Project title:	Packhouse cooling & crop storage: a commercial demonstration & economic evaluation of ground sink refrigeration
Project number:	CP57 Horticultural Development Company and R403 Potato Council Ltd
Project leader:	Tim Pratt, FEC Services Ltd
Report:	Final report, February 2009
Previous report	Interim report, September 2008
Key staff:	Jon Swain, FEC Services Ltd
Location of project:	FEC Services Ltd, Warwickshire A. Pearson and Sons, Cheshire
Project coordinator:	Phillip Pearson, A. Pearson & Sons
Date project commenced:	01 January 2008
Date project completed (or expected completion date):	31 January 2009
Key words:	refrigeration, packhouse, crop store, ground sink cooling, protected crops, potatoes, borehole, field vegetables, closed loop, open loop

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

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

Jon Swain
Projects Engineer
FEC Services Ltd

Signature .... Date ....

Report authorised by:

Tim Pratt
Technical Director
FEC Services Ltd

Signature .... Date ....

Contents

Grower Summary

Headline

Ground sink cooling can reduce the amount of energy used to cool packhouses and crop stores by as much as 42%. If recovered heat in the form of warm water can be put to good use then this can offset the energy used for cooling and, in effect, make packhouses and crop stores net energy producers rather than consumers.

Background and Expected Deliverables

This project forms part of the Defra Warwick HRI Innovation Network. The network was set up to develop and promote ways in which businesses can change their operations to adapt to the effects of climate change. One area highlighted was the challenge of meeting increasing demand for locally grown produce and the growing energy requirement of cooling equipment. This, set against the background of rising ambient temperatures and the consequential reduction in the efficiency of conventional, air cooled refrigeration units was identified as an increasing problem. A need was identified for more efficient refrigeration systems able to maintain their efficiency even when the ambient temperature is high. Following consultation with industry partners and engineers at energy consultants FEC Services Ltd, ground sink refrigeration (GSR) was identified as a possible solution.

Funding for this project was provided by:

- Defra Warwick HRI Innovation Network (WHRI).
- Horticultural Development Company (HDC).
- Potato Council Ltd (PCL).

The project was managed by FEC Services Ltd. The ground sink refrigeration system was supplied and installed by Ecotech (UK) Ltd. The trial site was a tomato nursery in Cheshire; A. Pearson & Sons Ltd.

Objectives

The objectives of this project were to:

- Demonstrate how ground sink cooling could reduce the amount of energy used for produce cooling & storage and its associated cost.
- Demonstrate how ground sink cooling could improve the environmental performance of horticultural businesses by reducing their CO_2 emissions.
- Provide information about the impact and economics of improved refrigeration efficiency on a variety of crop stores and packhouses.

Summary of the Project and Main Conclusions

Technology overview

Refrigeration

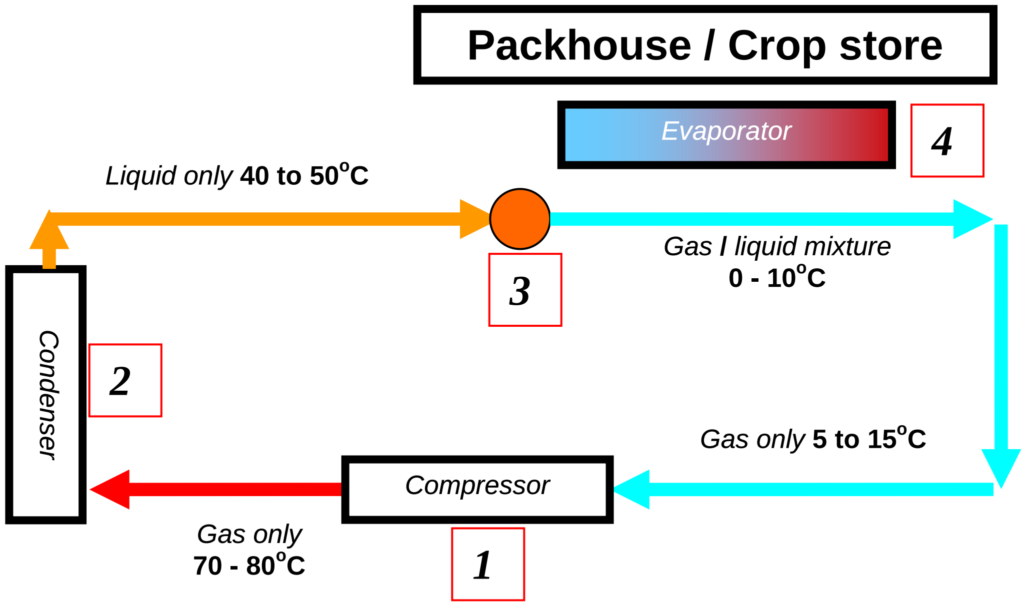


Figure 1 A typical direct expansion refrigeration system

The schematic above shows a typical direct expansion refrigeration system. This has four main parts.

