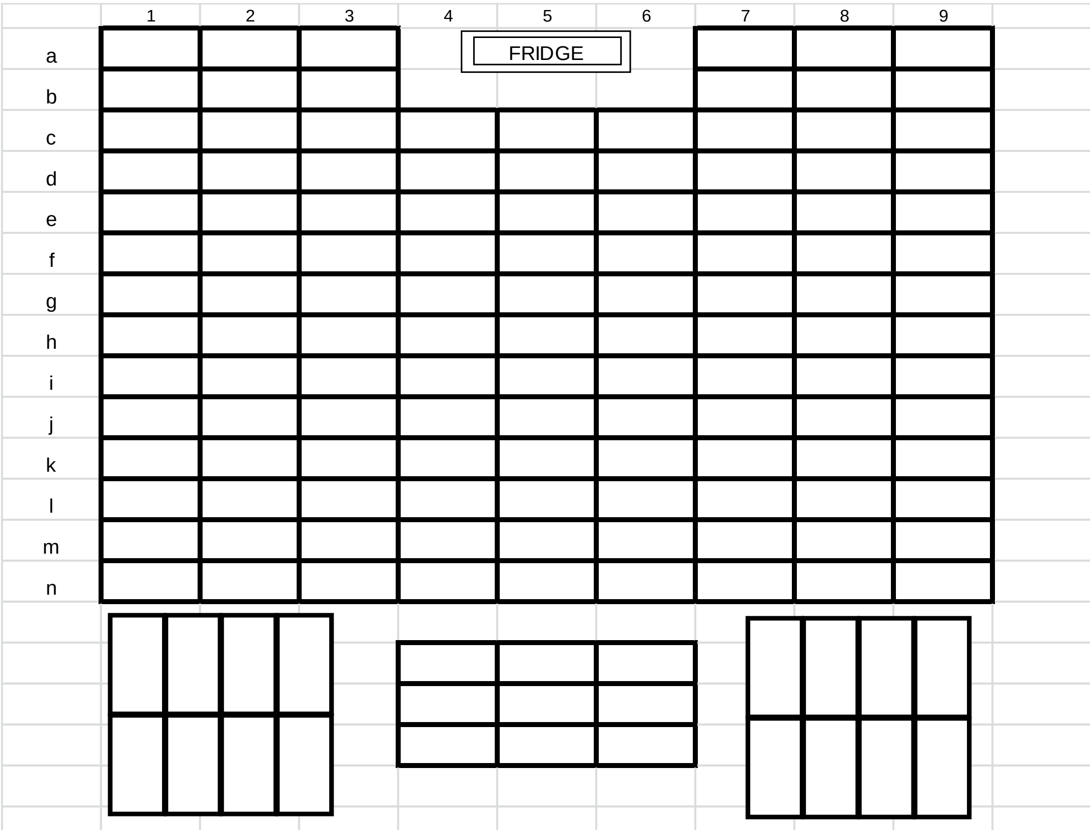


Figure 3.9.3 - Box stacking pattern

Conditions in each store were monitored using an Omni Instruments' GRD data logger linked to three air speed sensors, 32 temperature sensors and one RH sensor. Data was logged, nominally, every 30 mins and transmitted via a GSM website, from here it could be viewed in real time or downloaded when required.

Air speed sensors were arranged to monitor return air flow through the box pallet apertures at three heights, in Row N; Figure 3.9.4 shows these. The first set of measurements were taken at Column 3, additional measurements were made later at Column 1.

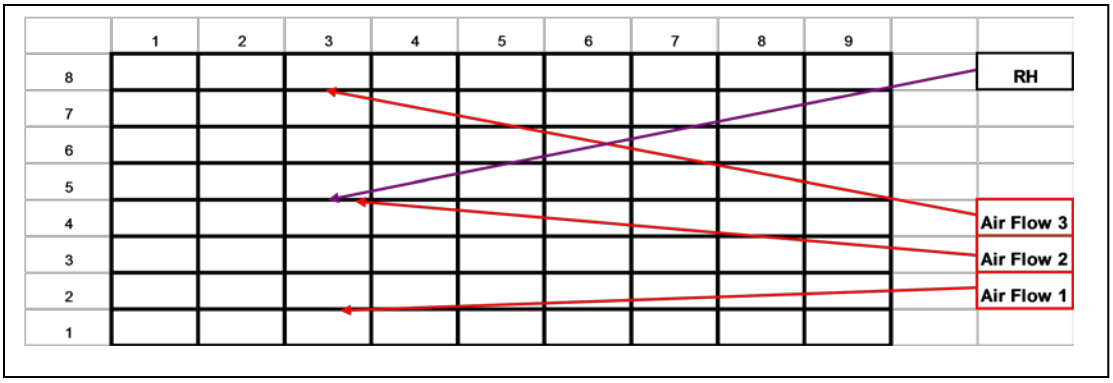


Figure 3.9.4 - Air flow measurement points

Temperature sensors were arranged to give a profile in three planes, top to bottom, front to back and left to right (Figure 3.9.5). The vertical sensor array was placed at position 13, eight positions (6-13).

	1	2	3	4	5	6	7	8	9
a					FRIDGE				
b									
c				23					
d				22					
e				21					
f				20					
g				19					
h	32	31	30	29	28	27	26	25	24
i				18					
j				17					
k				16					
l				15					
m				14					
n				13					

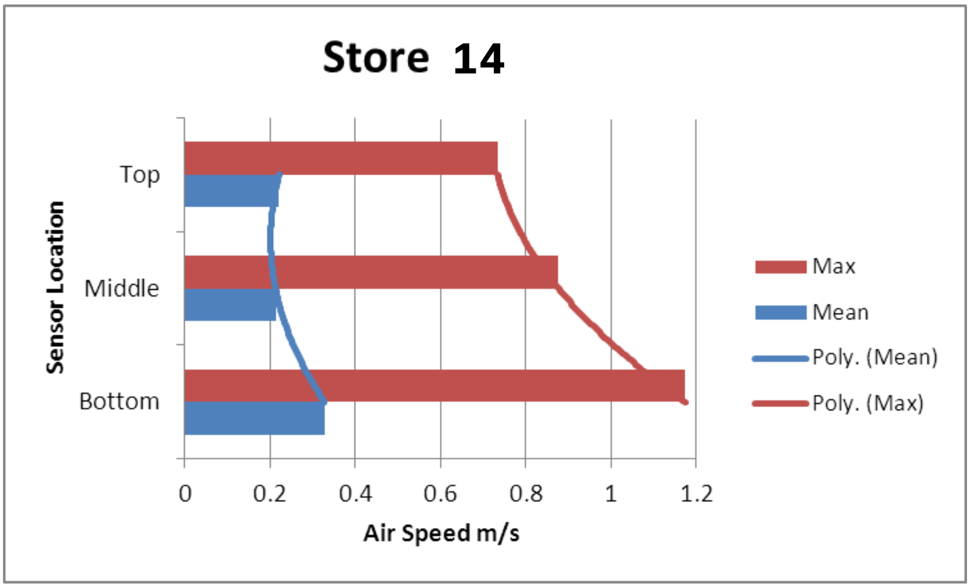
Figure 3.9.5 - Temperature sensor positions

Measurements were taken from 1st November 2011 until 16th January 1012 (Store 14) and from 15th October 2012 until 1st November 2012 (Store 16). Commercial operations prevented any extended monitoring beyond these periods.

2.9.3. Results

2.9.3.1. Air flow

Data were consolidated to give a representation of mean and peak air flow over each of the three locations (Figure 3.9.4).



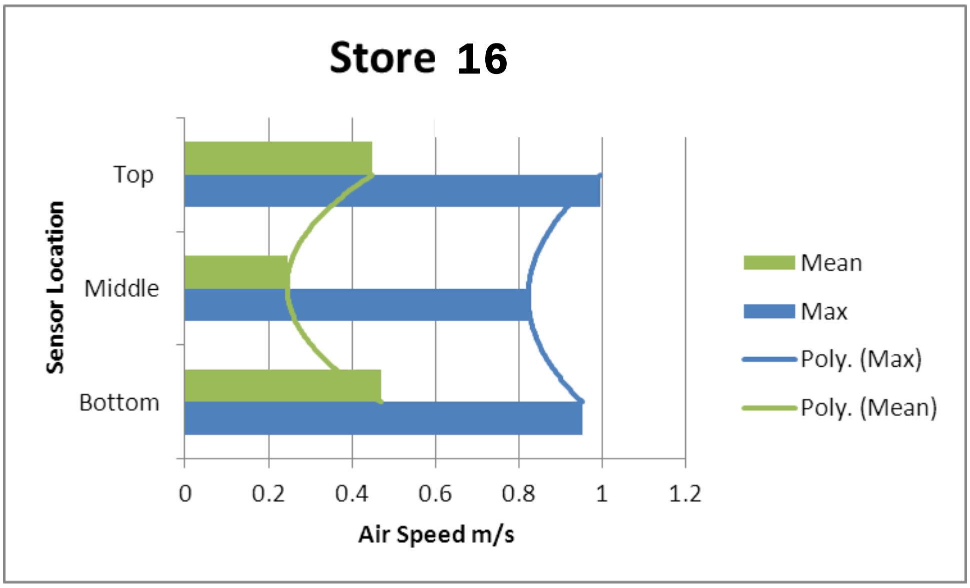


Figure 3.9.6 - Air speed profiles at a single plane in each store

The air divider to Store 14 appeared to alter the air flow profile with more air being returned to the evaporator via the lower pallet slots where the modification was made compared with the standard Store 16.

As mentioned above, some additional measurements of air speed were made in the boxes closest to the wall; these showed a distinct change in peak air flow at the bottom sensor position from those taken at the side of the store (Figure 3.9.5).

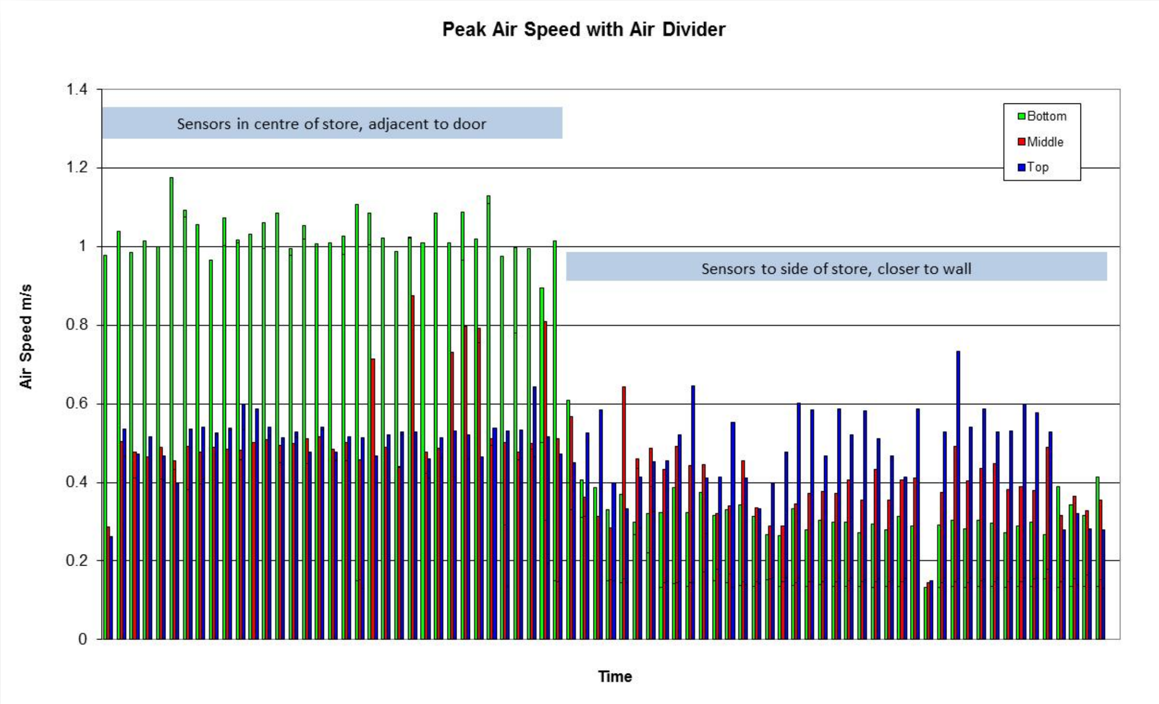


Figure 3.9.7 - Peak air speed, with air divider curtain in place, at two sensor locations

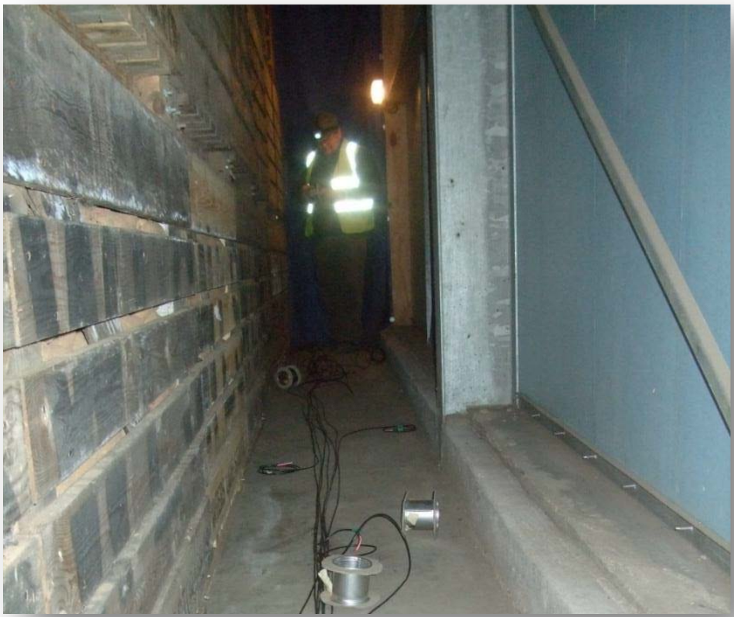
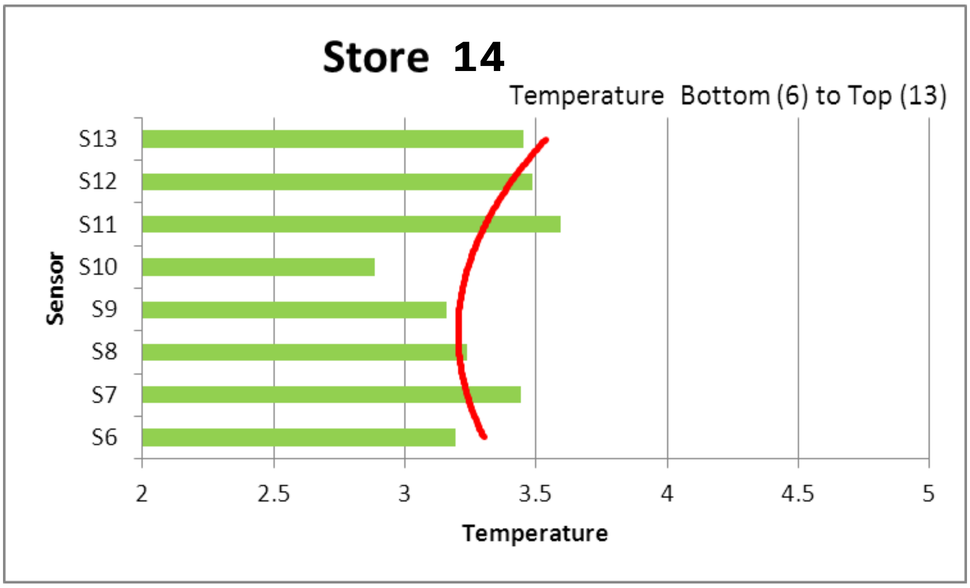


Figure 3.9.8 - Installation of temperature sensors in a commercial test store

2.9.3.2. Temperature

The mean temperature profiles from top to bottom (with trendline) are shown in Figure 3.9.7.