1. Compression of refrigerant into hot gas.
2. Cooling and liquefaction of hot gas in the condenser.
3. Conversion of liquid to gas at the expansion valve.
4. Delivery of cold air through the evaporator.

All direct expansion refrigeration systems require that the hot refrigerant is cooled at the condenser. This is most commonly achieved by passing the refrigerant through finned coils and blowing ambient air through them. The cooling capacity of condensers is reliant on:

- Size of coil (fixed).
- Fan power (fixed).
- Temperature of the cooling air (variable).

As the ambient air gets warmer the ability of the air to cool the refrigerant diminishes. This reduces the efficiency of the refrigeration system.

A water cooled refrigeration system replaces the fan and condenser unit with a plate heat exchanger and a pump. Water is passed through the heat exchanger to cool the refrigerant. Most systems circulate the water within a closed loop with a cooling tower being used to cool the water before it is returned to the condenser. As such these types of water cooled systems are still in effect air cooled systems and thus also lose efficiency at higher ambient temperatures.

Water cooled refrigeration can use ground water which is then discarded and not returned to the heat exchanger (open loop). This means that the water temperature is always constant (the water temperature from the ground is usually 10 – 12°C) and high efficiencies are maintained in all weather conditions. Using ground water for refrigeration is termed **ground sink cooling** and for the purposes of this report the equipment has been called a **ground sink refrigeration unit** (GSRU).

Water sources

Water for water cooled refrigeration is not always readily available. Although open loop sources such as boreholes, aquifers, rivers etc are cheap and easy to connect, they are not the only way in which the constant 10^{o}C of the earth can be used to provide cooling for a refrigeration system.

Closed loops can be installed that circulate water through a network of pipes buried in the ground and then into the refrigeration unit. These closed loops always have lengths of pipe beneath the surface although the orientation and layout of the pipe work can be different. The three layout types are shown in the table below with some detail regarding their suitability.

Type	Pipe lengths for 100kW (Km)	Ground area required (m^2)	Advantages	Disadvantages
Horizontal layer	3-4	>10,000	Shallow excavation Easy to lay pipe Reasonably cheap	Large surface area Extensive excavations
Trenches	4	6,500	Easy to lay Smaller surface area Cheap	Lots of trenches Trenches need to be 5m apart
Vertical borehole	3-4	1,000	Small surface area Easily connected	High cost Dependant on local geology

Relevant legislation

When performing extensive ground works, as would be required to lay the long pipe lengths detailed above, planning advice should be sought. Planning permission may not always be necessary but seeking advice ensures the proposed installation does not contravene regulations.

Closed loop systems which consist of pipes buried in the ground do not require water abstraction licenses. Open loop systems which use water sources such as boreholes or using river water will require a licence. Details are as follows:

Water requirement >20m^3 per day	Licence required
Duration of licence	Fixed (up to 5 years) after which time reapplication is necessary
Time to apply	3 – 4 months
Water is to be discharged	A discharge consent is also required if the water is warm or polluted

At the temperatures encountered (20 - 40^{o}C), the warm water could theoretically present a risk of Legionnaires disease. However, the risk is low because clean water with no nutrient source is used. Also the water is not atomised, as would be the case with a conventional cooling tower. Further advice is available from the Health and Safety Executive.

Trial site and equipment

The project was located at the premises of A Pearson & Sons of Alderley Edge, Cheshire; a tomato nursery with large packhouse facilities. This site was chosen because the existing packhouse layout and equipment enabled the ground sink refrigeration system to be easily installed and compared with an existing adjacent air cooled unit. A borehole was also already in existence so the water connection was straightforward.

A water cooled refrigeration unit with a cooling capacity of 108kW was installed alongside the existing 80kW capacity air cooled unit. Both were fitted with sensors and monitoring equipment to enable performance to be followed and efficiencies calculated. The existing building management software and hardware was extended to include the additional control required for the GSRU equipment. Connection to this was made available over the internet so that FEC engineers could monitor performance.

The trial site already used heated borehole water for irrigation. Therefore, there was an immediate application for the warmed water produced by the GSRU and an opportunity to offset conventional water heating energy use.