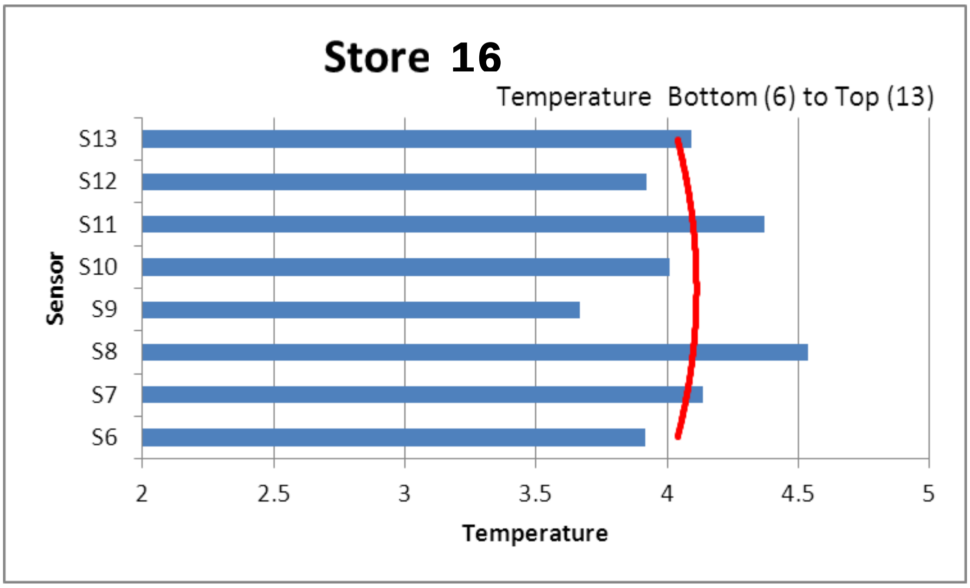


Figure 3.9.9 - Vertical temperature profiles at the front of the store

Higher air-flow through the lower pallet slots in the modified Store A led to lower temperatures at that point.

The mean temperature profiles from left to right (with trendline) across the top boxes in the centre of the store are shown in Figure 3.9.8.

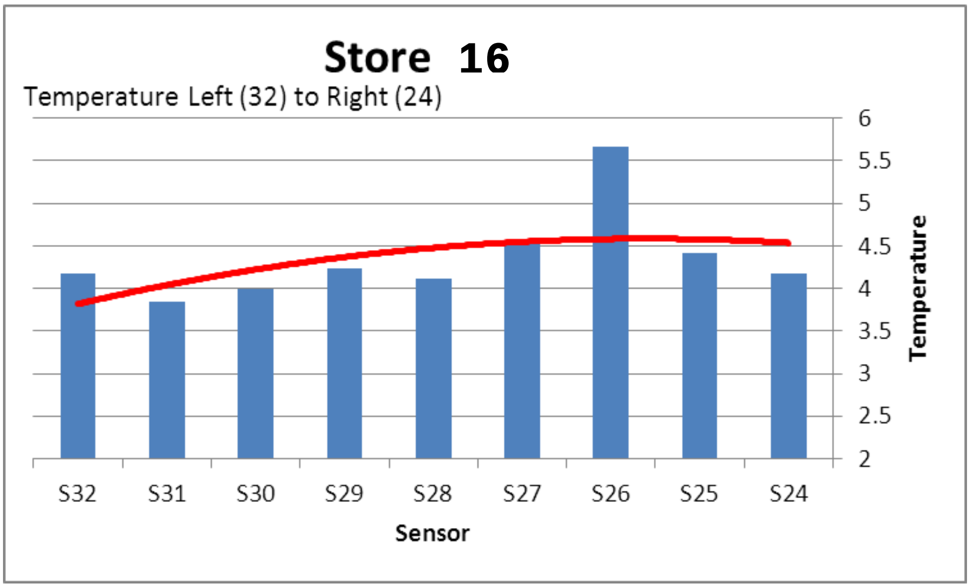
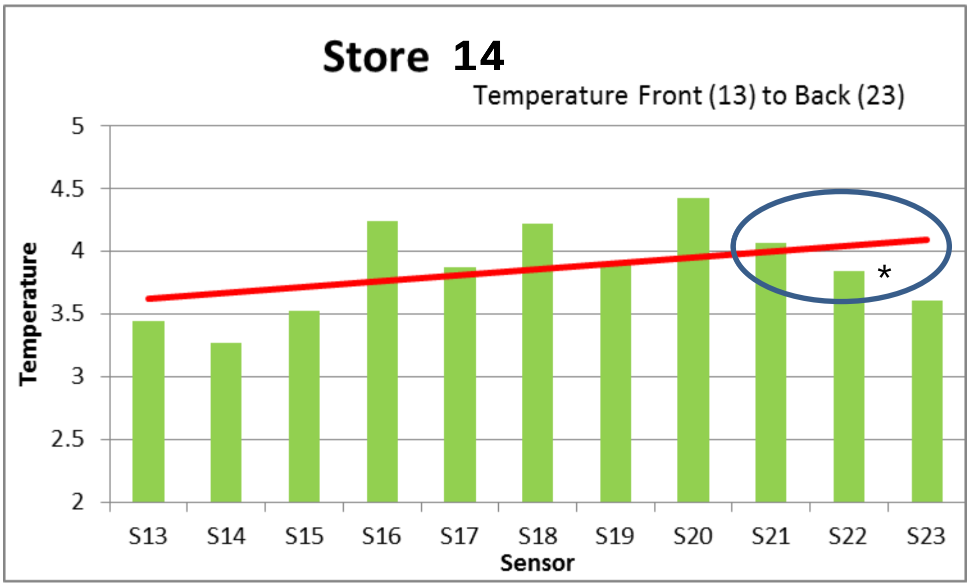


Figure 3.9.10 - Temperature profile across store: left to right

The horizontal temperature profiles at box 8 level, across the stores, were similar. There was a general trend for temperatures on the right side of the store to be marginally higher than on the left. This may mean there is a slightly skewed air distribution but no clear evidence was gathered to indicate why this might be the case.

The mean temperature profiles from front to back (with trendline) across the top boxes in the centre of the store are shown in Figure 3.9.9.



*Possible short-circuiting of cold air through top boxes (circled)

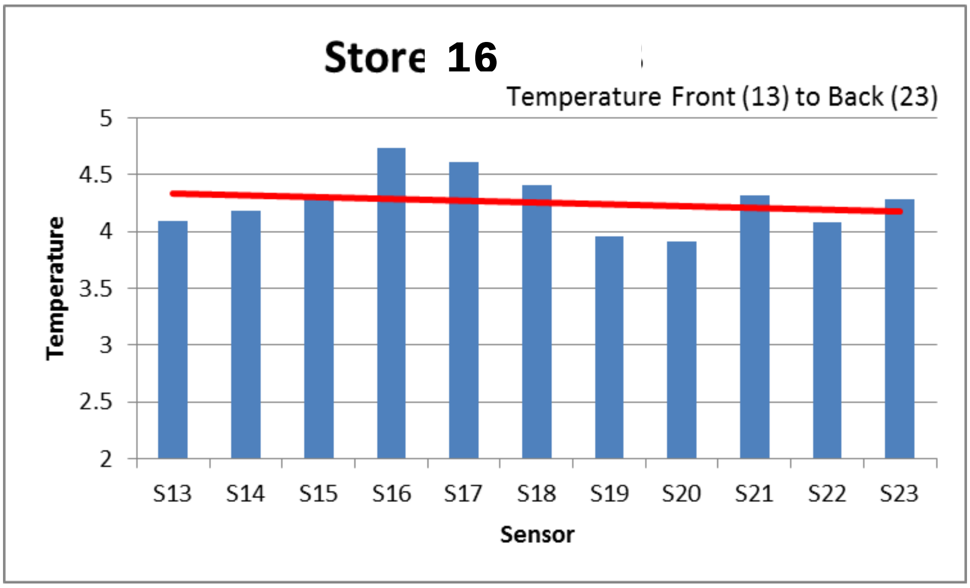


Figure 3.9.11 - Temperature profile across store: front to back

In the modified store, more air was being delivered to the point farthest from the discharge and resulted in a gradual temperature increase from front to back of the store, which is to be expected as heat is gradually removed on the air path. Some evidence of short circuiting from the positive to negative pressure side of the curtain through the top boxes closest to the curtain was seen (Figure 3.9.9: Store 14, circled).

The trend in the unmodified store was slightly in reverse, indicating that a proportion of the refrigerated air almost certainly "short-circuits" back to the evaporator through the boxes. Whilst the general temperature profile might suggest that this short-circuiting is not too much of a problem, more detailed analysis reveals a progression of temperature. This moves from LOW (S13) to HIGHER (S16) to LOWER (S20) to

HIGHER again (S23) across a range of 0.8°C and shows that there is a relatively high risk of condensation occurring as air moves from the front of the store to the back.

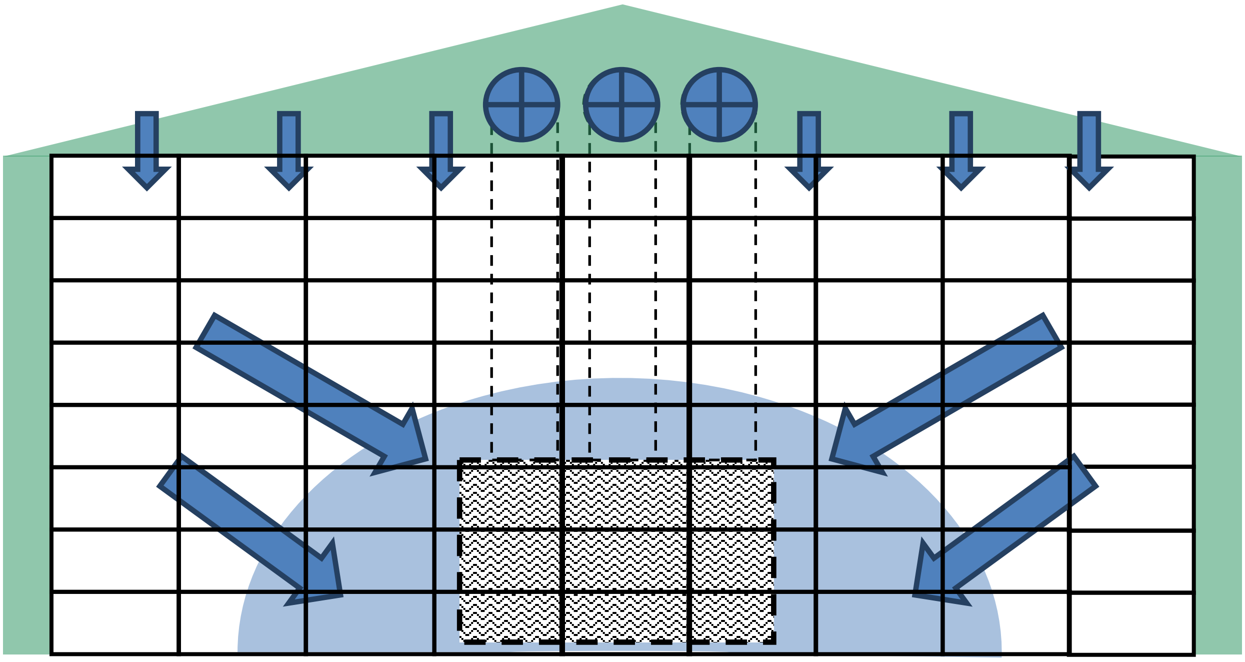
2.9.4. Discussion

Measurements of air flow and temperature in an unmodified ‘overhead throw’ potato store showed that temperature varied within the store by as much as 1.5°C across distances of less than 5 metres. This is a concern as temperature variation of this extent would be regarded as a significant condensation risk, especially during periods when the fans switch off and airflow is limited to just convective activity within the box stack.

The temperature profiles across the store fitted with an air divider curtain were more even than the control (unmodified) store, albeit still in evidence. A gradual temperature change across a store has to be accepted as, without it, there would be no means of removing heat from the store. By achieving a uniform, gradual change in temperature the risk of condensation is minimised and the efficiency of heat removal optimised.

There was evidence, that using an air divider curtain can increase the amount of air returned to the fan via the pallet slots; this is to be expected as it is the only open route that remains for air flow once the curtain is in place. Nevertheless, there was also evidence that this flow may be biased to the lower return slots, compared with those at the higher level in the store.

In addition, the peak air speed measurements at two points across the store suggest that there may be a further imbalance of flow across the store influenced by the negative pressure generated around the air return, in this case through the evaporator (Figure 3.9.10).



Air divider curtain shown in **green**. Cold air flow in **blue**.

Figure 3.9.12 - Possible residual skew in airflow with air divider curtain fitted

The extent of any gradient in air flow, if found to be a consistent effect, is something which will require further, more detailed, investigation to establish methods to counteract this.

If air divider systems are to be utilised more widely, e.g. to even out distribution of CIPC application in 'overhead-throw' box potato stores, this latter point takes on more immediate significance requiring action in light of the review of CIPC use by the Advisory Committee on Pesticides[14]

[14] Potato Industry CIPC Stewardship Group www.potato.org.uk/cipc. Accessed 4 April 2013.

2.10. Humidification and adiabatic cooling

2.10.1. Background

Humidification systems are increasing in popularity particularly in processing potato stores as store owners seek to cut weight loss and maintain quality. They offer:

- Reduced weight loss due to higher store RH.
- Adiabatic cooling giving reduced energy use and/or allowing ambient stores to achieve the required temperature later into the storage season.

Critically, humidification can only really be used to its best in a well-engineered store which is well insulated, well ventilated and where temperature gradients have been minimised. The benefit of adiabatic cooling – i.e. temperature reduction achieved through the evaporation of water – is a by-product of the humidification process. Whilst there is little doubt that adiabatic cooling works, there is little in the way of robust data to quantify its effect when used in a commercial potato store.

The energy consumed by evaporative systems comprises that associated with the water pump and any increase in fan power due to the resistance to airflow through the system.

Trials were undertaken to evaluate these issues.

2.10.2. Test method

Controller output predictions were recorded and spot measurements of temperature, humidity and pressure drop were taken to determine the effectiveness and impact of humidification installed in two commercial processing stores (Figure 3.10.1).

Figure 3.10.1 - Example commercial humidification system in test Store 7

2.10.3. Results

Data from the evaluations undertaken are presented in Tables 3.10.1 (Test Store 17) and 3.10.2 (Test Store 7).

HUMIDIFICATION	Run 1	Run 2
Humidifier intake side:	14.8°C 75 %RH	14.6°C 76.5 %RH
Post-screen output:	95.6 %RH At fans 12.6°C Pressure peak at 72 Pa for 5 m stack	91 %RH In duct: 13.1°C

ADIABATIC COOLING		Run 1	Run 2
	Ambient air:	---- 14.8°C	82.9 %RH ----
	Adiabatic prediction:	10.6°C (controller)	
	At inlet:	14.8°C 82.9 %RH	14.8°C 75.0 %RH
	Post-screen output:	11.8°C	12.6°C
	Variance fr. Predicted:	1.2°C	2.2°C
	Humidity	95.0 %RH	95.0 %RH
	Recirc duct temp	12.2°C	NR[15]
	Fan @ 80 % (40 Hz)		
	Water usage rates of up to 190 litres/hour were measured.		
Tested 27/10/2011			

Table 3.10.1 - Humidifier test results for Store 17

[15] not recorded

HUMIDIFICATION	Temperature	RH	
Ambient air	6.9°C	85.7 %	
Crop	13.2°C		
Roof	11.7°C		
Duct	11.7°C	88.3 %	
Humidifier	Rep 1	Rep 2	Rep 3
At inlet:	11.5°C	12.3°C	12.4°C
	98.8 %RH	98.9 %RH	98.4 %RH
Post-screen:			
(fans off)	11.3°C	12.6°C	12.4°C
	99.8 %RH	100 %RH	100 %RH

ADIABATIC COOLING	Rep 1	Rep 2	Rep 3
Ambient	------	8.0°C -----	7.6°C
		87.3 %RH	85 %RH
Recirc duct		10.7°C	10.7°C
		90.3 %RH	91.0 %RH
Adiabatic predict (controller)		7.2°C	6.7C
Ambient louvre 100 % open			
At inlet:	10.0°C	8.8°C	10.5°C
	95.1 %RH	92.2 %RH	97.4 %RH
Post-screen output:	8.1°C	7.9°C	11.1°C
Variance from predicted	0.9°C	0.7°C	3.4°C
Humidity	97% %RH	98.2 %RH	99.5 %RH Not evaporating?

Fan @ 80 % (40 Hz)
Assessed 06/11/2012

Table 3.10.2 - Humidifier test results for Store 7

2.10.3.1. Discussion

The data obtained in this evaluation confirmed the effectiveness of large scale humidification systems. Even when humidifying air at comparatively low RH (Store 17), the system quickly boosted humidity of the ventilating air to a high level (in excess of 90 %).

The value of humidification, in addition to reducing weight loss during ventilation (water usage rates of up to 190 litres (190 kg) per hour were measured when humidifying at a high rate at Store 17), is its potential to offer adiabatic cooling. This can reduce the need for refrigeration.

The results achieved, whilst good, did not quite provide the theoretical level of adiabatic cooling. This is because the system fails to keep the humidification cell completely moist. Where there is a high demand for water, maintaining adequate supply through the humidification pad is likely to be limiting.

Also, at the other end of the scale, as humidity moves towards the point of saturation the potential for evaporation reduces. Ultimately, no evaporation takes place so no temperature drop is achieved. In the tests in Store 7, the ambient condition on the day of the test was generally unfavourable with quite a low outside temperature and high relative humidity. Towards the end of the assessment, efficiency fell and errors increased as it became apparent that less evaporation was actually taking place.

Despite these inherent weaknesses, the process of adiabatic cooling has a lot of attraction from a number of perspectives. Where it increases the usability of ambient air cooling, it has the potential to cut energy bills on refrigeration significantly. But the greater attraction is perhaps the fact that it increases the opportunity for ambient ventilation in circumstances where, without humidification/adiabatic cooling, there would be none available. Even if it is not at its most efficient, there is scope to use ambient air when it is at a temperature equal or even warmer than the crop, as the temperature reduction gained on evaporation can be substantial (a 3.0°C drop was achieved at Store 17).

2.11. Store management and control

2.11.1. Test method

A survey of store management and control practices was undertaken by 45 industry respondents attending the British Potato 2011 event at Harrogate.

The questionnaire (Appendix 6) asked respondents for information on their stores and the way they are controlled and managed. Additionally questions were included on store upgrades and recording of energy use.

2.11.2. Results

Data are presented below as percentage of respondents.

Market and storage length

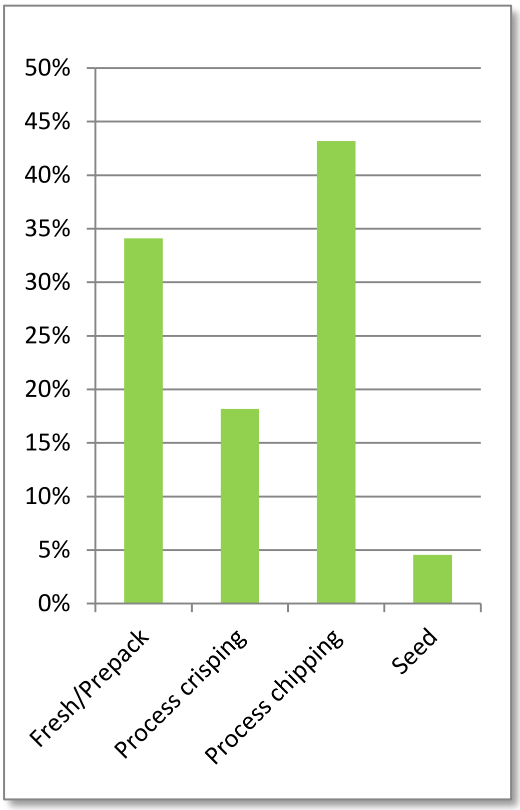


Figure 3.11.1 - Primary market

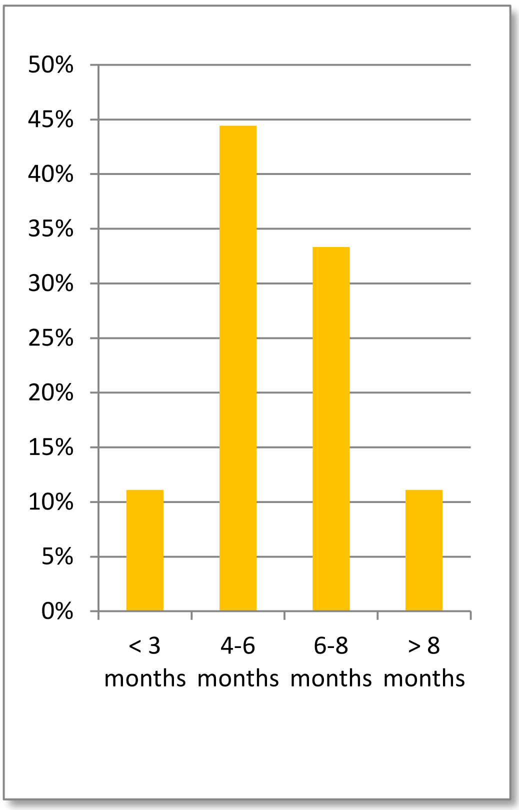


Figure 3.11.2 - Storage term

The respondents represented all major sectors of the industry (Figure 3.11.1) and the majority were looking to store crop for between four and eight months, largely as expected (Figure 3.11.2).

Store type

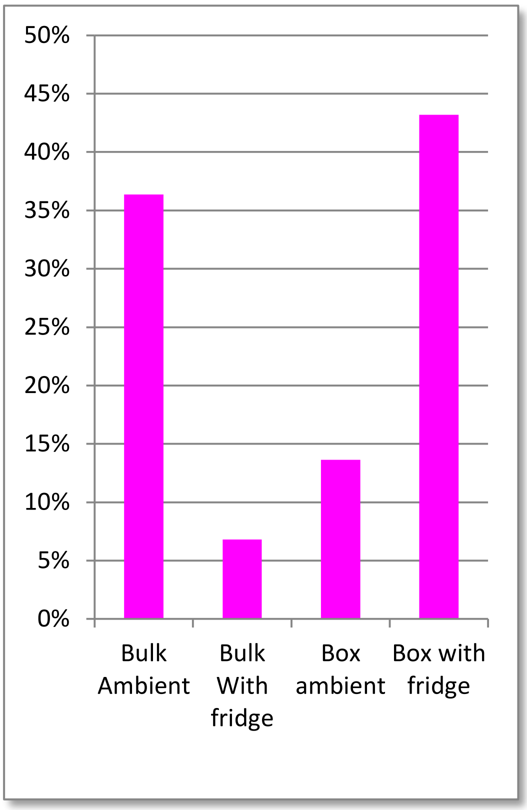


Figure 3.11.3 - Store type

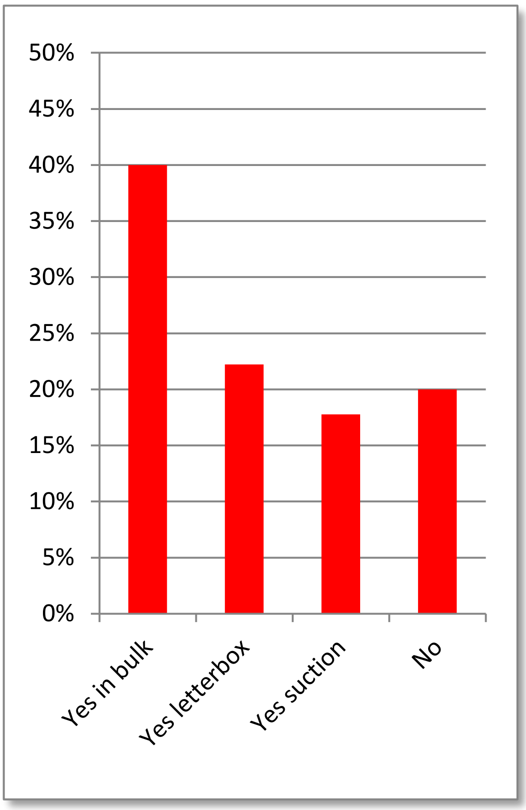


Figure 3.11.4 - Positive ventilation

Although almost 45 % of respondents had a box store with a fridge system (Figure 3.11.3), it was interesting to see that two thirds of these said they had positive ventilation systems in place (Figure 3.11.4). This is thought to be unlikely as the vast majority of the box stores in Great Britain are overhead-throw style stores which, whilst they might circulate the air via the pallet slots, do not offer true positive ventilation as the air only has to travel under the box not through the potatoes. The result therefore say more about how growers understand (or, more to the point, don't understand) the term 'positive ventilation'.

Store controls

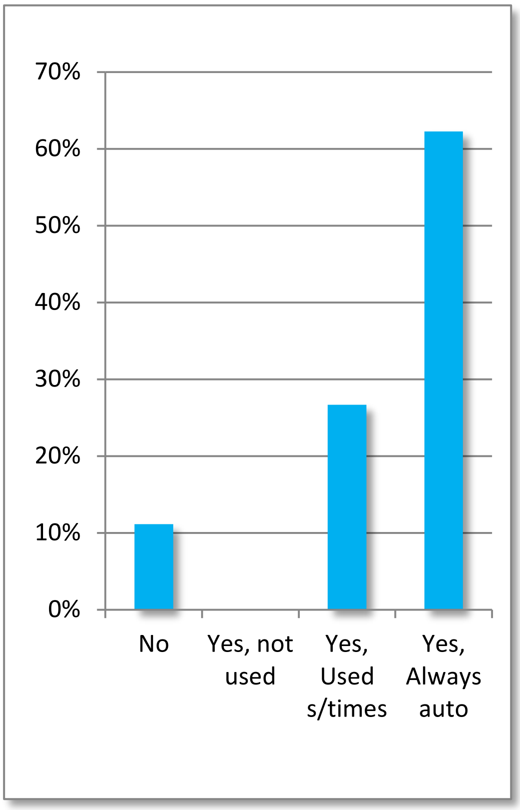


Figure 3.11.5 - Automatic control/use

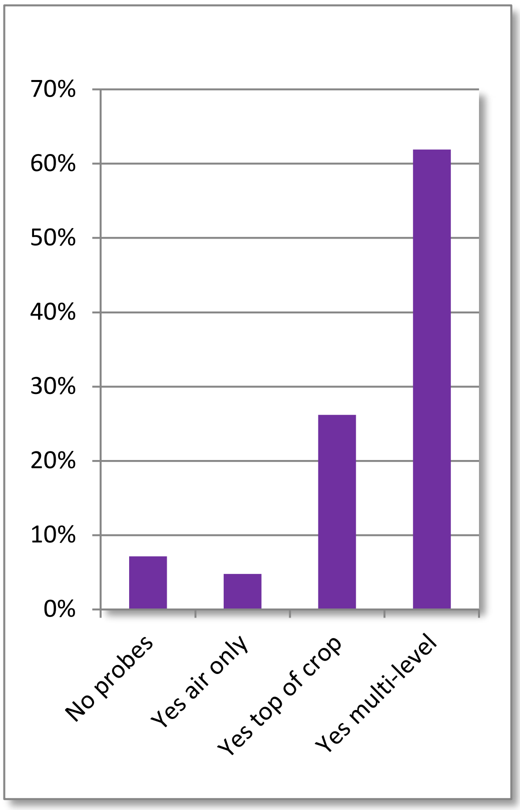


Figure 3.11.6 - Temperature probe placement

The use of automatic control systems was widespread although, disappointingly, there were still over 10 % of respondents who did not have such control available, making them prone to the influence of weather conditions on storage performance e.g. if fans are running when outside conditions change such that they then present a condensation risk (Figure 3.11.5). However, it was encouraging that over 60 % of store managers had sufficient confidence in their controller to use it all the time in accordance with best practice recommendations.