Other applications

The application of ground sink refrigeration is not limited to tomato packhouses. Long term crop storage and the packing facilities for other crops also require refrigeration and are potential users of this technology. A spreadsheet simulation of crop stores for different crops and packhouse facilities was created as part of this project to ascertain the potential for GSHU.

Results

Efficiencies from trial site

The efficiency of a refrigeration unit (or co-efficient of performance - CoP) is given by the calculation below.

$$CoP = \frac{\text{Cooling delivered (kWh)}}{\text{Electricity consumed (kWh)}}$$

CoP was calculated using several methods to check consistency of results. These included comparison of electricity consumption against cooling delivered and interpretation of pressure/enthalpy refrigeration charts. The table below shows the average of the results for the season's operation at the trial site.

	Average electricity consumed (kW)	**Average cooling delivered (kW)**	**CoP**
Air Cooled Unit	27	80	3
Ground Sink Refrigeration Unit	20	100	5

Table 1 Efficiencies achieved from the trial installation

Water use

The water flow rate through the ground sink refrigeration unit varied depending on the required cooling demand of the packhouse. At full cooling, the water demand was approximately 1l/s (3.6m^3/hour). The temperature of the cooling water was raised to between 15 and 40^{o}C.

Other applications and potential benefits

The following tables give an indication of potential energy savings and the value of recovered energy for a number of other agricultural cooling applications. The results come from the spreadsheet simulation.

Crop store type (1100 tonnes stored per annum)	Compressor energy used for conventional refrigeration (kWh)	Compressor energy used for ground sink refrigeration (kWh)	Energy saving (kWh)	Hot water energy available (ground sink cooling only) (kWh)
Onions	76,846	46,108	30,738	276,646
Potatoes (processing)	14,976	8,986	5,990	53,916
Potatoes (pre-pack)	48,168	28,901	19,267	173,406
Carrots	150,858	90,515	60,343	543,090
Cabbage	64,008	38,405	25,603	230,430
Apples	83,740	50,244	33,946	301,464

Table 2 Crop storage benefits

Crop type (annual tonnes packed)	Compressor energy used for conventional refrigeration (kWh)	Compressor energy used for ground sink refrigeration (kWh)	Energy saving (kWh)	Hot water energy available (ground sink cooling only) (kWh)
Lettuce (1,500)	69,178	41,525	27,653	249,150
Strawberries (500)	53,464	32,057	21,407	192,343
Tomatoes (1,400)	23,875	14,321	9,554	85,927

Table 3 Packhouse cooling benefits

Financial Benefits

Savings

Crop stores

Crop type	Electricity saved (kWh)	Cost saving @ 12p/kWh (£)	Hot water available (kWh)	Value of hot water @ 3.75p/kWh (£)
Onions	30,738	3,688	276,646	10,374
Potatoes (processing)	5,990	718	53,916	2,021
Potatoes (pre-pack)	19,267	2,312	173,406	6,502
Carrots	60,343	7,241	543,090	20,365
Cabbage	25,603	3,072	230,403	8,640
Apples	33,946	4,073	301,464	11,304

Table 4 Crop store results

Packhouses

Crop type	Electricity saved (kWh)	Cost saving @ 12p/kWh (£)	Hot water available (kWh)	Value of hot water @ 3.75p/kWh (£)
Lettuce	27,653	3,318	249,150	9,343
Strawberries	21,407	2,568	192,343	7,213
Tomatoes	9,554	1,146	85,927	3,222

Table 5 Packhouse results

Value of electricity saved has been calculated based on a cost of 12p/kWh; slightly inflated to allow for future price increases. The hot water value has been calculated by ascertaining the equivalent cost of the hot water if provided by a gas boiler operating at 80% efficiency – giving a gross cost per kWh of 3p.

Capital costs

The complexity and cost of the installation of water cooled refrigeration will be very site specific. In this example, the installation costs at the trial site are detailed below for guidance. If water cooled refrigeration is being seriously considered then a full cost benefit analysis would need to be carried out for the specific installation.

Item	**Cost**
Air cooled unit (80kW)	£10,000
Water cooled unit (100kW)	£13,000
Electrical connections for substitute unit	£500
Electrical works for each new unit	£5,000
Sinking borehole	£10,000
Pump and pipes	£5,000

Payback scenarios

Three scenarios have been postulated to illustrate how costs and returns can effect installation economics.

Scenario 1

This is based on the substitution of a faulty air cooled unit, a use for the hot water and an existing borehole.

Additional cost of water cooled unit versus air cooled unit	£3,000
Electrical installation cost	£500
Borehole cost	nil
Pipes installation and connections	£5,000
Value of electricity savings	£1,150
Value of hot water	£3,200
Payback period	2 years

Scenario 2

This is based on the substitution of a faulty air cooled unit, a use for the hot water and no borehole.