Temperature probe placement (Figure 3.11.6) largely mirrored the control results with six out of 10 stores reported to be using probes at multiple levels. Given that 40 % of the stores were bulk, where this is difficult (but not impossible) to achieve, this response should perhaps be treated with some scepticism.

Store improvements and monitoring

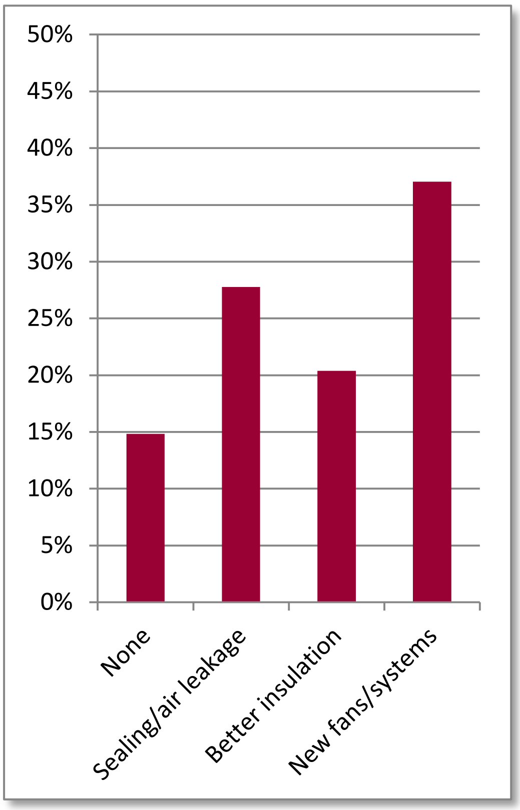


Figure 3.11.7 - Store improvements in last 3 years

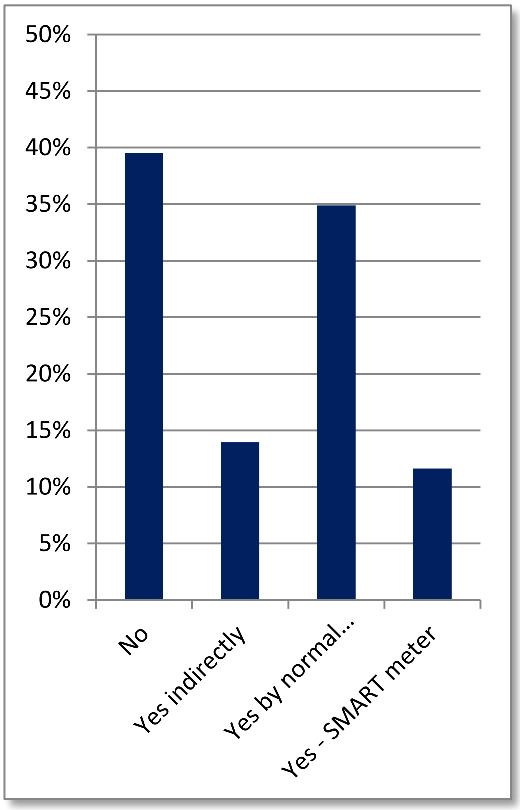


Figure 3.11.8 - Electricity metering

Respondents indicated that, in over 80 % of stores, improvements had been carried out in the last three years (Figure 3.11.7). Over a third of stores had benefitted from investment in new ventilation and control, but there was also plenty of emphasis on eliminating the effects of the external environment on the store with over a quarter of stores being improved in relation to sealing and a fifth receiving more insulation. It was notable that, of those stores which had received no improvements in recent years, 59 % were supplying into the processed chipping sector.

Energy (electricity) use was being measured in almost half of the stores surveyed (Figure 3.11.8) which was encouraging to note. A further 14 % were attempting to measure energy consumption by indirect means. although this can often be quite flawed if other large equipment, such as a grain drier or grading system, shares the meter. Over 50 % of respondents could get direct and immediate benefit by installing dedicated metering on to their stores (future-proof SMART metering is preferable), as evidence across the energy industry indicates that use is almost always reduced once it starts to be specifically measured.

Humidification

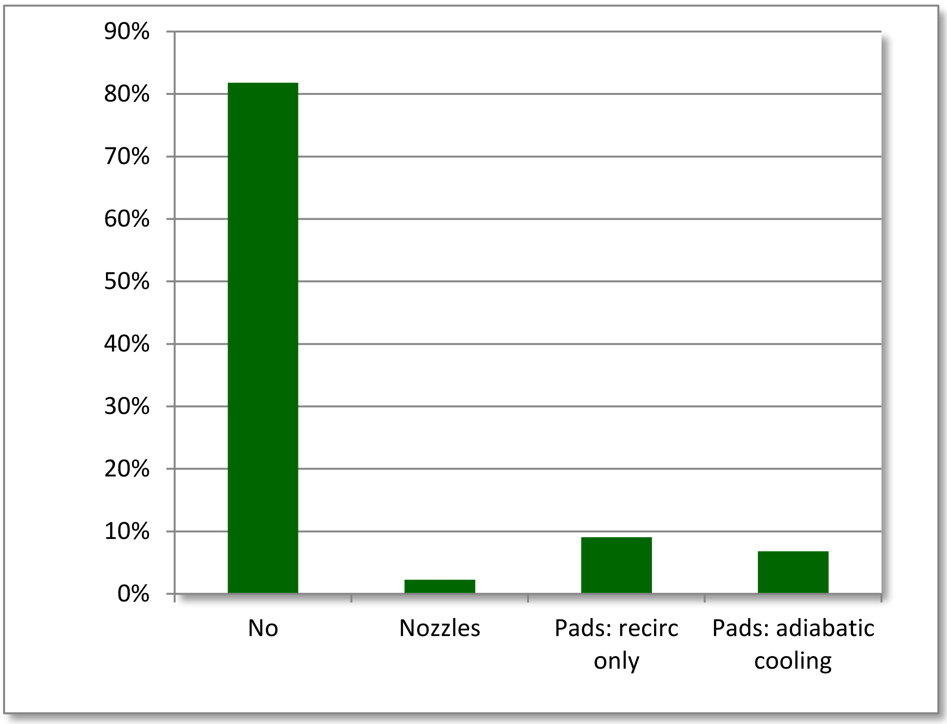


Figure 3.11.9 - Humidification

The data on use of humidification (Figure 3.11.9) show that, whilst the vast majority of stores (over 80 %) do not have it fitted, almost one store in five now has a system to add water to the ventilating air. Nozzle systems are often difficult to control so are understandably in the minority, but pad systems now feature in over 15 % of stores, either to supplement moisture levels through recirculation of air or – probably in the newest stores – to be used additionally for adiabatic cooling. This allows ambient air to be brought into the store and passed through the humidifier and the evaporation of moisture results in the air temperature falling to a level where it is suitable for cooling. Such a feature allows warmer air than would normally be used for ventilation from outside to be used, thus extending the ambient cooling time and reducing dependence on mechanical cooling.

2.11.3. Discussion

Overall, the store management survey indicates a positive trend both in store control and improvement which is helping to address some of the long-standing concerns about a decline in the quality of storage in Great Britain. However, the survey also indicates that a proportion of the industry is still struggling to justify further investment and improvement and this will need to be addressed if the industry is to be truly sustainable for future production and storage.

2.12. Carbon footprint

2.12.1. Introduction and standards

Carbon footprinting, as a way to identify the environmental impact of the storage process, has become more common in the industry. The carbon footprint of the total potato growing process, from planting all the way through to delivery of the final product, has been studied by several organisations and industry experts in recent years. Interestingly, carbon footprint figures have not always been consistent across the studies and we have spent some time exploring this and why it should be.

One obvious issue is what is included in a footprint. Some footprints cover the relevant processes alone – that is the carbon emissions associated with direct fuel use and other easily identifiable direct emissions in the process. Others go much further and include 'life-cycle' elements – that is emissions 'embedded' into fixed elements of the production system. This might include, for instance, energy expended in the production of building components or machinery components, like tyres. Other inputs, like the energy used in the production of fertilizer, may or may not be considered.

Other important differences pertain to the treatment of non-carbon greenhouse gases like methane and nitrous oxides. The gases are much more potent than carbon dioxide and have higher carbon dioxide equivalent levels (Methane 23, Nitrous Oxide 296). They are also much less easy to evaluate especially when they arise from field operations and where physical measurement is not practical.

Consequently, the biggest issue in carbon footprinting is determining the rules, by which the footprint is put together, and the setting of 'boundary' conditions setting out precisely what is and what is not being considered within the scope of an assessment.

2.12.2. Standards

The standard commonly used in the UK for carbon footprinting of products is defined in PAS 2050[16] - a joint BSI British Standards, Carbon Trust and Defra document that outlines what elements of emissions should or should not be included as part of an assessment.

There are three categories of emissions called Scope1, Scope 2 and Scope 3. Below is an extract from a Carbon Trust publication which outlines the definition of these and how they should be treated within a carbon footprint.

The Greenhouse Gas Protocol standard is commonly used to categorise an organisation's emissions into three groups or 'scopes':*

- *Scope 1 - Direct emissions*
  Direct emissions resulting from activities within the organisation's control.

[16] PAS 2050: Specification for the assessment of the lifecycle greenhouse gas emissions of goods and services 2011.

Includes onsite fuel combustion, manufacturing and process emissions, refrigerant losses and company vehicles.

- *Scope 2 - Indirect emissions: electricity and heat*
  Indirect emissions from electricity, heat or steam purchased and used by the organisation.
- *Scope 3 - Indirect emissions: other*
  Any other indirect emissions from sources not directly controlled by the organisation. Examples include: employee business travel, outsourced transportation, waste disposal, water usage and employee commuting.

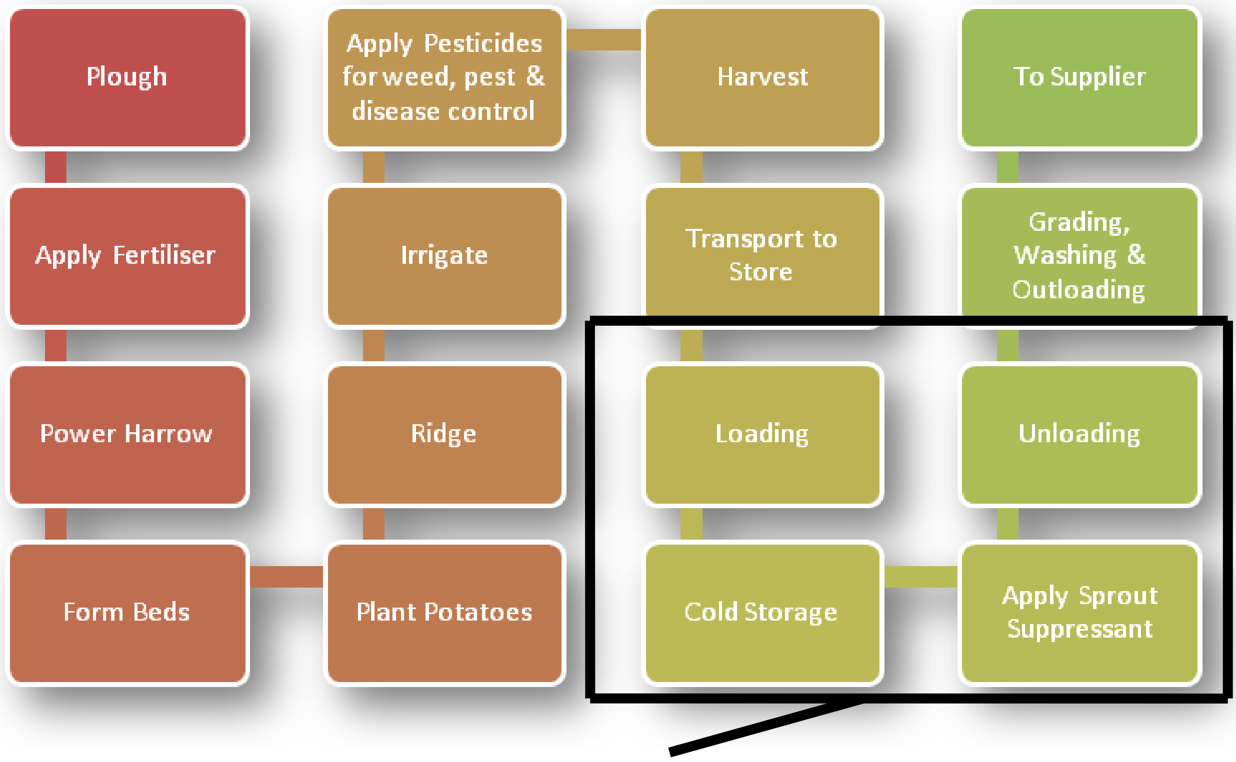
Any other indirect emissions from sources not directly controlled by the organisation. Examples include: employee business travel, outsourced transportation, waste disposal, water usage and employee commuting.

Under the Greenhouse Gas Protocol, an organisation must include scope 1 and 2 emissions within its carbon footprint. There is broad discretion about which scope 3 emissions should be included in a business carbon footprint – for example; organisations often include waste disposed to landfill and employee business travel from scope 3.

Extract from: http://www.carbontrust.co.uk/cut-carbon-reduce-costs/calculate/carbon-footprinting/pages/organisation-carbon-footprint.aspx

2.12.3. Defining boundaries

This project is primarily concerned with the storage of potatoes and hence any carbon footprints calculated are bounded by where storage starts and ends. Figure 3.12.1 shows the normal series of events in the potato growing process and where storage fits in this cycle.



Storage phase

Figure 3.12.1 - Processes involved in growing potatoes including focus on storage

Aspects of the storage process are illustrated in Figure 3.12.2 in more detail below.

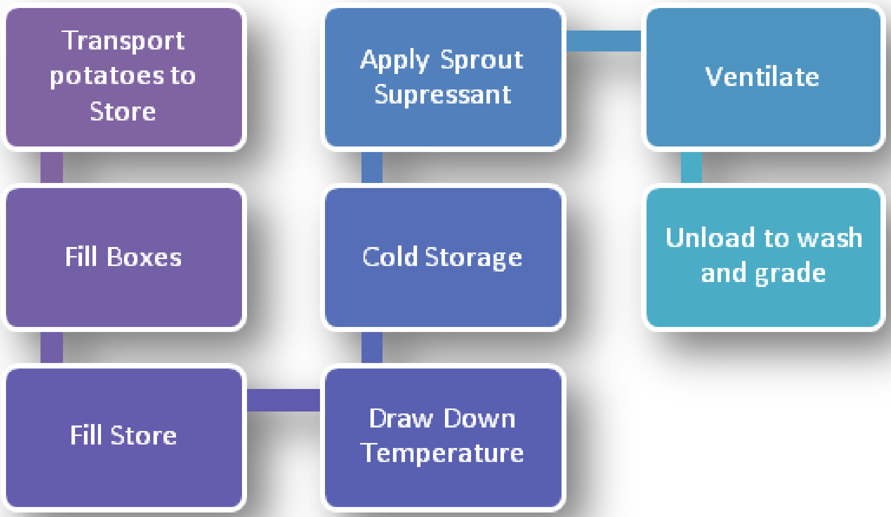


Figure 3.12.2 - More detailed view of the storage process

2.12.4. Aspects of storage that contribute to the footprint

The following table contains emission factors which may be useful when calculating your own carbon footprint.

Description	CO_2 emission value	Units
Electricity from the grid	0.545	$kgCO_2e/kWh$
Mains water	0.695	$kgCO_2e/litre$
CIPC sprout suppressant (production)	12.83	$kgCO_2e/kg$
CIPC sprout suppressant (application)	2.01	$kgCO_2e/kg$ applied
Ethylene suppressant (production)	1.875	$kgCO_2e/kg$
LPG forklift truck	6.549	$kgCO_2e/hr$
Diesel forklift truck	10.0624	$kgCO_2e/hr$
Refrigerant leaks	3300	$kgCO_2e/kg$
Wooden storage boxes	4.8	$kgCO_2e/box$
Use of HGV transport	1.5184	$kgCO_2e/mile$

Table 3.12.1 - Emission factors for storage carbon footprint

PAS 2050 states that a functional unit has to be defined to allow the mass of CO_2e[17] to be calculated per unit of produce. A functional unit of 1 tonne of potatoes will be used to ensure a good comparison of results.

2.12.5. Results

2.12.5.1. Publically-available carbon footprints

Four publically-available studies/methodologies have been considered to provide a carbon footprint of potato storage. These are:

1. CALM (Carbon Accounting for Land Managers) online calculation tool.
2. Cool Farm Tool - a potato-specific Microsoft Excel spreadsheet model developed by PepsiCo in conjunction with Unilever and the University of Aberdeen.
3. The carbon footprint produced by ADAS UK for Defra whilst preparing PAS 2050.
4. The carbon footprint calculated by Branston UK as part of a presentation to UK potato growers in 2010.

If these tools are used arbitrarily to determine the 'carbon footprint' of the storage of 1 tonne of potatoes, the results appear to vary considerably as shown in the table below:

[17] The unit of carbon footprints.

Branston	ADAS study	CALM online calculator	Cool Farm Tool (PepsiCo)	Units
32.68	39.10	34.63	49.83	kgCO_2e/tonne

Table 3.12.2 - Carbon footprint results

Both the Branston and the ADAS study provide a net figure for the carbon footprint of potato storage as part of a life cycle analysis of potato production. The specific assumptions detailing what was included as part of the storage carbon footprint were not available from ADAS. The value provided by Branston only includes the electricity used in storage and not emissions from loading/unloading or CIPC application.

Clearly, the underlying assumptions/boundaries must be different for each study to deliver different answers.

Both the CALM and Cool Farm Tool are interactive calculators which use parameters provided by the user to derive a carbon footprint. For the purposes of this project, the following assumptions and values were used:

- 1,200 tonne store size.
- 60,000 kWh electricity used.
- 470.8 litres LPG for forklift based on:
  - 4.4 litres/hr consumption.
  - 8 hrs a day loading.
  - 16 days.
- 32 grams CIPC/tonne applied.

The Cool Farm Tool has a specific potato module, which includes field and store energy use. The storage section considers electricity use, (fans, refrigeration, etc.) fuel use for loading and unloading and calculates diesel use for CIPC application based on number of fogging events and the tonnage of crop.

The CALM tool only allows the input of electricity, diesel and liquefied petroleum gas (LPG) quantities and asks the user to provide these. The values provided by the Cool Farm Tool and the CALM tool are close to those calculated by ADAS, indicating that the assumptions and basis of their calculations more than likely follow the guidelines of PAS 2050.

2.12.5.2. Independent carbon footprint calculation

The model store was used as the basis for calculating the carbon footprint of three different storage types:

1. Pre-pack storage at 3°C for 7 months, 1,000 tonnes.
2. Processing storage at 7.5°C for 10 months, 1,000 tonnes.
3. Processing storage at 10°C for 7 months 1,000 tonnes.

The tables below show the results achieved.

	Value attributed $kgCO_2e$/unit	Units	Total use	CO_2 footprint (tonnes)	CO_2 footprint ($kgCO_2$/tonne)
Electricity use	0.5450	kWh	45,570	24.84	24.836
CIPC use	2.0100	kg	32.00	0.064	0.064
Loading/unloading	6.5490	hours	107	0.7	0.701
Refrigerant leakage	3300.0	kg	6	19.8	19.800
TOTAL (based on weight in)					**45.401**

Table 3.12.3 - 1,000 tonne pre-pack store kept at 3°C for 7 months

	Value attributed $kgCO_2e$/unit	Units	Total use	CO_2 footprint (tonnes)	CO_2 footprint ($kgCO_2$/tonne)
Electricity use	0.5450	kWh	34,100	18.58	18.585
CIPC use	2.0100	kg	63.75	0.128	0.128
Loading/unloading	6.5490	hours	107	0.7	0.701
Refrigerant leakage	3300.0	kg	6	19.8	19.800
TOTAL (based on weight in)					**39.214**

Table 3.12.4 - 1,000 tonne processing store kept at 7.5°C for 10 months

	Value attributed $kgCO_2e$/unit	Units	Total use	CO_2 footprint (tonnes)	CO_2 footprint ($kgCO_2$/tonne)
Electricity use	0.5450	kWh	18,600	10.14	10.137
CIPC use	2.0100	kg	63.75	0.128	0.128
Loading/unloading	6.5490	hours	107	0.7	0.700
Refrigerant leakage	3300.0	kg	6	19.8	19.800
TOTAL (based on weight in)					**30.765**

Table 3.12.5 - 1,000 tonne processing store kept at 10°C for 6 months

The above figures consider all aspects of storage within the defined boundary of the potato storage process under the umbrella of PAS 2050.

2.12.5.3. Exclusions from PAS 2050

Materials that are used for the potato storage process are not included in the carbon footprint. For example, the carbon contribution of the production of CIPC is not included, nor is the production of the potato boxes, or transport of these or any other materials to site. Another exclusion from PAS 2050 is ‘biogenic’ carbon emissions, like the carbon emitted through respiration of the potatoes.

2.12.5.4. Ethylene

A store that uses ethylene will have a carbon footprint of approximately 28 % more than that of one which uses CIPC. The use of ethylene will increase the energy used for cooling in the store. This is because of respiration which causes more heat to be emitted from the potatoes, requiring more cooling load to keep temperatures stable. CIPC typically has negligible effect on respiration in potato stores.

2.12.5.5. Water

Water consumption in potato stores is usually linked to the use of humidification or adiabatic cooling and can be calculated using the emission factor given in Table 3.12.1.

2.12.6. Renewable energy

If renewable energy, i.e. power from wind turbines, solar photovoltaic (PV), heat from biomass etc., contributes towards supplying electricity to the store, it will reduce the carbon 'rating' of the electricity supplied to the store. However, any electricity exported cannot be used as 'negative' carbon and used to offset the carbon emissions associated with storage.

3. DISCUSSION AND CONCLUSIONS

This report brings together two years of monitoring and assessment on energy in potato storage. It covers everything from energy monitoring to assessment of specific energy efficiency practices. There are lots of useful conclusions from this work but the most important ones are that:

1. There's tremendous variation between energy use between the best and worst stores – this might be as high as 78 % for processing and 17 % for pre-pack storage. This highlights that in most cases, growers just don't know exactly how well or badly they are doing.
2. The reasons for high use are many and various but above all, in nearly all cases, there are cost effective solutions to enable significant energy and cost savings to be made.

In most cases energy use accounts for between 2 and 5 % of the value of the crop, so it is by no means the largest cost component. Nevertheless, the difference between the best and worst performance is significant and could make £1,760 difference in profit for a 1,000 tonne pre-pack potato store.

Energy monitoring is the central key to growers moving forward on energy efficiency because, simply speaking, if it isn't measured then it's impossible to predict and track the effect of energy efficiency actions. The project worked with four companies to monitor energy use in nine stores. The biggest challenges were:

- Installing relevant metering – that is metering covering just the store, and with the necessary recording capabilities and resolution to give the necessary information. It's important to know the shape of energy use throughout the day and week as well as net figures over a longer period of time.
- Analysis and reporting – being able to assess energy use in a simple way, with the minimal amount of time and effort is important because store managers have lots of other things to do.
- Automatic reading and analysis is very desirable. It's both achievable and affordable for stores with modern monitoring equipment and should be considered during planning and set-up.

On specific energy efficiency drivers, the main points have been identified as:

1. **Uncontrolled building air leakage** leads to higher heating and cooling energy use. Leaks come from doors, louvres and store construction joints. A selection of stores were leak-tested and the results showed that air leakage can be responsible for up to 37 % of the store's total energy consumption (pre-pack) and 55 % (processing). If store improvements are made, these figures can be reduced to 4 % and 2 % respectively. For doors and obvious structural 'holes' remedial work is relatively inexpensive and simple to do. However, tiny joint gaps in larger structures are harder to deal with on an existing store. For a new store this is a different issue and should lead specifiers to be more exacting about construction and design in this respect. So for instance, making erectors seal joints at every point, or put in membrane air seals, could make a massive difference to air leakage.

2. **Refrigeration System Efficiency.** The range of efficiencies as expressed in terms of COP (coefficient of performance – ratio of cooling capability to energy input) in the trials was 1.6 - 4, i.e*. a variation of 2.5 times from best to worst*. This points to the key fact that farmers should not regard refrigeration systems as a fixed efficiency device. Two major things to consider are the maintenance and optimisation of existing systems - either by the use of a refrigeration maintenance engineer, and the upgrading of refrigeration components to more efficient designs. The latter might include compressors, variable speed drives, fan types, defrost controls, and expansion valves. Either way, big savings can be made by looking at the refrigeration components and how they are integrated and used.
3. **Insulation** is a major component which is clearly important for energy efficiency. Better insulation reduces the need for heating or cooling of a building by reducing heat transmission through the structure. Savings with modest improvements in insulation in box stores (adding 50 mm of spray foam to a store with 50 mm spray foam initially) can result in savings of 11.8 %. Increasing composite panel thickness to 120 mm from 80 mm saw a 6 % saving, while going from 100 mm to 150 mm Styrofoam board resulted in a 7.6 % saving. The same improvements in a bulk store resulted in 1.4 %, 1.9 % and 2.1 % savings respectively. The big issue here is that the effect of insulation on store energy use, obeys the rule of diminishing returns. That is to say, each incremental thickness of insulation has a diminishing effect on running cost. So, increasing insulation on an uninsulated or very badly insulated structure will have a big effect on efficiency. But increasing the insulation on what is already a reasonably well insulated store will produce a lower return. One other thing of note is that the marginal costs of applying an extra thickness of insulation at the same time as the application of the initial thickness is comparatively low – it's only associated with the material itself as the installation labour is being paid for anyway.
4. **Air movement**; the business of moving air into and around the store is a big energy user. Electricity used by fans adds to the energy required to cool the store because ultimately this manifests itself as heat. We found that for some box stores, while the volume of air delivered was meeting guidelines, air speeds and consequently distribution was not satisfactory. In some cases too low velocities lead to inadequate air mixing. In other stores volume delivered was far more than was necessary. On the whole, fan installations were sized appropriately for early crop conditions, but appeared to be over-ventilated for the remainder of the storage time. Variable speed fans are the emerging solution to this and are just starting to become used. Two things which need to go hand in hand with the implementation of the technology are to define airflow requirements in a more dynamic way, and to introduce control technology.
5. **Temperature uniformity** within box storage is important to maintain good storage conditions and to ensure crops can be stored as long as possible. The use of a curtain to force air in the direction required is shown to improve storage conditions but there can be some strange directional influences on air movement. It is therefore important to set up the store correctly and to check airflows and temperatures.
6. **Humidification** was not a big issue as far as energy efficiency was concerned. It was shown to be effective but, like all other heat transfer

processes, was inherently prone to some inefficiency. The extent of any adiabatic cooling was evident and worthwhile in offering extended hours of ambient ventilation, but did not necessarily deliver the full theoretical cooling that it could have. Adiabatic cooling as a potential means of achieving closer control of temperature (especially after loading) and reducing dependence on refrigeration was demonstrated.