Additional cost of water cooled unit versus air cooled unit	£3,000
Electrical installation cost	£500
Borehole cost	£10,000
Pipes installation and connections	£5,000
Value of energy savings	£1,150
Value of hot water	£3,200
Payback period	4.25 years

Scenario 3

This is based on the replacement of a functioning unit with no need for additional cooling, no use for the hot water and no existing borehole.

Cost of water cooled unit versus air cooled unit	£13,000
Electrical installation cost	£500
Borehole cost	£10,000
Pipes installation and connections	£5,000
Value of energy savings	£1,150
Value of hot water	nil
Payback period	25 years

Conclusions

- Ground sink refrigeration uses 40% less energy than a conventional air cooled refrigeration unit.
- Ready access to a suitable ground sink cooling source e.g. borehole or reservoir, is a key factor in determining the technical and financial viability of ground sink cooling.
- Economics of installation and operation can be significantly improved if the warm water recovered from the cooling process can be used to displace that normally provided by a heating system.
- Where a new refrigeration system has to be installed, the additional cost of ground sink refrigeration compared to an air cooled unit is so small that the payback periods on energy saving can be as little as 12 months.
- Closed loops for ground sink cooling are prohibitively expensive.

Action Points for Growers

- Determine the running cost of your existing refrigeration equipment; this is best done from fitting electricity sub meters or using hours run meters and existing equipment kW ratings.
- Check if you have a suitable water source/ground sink. A borehole providing water will provide the best economics.
- Determine if there is a use for the waste hot water.
- Carry out an appraisal of the above in advance to ensure you make the most energy efficient decision when the existing unit requires replacement.

Science Section

Introduction

Refrigerated produce packing and storage facilities have to work harder and harder to keep up with the demands of the cool chain. Rising ambient temperatures and demand for higher quality produce, longer shelf-life and extended production seasons are pushing existing installations to and sometimes beyond their operating limits. The result is increased running costs (energy use) and greater risk of failure threatening product quality. But at the same time, increased awareness of climate change and the need to reduce carbon footprints is challenging growers to reduce energy use. These somewhat contradictory issues are applicable to a significant proportion of Horticultural Development Company and Potato Council Ltd levy payers.

There is therefore a need for proven, cost effective techniques to help deliver good cooling performance but at reduced energy input. This has been recognised by Defra who, through Warwick HRI, have funded 50% of the cost of this project. Potato Council Ltd and the Horticultural Development Company have provided the funding for the remainder.

In recent years there has been considerable interest in ground source heat pumps (GSHP). However, installations have been dominated by domestic heating applications with only a small number of commercial (office) installations being installed. A similar concept, ground sink refrigeration (GSR), can be used for refrigeration and can be applied to packhouse and crop store cooling applications. The technique uses the thermal mass of the earth instead of ambient air to absorb reject heat from a refrigeration system. This can improve the performance of a refrigeration system by up to 50% on a hot summer's day. It reduces energy use and cost and also ensures that the cooling capacity of the refrigeration system remains constant regardless of the ambient temperature. The technology behind GSR is relatively well established. However, its financial and technical performance for large scale produce cooling applications remains unproven. Until such information is widely available growers will not be in a position to assess the true benefits to their business.

Objectives

The main objective of the project was to assess the ability of a ground sink refrigeration unit to reduce the energy use for crop refrigeration. Specific objectives were to:

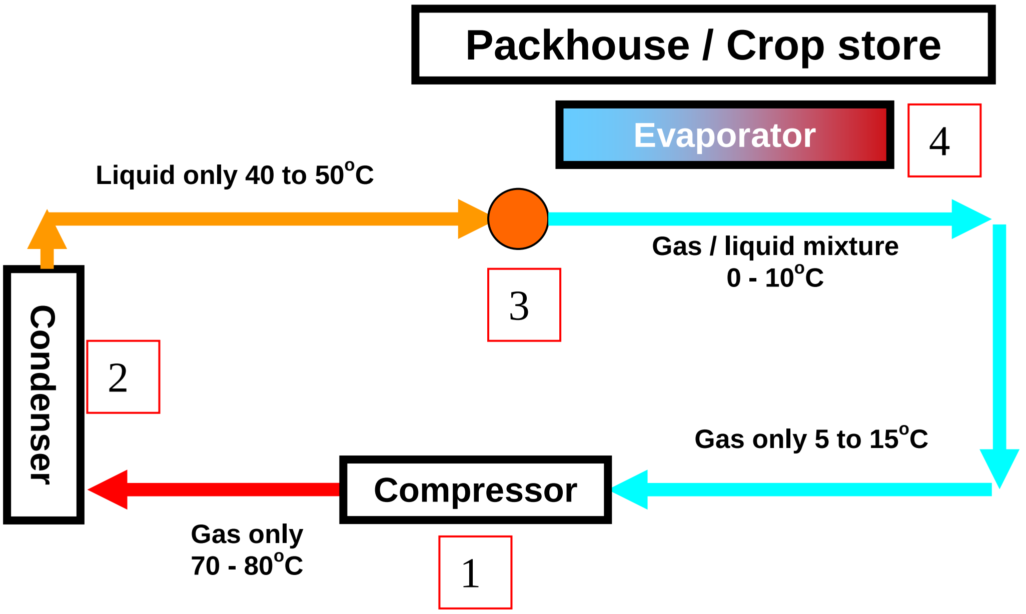
- Reduce the cost of energy for produce cooling and storage.
- Support produce quality and shelf-life by sustaining the performance of the cooling system during warm periods.
- Reducing CO_2 emissions from produce cooling and storage.
- Model the impact of ground sink cooling on a range of other agricultural and horticultural applications.

Technology Overview

Fundamentals of refrigeration

Packhouses or crop stores that require temperatures colder than ambient air are fitted with refrigeration systems; these commonly follow the principles set out in Figure 2 overleaf.

Figure 2 Schematic representation of a common refrigeration system



Refrigerant is pumped around a closed loop including several key items of equipment; these are:

1. Compressor – the refrigerant is compressed to a high pressure gas. This processes also increases its temperature.
2. Condenser – the hot gas passes through a ventilated finned coil which cools the gas refrigerant and allows it to condense into a liquid. Condensers are normally situated outside and are ventilated by fans built so that enough ambient air is available to remove the heat.
3. Expansion valve – the cooled liquid is forced through a valve which allows it to expand. In doing so the refrigerant cools rapidly and starts to change state from a liquid to a gas.
4. Evaporator – this is another set of finned coils, these are located within the building requiring cooling. The gas/liquid mixture evaporates within the coil causing a rapid drop in temperature and air passing across the coil is cooled. The low pressure gas is then returned to the compressor and the cycle continues.

The efficiency of the refrigeration cycle is highly dependant on the ability of the condenser to remove the heat from the hot refrigerant after compression.

The efficiency of refrigeration is expressed as a factor called the Coefficient of Performance (CoP). This is the ratio of the electrical energy required to operate the refrigeration cycle to the quantity of cooling produced. The electrical energy required includes that needed to operate the compressor, the condenser fans (if fitted) and the evaporator fans. Because the amount of cool energy delivered by a system is greater than the electrical energy required to operate it, the CoP is always greater than 1 (100% or more). Older poorly maintained systems may have a CoP of between 1 and 3, whereas more modern systems can have a CoP between 5 and 7.

It is important to understand that although the cooling energy delivered by a refrigeration system is greater than the electrical energy required to operate it, this does not mean that energy is 'created' by the refrigeration process. A refrigeration system is simply a device for moving heat energy from a low temperature source to a higher temperature. As such the CoP is simply an expression of the ratio of energy **moved** to the energy **consumed** by the pump. The apparent 'increase' in energy availability just reflects that more heat energy can be transferred from evaporator to condenser than is required to operate the system.

Air cooled refrigeration

Air cooled refrigeration is where all the cooling of the hot refrigerant is carried out by forcing outside/ambient air across the finned coils of the condenser. Figure 3 below shows a typical air cooled condenser unit as installed at the project site.

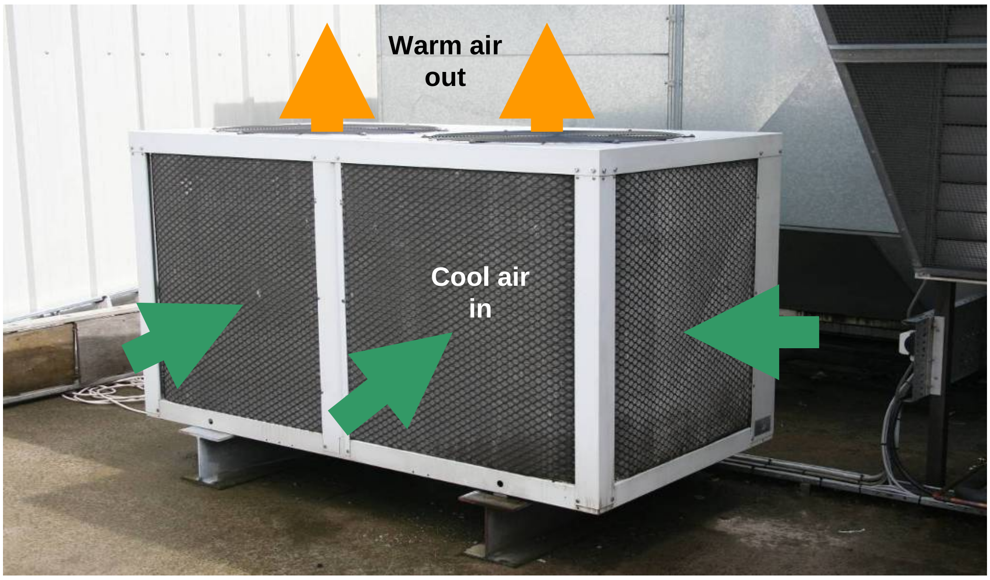


Figure 3 Air cooled condenser unit

Air is drawn through the coils rather than blown through it. This allows a more even flow of air across the whole surface of the coil and also ensures that the air is not heated by the fans before cooling the refrigerant.

The big advantage of air cooled condenser units is that they can be sited almost anywhere where there is access to outside air; air is also a 'free' cooling source and always available. Unfortunately, the temperature of the outside air in the UK varies by approximately 30^{o}C, from summer to winter and hence the ability of the air to cool the refrigerant is variable.

The efficiency of air cooled systems is specified at certain design parameters. A typical air cooled unit, as installed at the project site, has a CoP of 2.75 at a condensing temperature of 35^{o}C and an evaporating temperature of 7^{o}C. The CoP of air cooled systems is better at lower ambient temperatures but paradoxically when these conditions occur less refrigeration is required.

Other factors that reduce the CoP of air cooled units are:

- Blocked condenser coils - this happens when the surrounding conditions are dirty or dusty.
- Incorrect siting of the condenser unit, such that warmed air is drawn back into the coils effectively increasing the temperature or the air going through the condenser.
- The location of warm machinery/air vents located close to the coils.
- The air passing through the coils can not be exhausted properly.

If refrigeration systems are always to be operated at their most efficient the condenser must always be provided with a free flow of cool air. This is sometimes difficult to achieve in practice.

Water cooled refrigeration

Instead of an air-cooled coil, water cooled refrigeration uses a heat exchanger and pump to allow the hot refrigerant to be cooled by cold water. Figure 4 below shows the inside of a water cooled unit highlighting the heat exchanger unit.