7. The survey of **store management** and improvement showed adoption of improved monitoring and ventilation technology especially within existing stores. However much still needs to be done to make managers aware of things which can improve efficiency, as this is not high on the list of priority areas. So ventilation changes for example, have perhaps been in response to CIPC sprout suppressant use but not to improve energy efficiency. It was also evident that some parts of the industry, notably the processed chipping sector, have failed to make improvements to stores as much as others.

The following table summarises these major factors in improving efficiency and the way forward to their implementation.

Issue	Impact	Solution complexity	Cost
Monitoring	Key to all aspects of energy saving (10 to 15 % of energy use).	Anything from a manually read meter to a networked energy data logging, communication and analysis system.	Low to medium
Air leakage	Not easy to quantify, hence often neglected as an area. Our research shows that this can be up to 55 % of heat gain.	Some aspects like door sealing are simple. Sealing the tiny structural cracks in a building is more challenging but should be inherent in new build.	Low to medium
Refrigeration efficiency	Can be enormously significant for some farms and an 'invisible' inefficiency (20 to 60 %).	Varies between simple maintenance and cleaning to better components and control.	Low to medium
Insulation	Only massive in extreme cases, but a relentless influence on energy use season after season (5 to 30%).	Straightforward and obvious, from repairs to complete refurbishment.	Low to high depending on extent of work
Air movement	Most significant for ambient stores. More research needed to determine solutions in connection with variable speed systems (5 to 20%).	May need anything from some trial and error adjustments to re-engineering. Variable speed fan technology is a major theme.	Low to medium
Humidification	Fairly small but will have impact on crop quality (< 5%).	Medium. Fairly easy to retrofit.	Medium
Temperature uniformity	Fairly small but will have impact on crop quality (< 5%).	Straightforward and easy to retrofit.	Low to medium
Store management	Quite important for energy use but fundamental to quality issues.	Requires good training and understanding of cause, effect and solution to problems.	Low

The **store management survey** suggested that there is a significant part of the industry which, whilst it might not be investing in new, green-field site storage, is prepared to put some money into improving store ventilation systems and structures. The payback on some of these changes can be rapid; this is an area which requires on-going knowledge transfer to ensure such investment is continued.

On **carbon footprinting**, we showed that there was some inconsistency between one method and the next and that farmers should not regard answers from a particular source to be an ‘absolute’. We have shown that using off-the-shelf systems for calculating carbon footprints can give very different results (without really informing the user what exactly is being calculated and where the boundaries of emission lie). Much more needs to be done to direct organisations to a common methodology for all calculations in this area. The guidelines of PAS 2050 are a good starting point, but much needs to be done to tighten the detailed specification and boundaries for a study.

Using PAS 2050 and industry standard values for emission values, we have calculated the following carbon footprints for ‘typical’ storage systems:

1. Pre-pack, 3°C, 7 months – 45.4 kgCO_2e/tonne.
2. Processing, 7.5°C, 10 months – 39.2 kgCO_2e/tonne.
3. Processing, 10°C, 6 months – 30.77 kgCO_2e/tonne.

Enough information has been given within this report to enable a store manager to calculate their own carbon footprint. In the context of the UK carbon emission reduction targets, doing so will become increasingly important to demonstrate compliance.

The need to reduce energy consumption is important, not just to reduce carbon emissions but also to counteract the effect of rising energy prices. Since the beginning of project R401, the electricity cost of a typical 50,000 kWh consumption store has risen by £1,050 per year. All measures that can be implemented to reduce the energy dependence of potato storage are therefore very important. Overall, this project has served to further highlight and quantify the extent to which there is potential for energy saving in store. Extending the trend seen in work carried out in project R401, wide ranges in energy use continued to be measured in commercial units, although this perhaps had a greater bias to the more efficient set-ups than previously observed. But there remain a lot of stores where there is massive scope for improvement and these businesses will be incurring unnecessary costs for storage as a result.

Improving knowledge transfer on these technical areas of storage is undoubtedly a requirement as understanding amongst store managers and owners remains poor and is limiting their scope to tap into the potential benefits this project has highlighted.

4. REFERENCES

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Swain, J. (2010) R401 Reducing the Energy Cost of Potato Storage. Final Report, 30 September 2010. Undertaken by FEC Services Ltd and SBCSR for and on behalf of Potato Council.

OTHER REFERENCES:

NPower RWE, Energy Market Pulse, weekly energy price report.

Air leakage testing guidance http://www.attma.org/

Carbon footprint guidelines:
PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.

CALM carbon footprint calculator www.cla.org.uk

Cool Farm Tool - provided courtesy of PepsiCo. www.coolfarmtool.org

F gas information
http://www.defra.gov.uk/environment/quality/air/fgas/

Government carbon emission targets
http://www.decc.gov.uk/en/content/cms/funding/funding_ops/cert/cert.aspx

Potato Industry CIPC Stewardship Group www.potato.org.uk/cipc

5. APPENDIX 1 DATA COLLECTION

This appendix reproduces the data collection section from R401 – 'Reducing the energy cost of GB potato storage', interim report 2008.

5.1.1. Data capture

The focus of the project is to provide good quality information about the energy consumption used for the storage of potatoes. At the fundamental level the information required to do this is expressed in terms of kWh of electricity consumed by the store against the quantity of potatoes kept. In addition, the ambient temperature and storage temperature are required in order for reasons for energy consumption fluctuations to be understood.

5.1.2. Store electricity monitoring

All stores were required to be independently sub-metered to separate them from other processes on the storage site.

One store (Store 2) already had an electricity meter fitted. The other seven stores required the fitting of an electricity meter. The meters supplied and installed were Iskramenco MT1070 types (Figure 6.1.1), being OFGEM-approved billing meters.

Figure 6.1.1 - Electricity meter as installed

on the sites

Figure 6.1.2 - Current transformers (CTs)

Current Transformers (CTs) were fitted over the load-carrying conductors feeding electricity to the store and connected to the meters to facilitate the monitoring of power delivery.

(Figure 6.1.2) The CTs produce an output current that is proportional to the current being drawn by the store. This signal is converted to energy consumption by the electricity meter.

The electricity meters have a pulse output which sends a signal each time 1 kWh of electricity is consumed. This pulse output is connected to a wireless radio frequency signal transmitter which counts the pulses and sends this information to a data logger every half hour (see Data Logging section).

5.1.3. Store temperature monitoring

Independent temperature sensors were fitted to all stores, except Store 2, as it was not practical for the existing store temperature control probes to be connected to an external logger. One temperature probe was fitted in each store and was placed such that it measured the temperature of the crop at the top of the store.

The temperature sensors were connected to the central logger via radio frequency wireless transmitters (Figure 6.1.3). The temperatures were logged at half-hourly intervals.

At each site an identical temperature sensor and transmitter was installed to capture the outside temperature (Figure 6.1.4).

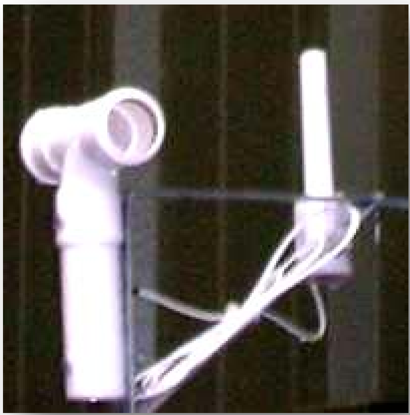


Figure 6.1.3 - Store temperature transmitter

Figure 6.1.4 - Ambient temperature transmitter

5.1.4. Data logging

The data loggers installed were Radio Tech RTcom 434 Data Concentrators (Figure 6.1.5). One logger was installed at each site. These collected and stored the half-hourly transmitted information from each sensor/meter installed on the site. The data loggers have a storage capacity of between 5 to 14 days depending on the complexity of the inputs. Stored data was uploaded to FEC Services on a regular basis through a GSM data link.

Figure 6.1.5 - Radio Tech RTcom 434

The logging system was chosen primarily for its wireless capability alleviating the need for connecting cabling and ensuring that installation was quick and simple. The ability to capture data from many probes/meters simultaneously was also seen to be an important feature. The GSM link enabled data to be collected remotely without having to rely on postal returns or regular site visits.

As a whole, the data collection systems operated effectively – in two cases, additional aerials were required to ensure a GSM link could be established reliably. On large sites, the wireless signals between the sensors and logger were boosted by a signal repeater.

5.1.4.1. Store 2

Store 2 was treated slightly differently from the other stores. The site uses a Cornerstone Crop Controller which, as well as providing control, monitors and stores information from all the sensors within the store. The store had its own meter fitted which was linked to the Cornerstone. The system was interrogated over the Internet and data was downloaded weekly using this method.

5.1.5. Manual data collection

In addition to automatic data logging systems, monthly electricity meter readings and details of the quantities of potatoes in store were provided by the site managers for cross reference and backup. All the data collected was analysed and manipulated using standard office-based software. This allowed evaluations to be carried out and communicated simply and effectively.

6. Appendix 2 - Methods of expressing store energy performance

This appendix reproduces the methods of expressing store energy performance section from R401 - Reducing the energy cost of GB potato storage, interim report 2008. On the face of it, expressing the efficiency of store energy can be done reasonably simply, and in terms of kWh of electrical energy used.[18]

However, if figures are to be used for meaningful comparison purposes then evaluation of energy use needs to be more sophisticated. How, for instance, might a grower compare his store with another of a different size, operating a different storage temperature, or over a different season period? In this case, measurements need to take into account:

- Storage tonnage.
- Length of storage period.
- Storage temperature.
- Ambient temperature.

Inevitably, the more reliable and meaningful the measure of energy efficiency, the more difficult it is to derive and the more additional information is needed to calculate a result. So there is a trade-off between simplicity and relevance.

The following paragraphs describe and discuss a number of evaluation methods.

Entire Season Specific Energy Consumption (kWh/tonne)
This measure provides the simplest approach to analysing the energy efficiency of a potato store and is used commonly as a simple way of expressing performance. To calculate the value, take the amount of electricity consumed during the storage season (in kWh) and divide it by the quantity of potatoes stored during the season (in tonnes). For example, if the store uses 20,000 kWh during the season and 1,000 tonnes were stored, then the *Entire Season Specific Energy Consumption* would be 20 kWh/tonne.

The advantage of using this measure is that it is easily calculated and understood and gives an instant 'headline' figure. It does however have a number of serious disadvantages in truly reflecting performance. These are:

- It takes no account of storage period.
- It takes no account of the effect of part unloading of a store at some point during the season.
- It takes no account of temperature or weather differences.

[18] kilowatt hour (kWh)
This is a unit of energy measurement and refers here to electricity. A kWh is sometimes referred to as a 'unit' of electricity. It is defined as the amount of energy used by a load of 1 kW in 1 hour. So, a machine of power 2 kW (or 2000 Watts) operating for three hours would consume 6 kWh (or 6 units) of electricity. The kWh is the common unit used by electricity utilities when billing electricity.

Average Daily Energy Consumption (kWh/tonne/day)
This measure takes the *Entire Season Specific Energy Consumption* and divides it by the storage period in days, to give a daily average value. This makes comparisons between stores with different lengths easier. The disadvantage of this measure is that as a small value it may sometimes not be easily comparable. It may be useful to express this as kWh/100 tonnes/day.

Full Store Specific Energy Consumption (kWh/tonne/day)
This measure is calculated in the same way as the *Average Daily Energy Consumption* but it only covers the period when the store is **fully loaded**. So, for a 1,000 tonne store which has used 10,000 kWh from the end of filling to the beginning of out-loading over 100 days and then a further 2,000 kWh over the part loaded period, the *Full Store Specific Energy Consumption* would only take into account the energy use in the ‘full’ period. Therefore, the *Full Store Specific Energy Consumption* in this case would be 0.1 kWh/tonne/day.

This measure provides a useful way of comparing the performance of stores when the stores are full. The obvious disadvantage of this measure is that it takes no account of the marginal performance of part loaded stores in either the loading period or the unloading period of storage and so cannot be used to reflect full season performance.

Cumulative Specific Energy Consumption
In order to calculate this number, each daily energy use is divided by the quantity of potatoes in the store during that day. These values are summated over the period of storage to give *Cumulative Specific Energy Consumption*.

As an example, if the first day’s energy consumption was 4 kWh/tonne, the second day 3 kWh/tonne, the third day 2 kWh/tonne, the *Cumulative Specific Energy Consumption* for the period would be 4 + 3 + 2 = 9 kWh/tonne.

The advantage of this measure is that, over a season, it gives a ‘weighted average’ reflecting the disproportional effect of high energy use per tonne at the beginning and end of the storage period. Used to analyse the latter period of storage it can provide marginal costing information which can help in deciding the viability of storing a small quantity of potatoes for an extended period.

The disadvantage of using this measure is that any store part loaded for a long period is not readily comparable with a store that is kept full and then emptied rapidly. In this case it may be better to compare store performance using the *Full Store Specific Energy Consumption* metric.

7. APPENDIX 3 - AIR PERMEABILITY OF BUILDINGS

This appendix contains the introduction to: *TECHNICAL STANDARD L1. MEASURING AIR PERMEABILITY OF BUILDING ENVELOPES (DWELLINGS) October 2010 Issue.*

The full version is downloadable from the ATTMA website at www.ATTMA.org.

Section 1 – Introduction

1.1 Basis for measurement

The requirements of ATTMA for the measurement of the air permeability of buildings are generally based on BS EN 13829:2001 - 'Thermal Performance of Buildings - Determination of air permeability of buildings - Fan pressurisation method' with enhancements recommended by ATTMA.

This document provides the technical standard to be followed for the testing of Dwellings as set out in Regulation 20B and Approved Document L1A 2010 of the Building Regulations for England and Wales, Technical Booklet Part F1 in Northern Ireland, and Section 6 of the Domestic Handbook (Scotland).

For a testing organisation to show full compliance with this standard, they should have suitable third party monitoring systems in place. This is demonstrated by either holding building air leakage testing UKAS accreditation for organisations in line with BS ISO:17025:2005 or having an active registration with the BINDT L1 testing scheme.

Guidance for test procedures for the testing of Non-Dwellings (as set out in Regulation 20B and Approved Document L2A 2010 of the Building Regulations for England and Wales, F2 in Northern Ireland, and Section 6 (Commercial) in Scotland) is provided within companion reference document ATTMA Technical Standard L2 (downloadable from www.attma.org).

1.2 Background

1.2.1 What is air leakage?

Air leakage is the uncontrolled flow of air through gaps and cracks in the fabric of a building (sometimes referred to as infiltration or draughts). This is not to be confused with ventilation, which is the controlled flow of air into and out of the building through purpose built ventilators that is required for the comfort and safety of the occupants. Too much air leakage leads to unnecessary heat loss and discomfort to the occupants from cold draughts. The increasing need for higher energy efficiency in buildings and the need in future to demonstrate compliance with more stringent Building Regulations targets means that airtightness has become a major performance issue. The aim should be to *'Build tight – ventilate right'*. Taking this approach means that buildings cannot be too airtight, however it is essential to ensure appropriate ventilation rates are achieved through purpose built ventilation openings.

1.2.2 What is the impact of air leakage?

Fabric heat losses have been driven down over many years by the various versions of the Building Regulations and there is limited return in reducing them down significantly further. The improvements made in the thermal performance of building materials have raised the importance of designing and constructing less leaky building envelopes.

Airtightness of buildings was addressed for the first time in the UK in the 2002 edition of Part L of the Building Regulations (England and Wales), and in subsequent years has also been incorporated in various degrees in to Part F (Northern Ireland), and Section 6 (Scotland). The airtightness of the UK building stock has traditionally been proven to be poor, which leads not only to unnecessary ventilation heat loss but also to widespread occupant dissatisfaction.

1.2.3 Why should we test?

Gaps and cracks in the building fabric are often difficult to detect simply by visual inspection. Air leakage paths through the building fabric can be tortuous; gaps are often obscured by internal building finishes or external cladding. The only satisfactory way to show that the building fabric is reasonably airtight is to measure the leakiness of the building fabric as a whole. Air leakage is quantified as *Air Permeability*. This is the leakage of air ($m^3.h^{-1}$) in or out of the building, per square metre of building envelope at a reference pressure difference of 50 Pascals (i.e. $m^3.h^{-1}.m^{-2}$ @ 50 Pa) between the inside and outside of the building.

1.3 Measuring air leakage

Assessment of building envelope air leakage involves establishing a pressure differential across the envelope and measuring the air flow required to achieve that differential. This is normally achieved by utilising variable flow portable fans which are temporarily installed in a doorway, or other suitable external opening.

HVAC plant is switched off and temporarily sealed prior to the test. Passive ventilation should also be temporarily sealed. All doors and windows on the exterior of the air test envelope are closed. The test fans are switched on and the flow through them increased until a building pressure of 50 – 100 Pa is achieved. The total air flow through the fan and the building pressure differential created between the inside and outside is recorded. The fan speed is then slowly adjusted to produce sequential steps of not more than 10 Pa building pressure differential, with the fan flow and pressure differential data recorded at each step.

The recorded fan flow (Q) and building pressure differential (Δp) data allow a relationship to be established. This can be defined in terms of the power law equation:

$$Q = C\,(\Delta p)^{n} \qquad 1$$

Where C and n are constants that relate to the specific building under test.

The total air flow required to achieve the reference pressure differential of 50 Pa can then be calculated from the equation (see Appendix A). This airflow is then divided by the total building envelope area (A_E) to provide the leakage rate in $m^3.h^{-1}.m^{-2}$ @ 50Pa.

1.4 Fan Pressurisation Systems

Single fan in single door used for dwellings (door fans typically move 2 $m^3.s^{-1}$, which allows properties with envelope areas of up to $720m^2$ to be tested at a specification of 10 $m^3.h^{-1}.m^{-2}$ @ 50 Pa).

8. APPENDIX 4 - SAMPLE AIR LEAKAGE TEST REPORT

TECHNOLOGY

Contents

Details of Tested Building

Building Tested:	*Store B, Co-Op F Coldham Wisbech PE14 0L*	Nett Floor Area, A_F: Volume, V:	526.0 m^2 4,923.8 m^3
Est. Year Built:	2011	Geometry Prepared By:	David Tetchner of Stroma
Test Date:	26th July 2011	Geometry Verified By:	None
Building Heating:	N/A	Test Method:	B (Building envelope)
Building Ventilation:	N/A	Test Engineer:	David Tetchner

Interpretation of Results

The airflow rate through the envelope of the building/zone was determined at a pressure differential of 50 Pa; this result is expressed as an airflow rate per m² of building envelope. For more information on the calculations used to determine the air permeability or the air leakage index please visit *www.stroma.com/downloads/air_permeability_calculation.pdf.*

Temporary Sealing for Each Test (Test 1 to Test 5)

	Test 1	*Test 2*	*Test 3*	*Test 4*	*Test 5*
Party Wall to Floor Slab Interface	Yes	**No**	No	No	No
Main Up & Over Door	Yes	Yes	**No**	No	No
Extract Louvres	Yes	Yes	Yes	**No**	No
Intake Louvres	Yes	Yes	Yes	Yes	**No**

Note: Changes in temporary sealing are highlighted in bold.

Test 1 Results: Everything Temporary Sealed

Air Change Rate, n_{50}:	**1.35 h^{-1} @ 50 Pa**
Effective Leakage Area:	0.33 m² @ 50 Pa
Correlation of results, r^2:	0.9990
Slope, n:	0.58
Air Flow Coefficient, C_{env}:	675.6 $m^3.h^{-1}.Pa^{-n}$
Intercept, C_L:	682.5 $m^3.h^{-1}.Pa^{-n}$

Test 2 Results: As Test 1 with Party Wall to Floor Slab Interface *NOT* Temporary Sealed

Air Change Rate, n_{50}:	**1.41 h^{-1} @ 50 Pa**
Effective Leakage Area:	0.35 m² @ 50 Pa
Correlation of results, r^2:	0.9957
Slope, n:	0.57
Air Flow Coefficient, C_{env}:	750.5 $m^3.h^{-1}.Pa^{-n}$
Intercept, C_L:	758.3 $m^3.h^{-1}.Pa^{-n}$

Test 3 Results: As Test 2 with Main Up & Over Door *NOT* Temporary Sealed

Air Change Rate, n_{50}:	**1.48 h^{-1} @ 50 Pa**
Effective Leakage Area:	0.36 m² @ 50 Pa
Correlation of results, r^2:	0.9977
Slope, n:	0.52
Air Flow Coefficient, C_{env}:	934.6 $m^3.h^{-1}.Pa^{-n}$
Intercept, C_L:	944.4 $m^3.h^{-1}.Pa^{-n}$

Test 4 Results: As Test 3 with Extract Louvres *NOT* Temporary Sealed

Air Change Rate, n_{50}:	**1.48 h^{-1} @ 50 Pa**
Effective Leakage Area:	0.36 m² @ 50 Pa
Correlation of results, r^2:	0.9980
Slope, n:	0.61
Air Flow Coefficient, C_{env}:	666.4 $m^3.h^{-1}.Pa^{-n}$
Intercept, C_L:	671.7 $m^3.h^{-1}.Pa^{-n}$

Test 5 Results: As Test 4 with Intake Louvres *NOT* Temporary Sealed

Air Change Rate, n_{50}:	**2.17 h^{-1} @ 50 Pa**
Effective Leakage Area:	0.53 m² @ 50 Pa
Correlation of results, r^2:	0.9943
Slope, n:	0.55
Air Flow Coefficient, C_{env}:	1.230.4 $m^3.h^{-1}.Pa^{-n}$
Intercept, C_L:	1,241.4 $m^3.h^{-1}.Pa^{-n}$

Test Date: 27 July 2011
Test Time: 10:54

Engineer Controlling Test: DT

Test No: 1

Type of Test Undertaken: Pressurisation

Engineer Locations: Outside the building under test.

Pre Test Conditions

Atmospheric Conditions

Windspeed: 2.7 m/s

			Location of Reading
Internal Temperature #1:	16.1	°C	Cenre of warehouse floor
Internal Temperature #2:		°C	
Internal Temperature #3:		°C	
Internal Temperature #4:		°C	
Internal Temperature #5:		°C	

External Temperature: 16.6 °C

Barometric Pressure: 1,018 mbar

Fan Off Pressures

Manometer Number	#1	#2	#3	#4	#5
Gauge Serial Number	724206A				
Readings (Pa)	-1.9				
	-4.2				
	-3.3				
	-3.4				
	-2.9				

	Corrected Values
Average Positive Values, $\Delta p_{0,1+}$	Pa
Average Negative Values, $\Delta p_{0,1-}$	-3.2 Pa
Total Average Values, $\Delta p_{0,1}$	-3.2 Pa

Post Test Conditions

Atmospheric Conditions

Windspeed: 3.1 m/s

			Location of Reading
Internal Temperature #1:	16.3	°C	Cenre of warehouse floor
Internal Temperature #2:		°C	
Internal Temperature #3:		°C	
Internal Temperature #4:		°C	
Internal Temperature #5:		°C	

External Temperature: 16.6 °C

Barometric Pressure: 1,018 mbar

Fan Off Pressures

Manometer Number	#1	#2	#3	#4	#5
Gauge Serial Number	724206A				
Readings (Pa)	-1.2				
	-1.5				
	-3.0				
	-0.8				
	-3.3				

	Corrected Values
Average Positive Values, $\Delta p_{0,2+}$	Pa
Average Negative Values, $\Delta p_{0,2-}$	-2.0 Pa
Total Average Values, $\Delta p_{0,2}$	-2.0 Pa

Average Test Conditions

Corrected Average Internal Temperature: 16.0 °C
Corrected Average External Temperature: 16.4 °C

Corrected Average Barometric Pressure: 1,023.0 mbar

Internal Air Density, ρ_i: 1.23 $kg.m^{-3}$
External Air Density, ρ_e: 1.23 $kg.m^{-3}$

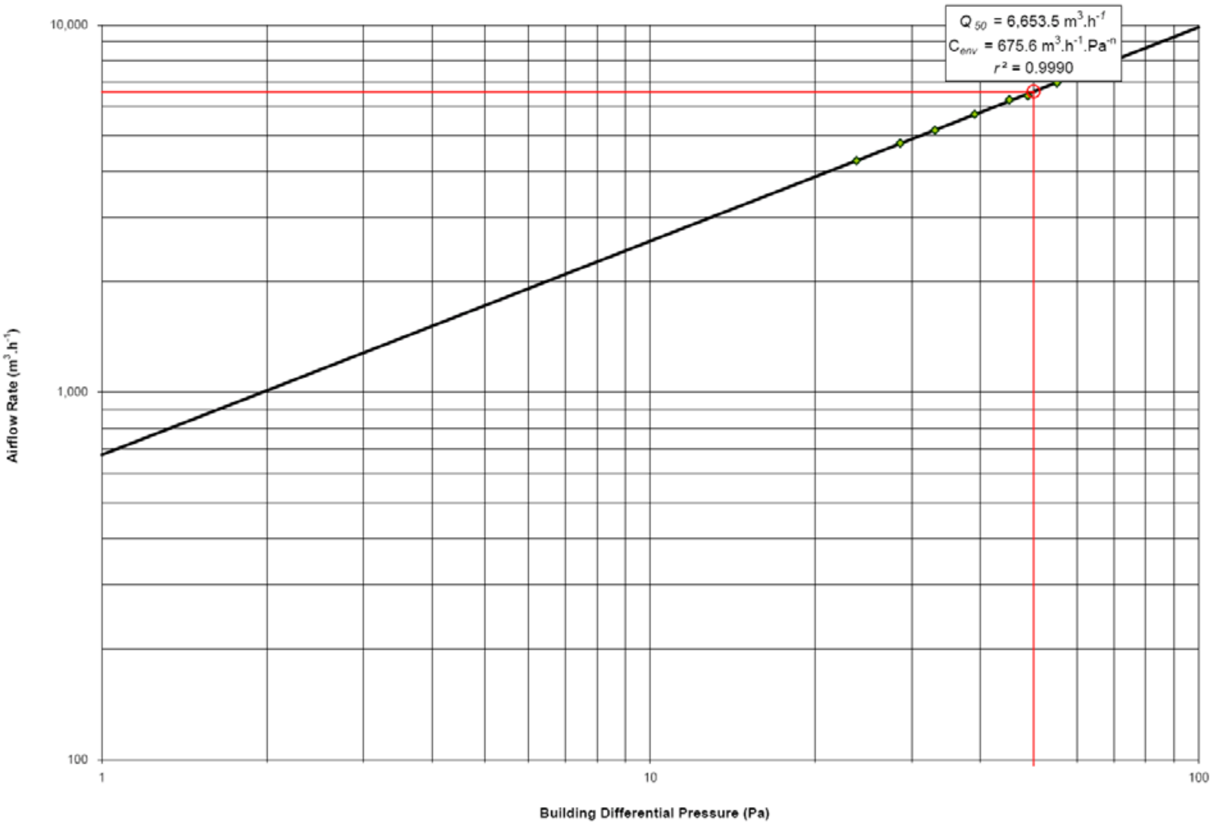
Assumed Relative Humidity: 50%

Summary of Building Test Results

Air Change Rate @ 50 Pa, n_{50} h^{-1}	Flow @ 50Pa, Q_{50} $m^3.h^{-1}$	Effective Leakage Area, A m^2	Flow Exponent, n	Flow Coeff, C_{env} $m^3.h^{-1}.Pa^{-n}$	Air Leakage Coeff, C_L $m^3.h^{-1}.Pa^{-n}$	Correlation r^2
1.35	6,653	0.33	0.58	675.6	682.5	0.9990

Calibration Information for Equipment Used

Serial Number	Equipment Type	Calib. Expiry Date
0609-83873-3	Anemometer	15 June 2012
61878295	Barometer	14 February 2012
630488	Thermometer	22 May 2012
724206A	Manometer (Build)	14 February 2012
724206B	Manometer (Fan)	14 February 2012
097124	Fan	21 October 2011



Q_{50} = 6,653.5 $m^3.h^{-1}$
C_{env} = 675.6 $m^3.h^{-1}.Pa^{-n}$
r^2 = 0.9990
10,000
1,000
100
1
10
100
Airflow Rate ($m^3.h^{-1}$)
Building Differential Pressure (Pa)

9. APPENDIX 5 REFRIGERATION CASE STUDIES

The following case studies give more detail to a selection of the results shown in Section 3.6, Table 3.6.2.