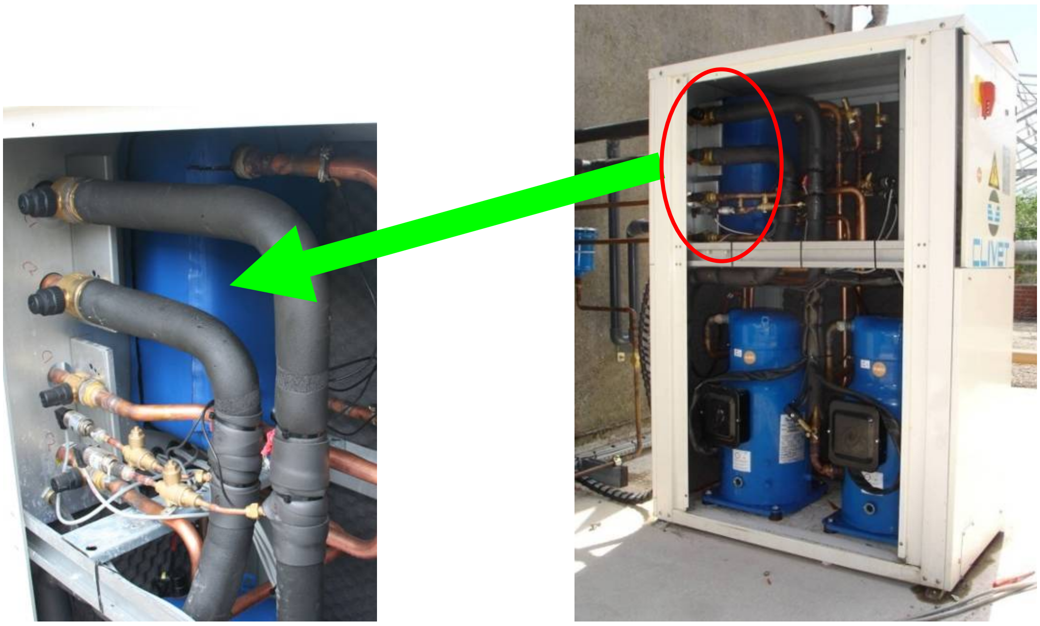


Figure 4 Plate heat exchanger inside water cooled refrigeration unit

Most water cooled refrigeration systems use a closed circuit water loop with a cooling tower to cool the water after it has picked up the heat from the condenser. This means that the system is still reliant on the temperature of the outside air. With ground sink refrigeration the system is either open loop with water coming directly from the ground e.g. from a borehole, or closed loop with water being circulated around a pipe buried in the ground. Using ground water is beneficial because below a few metres, the ground is consistently at a temperature between 10^{o}C and 12^{o}C. The consistency of temperature and the coolness of the water mean that the efficiency of ground sink refrigeration can be significantly higher than air cooled refrigeration. CoP's between 5 and 7 are not uncommon. The efficiency also remains high regardless of the ambient temperatures.

There are several other advantages to using a heat exchanger and pump rather than the conventional air cooling system:

- Cooling units are physically smaller – compared with air cooled finned coils which rely on large surface areas and big fans to get the required amount of air across them.
- The units are quieter – the pump is much quieter in operation than fans pulling air through coils. The pump can also be sited at the water source if required.
- Units can be housed inside a building as the heat exchanger is insulated and does not require cold air to flow through it.
- Cooling units are less susceptible to fouling with dust and debris.

The obvious disadvantage to ground sink cooling is that it requires either a suitable water source in the form of a borehole, or a significant area of land in which pipe loops can be buried.

Other disadvantages might include:

- Use / disposal of warmed water.
- Complexity of installation involving burying pipes in trenches.
- Cost of pipework and connections.
- Planning rules/regulations.

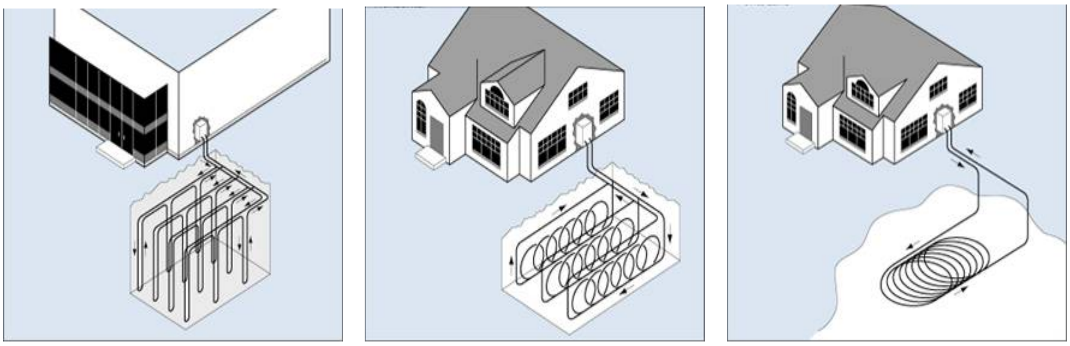
Water sources

As mentioned in the previous section the source of water for a ground sink refrigeration system can be closed or open loop systems.

Closed loop systems

Closed loop systems use water circulated through loops of pipe buried in the ground. By burying pipe in the ground the water that is circulated to and from the heat exchanger is cooled by the large thermal mass of the earth. If the pipes are sufficiently well spaced and the pipe runs are long enough it is possible to cool the water in the loop to 10 - 12^{o}C.

Closed loop pipes can be placed in the ground in many different orientations and layouts. The commonest systems are vertical boreholes, trenches and horizontal layer. These are shown in the diagrams Figure 5 below.



Vertical borehole Trenched system Horizontal layer

Figure 5 Closed loop installations

All closed loop systems require that the loops are spaced far enough apart so that they do not influence each other. For closed loop ground sink refrigeration warmed liquid water is returned to the loop causing the adjacent ground to also be warmed. If the loops are not far enough apart then the ability of the ground to dissipate the heat will be impaired. Spacing of loops in vertical boreholes and distance between trenches should be no less than 4 – 6 metres.

The length of the pipe loop determines the cooling capacity of the system. A 100kW refrigeration system such as that installed on the project site would require between 3 – 4km of pipe. 4km of pipe in a horizontal layer system would require too much topsoil to be removed that this option would be uneconomic.

For vertical borehole systems with a borehole depth of 115 metres a 100kW system would need 30 boreholes at a spacing of 5 metres. This is an area of 1,050m^2 or 30m x 35m. For most agricultural/horticultural installations, this size plot should not be difficult to find. It may even be possible to install these underneath a new building if necessary. The cost of drilling the boreholes and installing the pipework would be approximately £30,000 - 40,000.