9.1.1. Store 10 - 'State of the art' refrigeration system

Store 10 is designed to cool produce to -2°C; a somewhat lower temperature than is used in an ordinary potato storage. The store was included in this project because it has many 'state of the art' features, which would tend to make the refrigeration system higher in efficiency than normal.

Figure 6.5.1 - Store 10

Figure 6.5.2 - State of the art refrigeration plant

A test was carried out on the 5th April 2011 and the efficiency (COP) was measured at 3.87. This was achieved with a target store temperature of -2°C. (At a higher store temperature of 2 – 3°C, the COP might be expected to be nearer to 4.5). This is a good efficiency level.

The components of the system which made this system more efficient were:

- Variable speed drive compressors – allowing exact matching of cooling demand to performance.
- Variable speed condenser fans – ensuring the system operated in very stable conditions.
- Large condenser – ensuring heat could be removed quickly and efficiently.
- Dedicated sub cooling – ensuring the refrigerant was presented to the compressors at optimal conditions.
- Electronic expansion valves – ensuring correct utilisation of the evaporators for maximum stability and performance.

None of the technology installed on this store could be considered as being exotic or prohibitively complex or expensive. It is all readily-available for potato store refrigeration plant installations.

As an illustration of the benefit of this type of equipment, running cost figures are shown for a typical pre-pack store running at an average COP of 2.6 and one running at an average COP of 4.

	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes pre-pack storage in Store 5
COP 2.6	38.5	**£4,950**
COP 4	22.2	**£2,860**

Table 6.5.1 – Comparison of cooling costs at higher COP

9.1.2. Store 5 - Condenser fan replacement

The refrigeration system on Store 5 consists of an in-store evaporator in an air handling unit (overhead throw) with a remote external drive compressor and externally-mounted condensers. This is shown in the photos below.

Figure 6.5.3 - Store 5 refrigeration plant

Figure 6.5.4 - Store 10 condensers

The original efficiency tests carried out on 5th April concluded that the system had an efficiency COP of 2.66, which could be improved to 2.81 with the following improvements:

- Install VSD or EC (electronically commutated) fans to control condensing pressure.
- Alter TEV settings or install electronic expansion valves.

EC fans were provided by the manufacturer (EBM Papst) for us to trial. The installation was carried out on 20th September 2011. A full retest was carried out on this day prior to and after the new EC fans were installed.

The system efficiency was calculated in a slightly different way (the electricity consumption of the fans was included in the COP calculation) to ensure that the results were comparable.

The results achieved were:

- An increase in cooling duty of 8.5 kW (10 %).

- A slight electrical power increase of 0.8 kW.
- An increase in whole system efficiency of 10 %.
- COP prior to installation of 2.9 and COP after installation of 3.2.
- A much more stable cooling delivery.

The effect of the change of fans is a system inherently more stable and predictable in operation, with less potential for breakdowns and with an efficiency improvement of over 10 %.

Table 6.5.2 below shows the effect on operating costs that this change will have.

	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes pre-pack storage in Store 5
COP 2.9	34.5	**£4,438**
COP 3.2	31.3	**£4,022**

Table 6.5.2 - Comparison of cooling costs with EC fans

The EC fans will cost £60 - £100 each and this installation would cost approximately £500-£750 fully installed.

9.1.3. Store 7 - Condenser and TEV optimisation

Store 7 refrigeration is a remote condenser/compressor unit (Friga-Bohn) with an in-store evaporator. Being a bulk store the evaporators sit at the top of the crop and air is pulled through them for redistribution via the central duct and lateral underfloor ducts.

Figure 6.5.5 - Remote condenser/compressors

Figure 6.5.6 - Main store fans

During the first test, the refrigeration system was operating at part load and the condenser fans were found to be cycling from both fans off to one fan running, to both fans running and back again. This was leading to instability of cooling delivery and causing the unit as a whole to operate below maximum efficiency.

Two suggested condenser improvements were to:

3. Reduce the condensing temperature set point so that the fans cut in earlier; and
4. Remove the grilles from the base of the condenser pack to allow a better flow of air.

In addition, it was believed that the TEV settings were sub-optimal, as the store was designed to provide cooling for onion storage as well as potato storage.

The following table details the results and the expected efficiency increase for the suggested changes:

Capacity	Power input	Evaporating	Superheat	Condensing	Sub cooling	COP
kW	kW	°C	K	°C	K	x:1
101.3	**38.9**	**-5**	**15**	**44**	**8**	**2.60**
111.3	39.2	-3	12	42	7	2.84
117.6	38.8	-2	10	40	6	3.03
123.2	38.3	-1	8	38	5	3.22
132.9	**37.2**	**0**	**5**	**35**	**4**	**3.57**

Table 6.5.3 - Improvements to Store 7 system efficiency

A retest was carried out on 12th September after the settings were changed. Unfortunately, the benefits of the change were not obvious, as the system was operating at full load and the changes that were made only affect the efficiency at partial load. Additionally, the refrigerant charge was low and this affected the TEV operation which remained fully open throughout to compensate.

Table 6.5.4 below shows the effect on operating costs for 1,000 tonnes of processing storage with the improvement shown in Table 6.5.3. This change is a very low cost (sub £250) alteration, as it is only altering the settings on the system and does not require additional or replacement equipment.

	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes processing storage in Store 7
COP 2.6	13.9	**£412**
COP 3.57	13.3	**£395**

Table 6.5.4 - Savings achieved by improving COP on 1,000 tonnes processing storage

9.1.4. Store 9 - Maintenance

The refrigeration system on Store 9 is typical of many refrigeration units found in box potato stores. As a packaged unit, it has two compressors with the condensers built into the box beneath the evaporator. A photo of this is shown on the following page.

Figure 6.5.7 - Refrigeration system in Store 9 *Figure 6.5.8 - Compressors in Store 9*

The system was tested first on 10th May 2011 and the COPs achieved at that visit were:

- Large compressor circuit - 1.57.
- Smaller compressor circuit - 1.67.
- Average - 1.62.

The system may have been said to have been 'showing its age' and total replacement was suggested. If it was to be kept, then remedial works were necessary to keep the system operational including repairing a refrigerant leak, and needing to recharge the system with refrigerant and top up with oil (during the test the compressors continually tripped out on low oil pressure).

The system was repaired and a retest was carried out on 19th September 2011. The following COPs were measured:

- Large compressor circuit - 1.51.
- Smaller compressor circuit - 1.77.
- Average - 1.64.

The system performance improved for the smaller compressor but was worse for the larger compressor. Again, the system continually tripped out on low oil, suggesting that the repairs have not been successful. It has subsequently been recommended that there is a total replacement of the unit in order to achieve an average system COP of 3.3.

Table 6.5.5 below shows the anticipated difference in cost by replacing the refrigeration system on electricity use alone. The savings will be far greater than this, as there will be reduced maintenance and also the risk of cooling loss is mitigated, and hence the savings from maintaining crop quality will be great.

.	Electrical consumption per hour	Anticipated annual cost of cooling for 1,000 tonnes processing storage in Store 9
COP 1.6	22.6	**£1,193**
COP 3.3	11	**£580**

Table 6.5.5 – Savings achieved by replacing the refrigeration system in a 1,000 tonnes processing store

Although a payback on capital based on energy saving alone would be long for this store, the existing system could ultimately fail to deliver critical cooling and could jeopardise the quality of the crop in the store. Continuing heavy repair costs for this system also needs to be considered as it deteriorates further.

10. APPENDIX 6 - SAMPLE FAN DESIGN CURVE

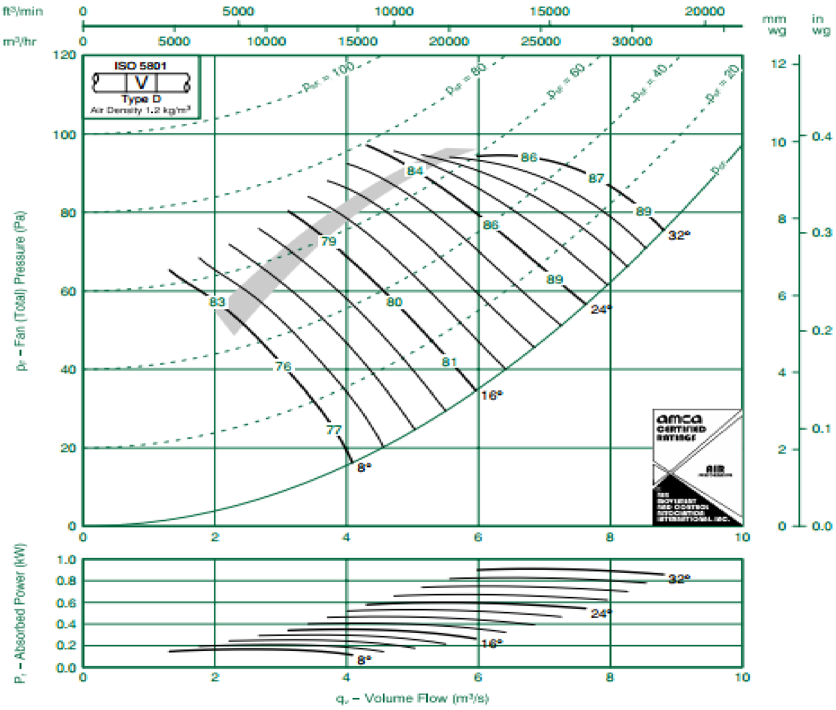
JM AEROFOIL

Woods

BS 5750 Pt 1
EN 29001
ISO 9001

Fan Code: 100JM/25/8/3/...
1000 mm 695 rev/min 3 Blades 50 Hz

Performance Data ISO 5801: The AMCA Certified Ratings Seal applies to air performance only
Performance shown is for installations type D —Ducted inlet, Ducted outlet. Performance ratings do not include the effects of appurtenances.



Sound Data BS848 Part 2 1985:
Single figures on performance curves are overall inlet sound power levels, derived from measurements taken in Woods laboratory specifically under ducted conditions. For sound power levels in eight octave bands, apply the following corrections to the overall level.Use upper corrections when operating point is above shaded area, or lower corrections when operating point is below shaded area.

Inlet Levels

Pitch Angle	Octave Band Centre Frequency (Hz)							
	63	125	250	500	1k	2k	4k	8k
8	—14 —7	—13 —9	—6 —8	—4 —7	—7 —7	—13 —1	—18 —15	—26 —20
16	—5 —4	—9 —8	—8 —9	—8 —9	—9 —1	—1 —13	—15 —17	—19 —21
24 —32	—6 —4	—7 —8	—8 —9	—9 —9	—10 —10	—13 —13	—18 —16	—22 —20

Outlet Levels

Pitch Angle	Octave Band Centre Frequency (Hz)							
	63	125	250	500	1k	2k	4k	8k
8	—12 —5	—13 —9	—6 —8	—4 —7	—7 —7	—12 —9	—17 —14	—23 —19
16	—4 —3	—9 —8	—8 —9	—8 —9	—9 —1	—1 —13	—13 —15	—16 —19
24 —32	—4 —3	—7 —8	—8 —9	—9 —9	—10 —10	—13 —12	—16 —15	—20 —18

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10.1. Appendix 6 - Store management questionnaire

STORE MANAGEMENT PRACTICES QUESTIONNAIRE

SUTTON BRIDGE Crop Storage Research

POTATO COUNCIL

Please take 5 minutes to fill in this questionnaire to assist us with our work on energy saving & carbon footprinting. **Thanks for your help.**

Q1	**Of which type of storage do you have the biggest tonnage?**	Bulk ambient ☐	Bulk with fridge ☐	Box ambient ☐	Box with fridge ☐
Q2	**Are these stores fitted with positive or forced ventilation?**	Yes (in bulk) ☐	Yes (letterbox) ☐	Yes (suction) ☐	No ☐
Q3	**Which is your primary market for the above stores in most seasons?**	Fresh/ prepack ☐	Process crisping ☐	Process chipping ☐	Seed ☐
Q4	**How long do you typically plan to store for in the above stores?**	3 months or less ☐	4-6 months ☐	6-8 months ☐	Over 8 months ☐
Q5	**Do these stores have automatic control systems (tick all that apply)?**	No ☐	Yes Not used ☐	Yes Used sometimes ☐	Yes Always on auto ☐
Q6	**If you have answered Yes in Q5, do you have probes in the air or crop?**	No probes ☐	Yes air only ☐	Yes top of crop ☐	Yes multi-level ☐
Q7	**Which aspects of stores have you upgraded in the last 3 years (tick all)?**	None ☐	Sealing/ air leakage ☐	Better insulation ☐	New fans/systems ☐
Q8	**Do you measure energy use specifically for your store(s)?**	No ☐	Yes indirectly ☐	Yes by normal meter ☐	Yes by SMART meter ☐
Q9	**Do you use humidification in any of your stores (tick all)?**	No ☐	Nozzles ☐	Pads: recirc only ☐	Pads for adiabatic cooling ☐

STORAGE PRACTICES SURVEY		BP2011: RAW DATA
STORE TYPE	POSITIVE VENTILATION	PRINCIPAL MARKET

Q1				Q2				Q3			
Bulk Ambient	Bulk With fridge	Box ambient	Box with fridge	Yes in bulk	Yes letterbox	Yes suction	No	Fresh/Prepack	Process crisping	Process chipping	Seed
16	3	6	19	18	10	8	9	15	8	19	2
			44				45				44
36%	7%	14%	43%	40%	22%	18%	20%	34%	18%	43%	5%

STORAGE TERM				AUTOMATIC CONTROL/USE				TEMPERATURE PROBES			
Q4				Q5				Q6			
< 3 months	4-6 months	6-8 months	> 8 months	No	Yes, not used	Yes, Used s/times	Yes, Always auto	No probes	Yes air only	Yes top of crop	Yes multi-level
5	20	15	5	5	0	12	28	3	2	11	26
			45				45				42
11%	44%	33%	11%	11%	0%	27%	62%	7%	5%	26%	62%

STORE IMPROVEMENTS				ELECTRICITY METERING				HUMIDIFICATION			
Q7				Q8				Q9			
None	Sealing/air leakage	Better insulation	New fans/systems	No	Yes indirectly	Yes by normal meter	Yes - SMART meter	No	Nozzles	Pads: recirc only	Pads: adiabatic cooling
8	15	11	20	17	6	15	5	36	1	4	3
			54				43				44
15%	28%	20%	37%	40%	14%	35%	12%	82%	2%	9%	7%