If horizontal trenches are to be used, 4km of pipe can be installed in twenty 65m trenches (slinky style). The trenches would need to be at least 2m deep. At a required 5 metre spacing this gives a surface area of 6,500m^2 or a plot size of 100m x 65m.

Other closed loop systems available include sinking pipe loops in a pond or reservoir to use the water as the heat sink, or extracting water from a lake at one point, passing it through the refrigeration unit and returning the water to the lake at another point. This last type of system can be considered as being semi closed and is a variation of the open loop system discussed below.

Open loop systems

The predominant open loop system suitable for use for ground sink refrigeration uses borehole water. Simply, ground water is extracted, passed through the cooling unit and then used elsewhere or discarded. Figure 6 below shows this principle. In this case, water is discarded to another borehole (a version of semi closed).

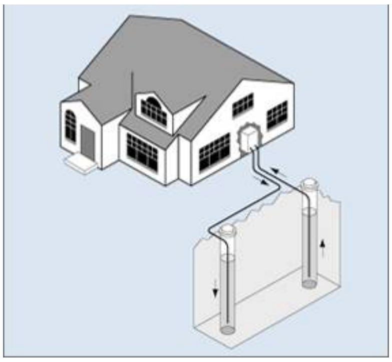


Figure 6 Open loop/semi closed installation

There are several advantages to using a water borehole as a source for ground sink refrigeration. The biggest advantage is the simplicity of the system. It does not require large quantities of pipe or complicated installation procedures. If a site already has a borehole it may be possible to connect to this.

In order to use borehole water an existing borehole must be diverted or a new borehole drilled. The availability of ground water for extraction is limited in some parts of the country. An indication of the availability can be determined by examining a hydro-geological map of the UK. However because of the wide variety in geology across the UK, a geological survey will be necessary to properly assess the potential.

Other water sources include river and streams, lakes and lagoons and, if there is a use for the water, mains water. Existing lakes and lagoons will provide a very cheap water source and may be considered.

Water consumption

The secondary use of the water is an important consideration. It is likely that the economic and environmental suitability of using borehole water will depend on there being a use for the warmed water. A 100 kW system operating at full capacity will be delivering approximately 1 litre per second (3.6 m^3 per hour).

The quantity of hot water produced is dependant on the electrical capacity and the efficiency of the system being served. If the cooling efficiency of the system is 4 times electrical input (CoP of 4) the energy available in the hot water will be 5 times electrical input (that is 4 units of transferred heat plus one unit of heat from the electrical input to the system - heating CoP of 5). This energy will be in the form of low grade heat – up to a maximum of 40 Degrees C.

Possible uses for this might include:

- Heating irrigation water.
- Washing.
- Pre-heating of water before entering a boiler.
- Heating of buildings (underfloor).
- Greenhouse heating.

Rules and regulations regarding the use of ground water

Extracting ground water for use is regulated by the Environment Agency. If more than 20m^3 per day is required then an abstraction licence is required. This must be applied for and approved before any excavation work can commence. Applications can take between three and four months. An application fee is charged and an ongoing charge for the water extracted will also be levied.

An abstraction licence is granted for a fixed period of time and only for the quantity and use stated in the application. Should these change then an amendment to the application will be necessary. Renewal of the licence is straightforward providing there is still a need for the water and it is being used efficiently.

Depending on the temperature to which the water is being warmed, the Environment Agency may class it as a ‘pollutant’ as a result of its elevated temperature. In order to return this water to a watercourse or aquifer, a discharge consent will be required. Where closed loop systems have the potential to warm surrounding water courses or aquifers these will also require discharge consents.

Legionnaires disease is caused by naturally occurring bacteria found in water sources where the environmental conditions are right for its development. It is caught by humans inhaling droplets of water containing the bacteria. The conditions that increase the risk of Legionnaires disease are:

- Water temperatures between 20 and 45^{o}C.
- Source of nutrients e.g. sludge, algae, other organic matter.
- A way of producing breathable droplets e.g. spray from pipes.

If the water is discharged in a safe manner then Legionnaires disease should not be a problem. Using a cooling tower however would require a detailed investigation. A regular cleaning regime and good design of the system should reduce the risk; more detailed information can be obtained from the Health and Safety Executive (HSE).

For closed loop systems that require excavation of a large area of land, planning permission may have to be applied for and granted.

Materials and Methods

Trial site and installation

The site chosen for the installation was A. Pearson and Sons’ Woodhouse Nursery in Cheshire. This is a tomato growing nursery with packhouse facilities. The packhouse works for approximately 30 weeks of the year (March to end of October) packing and holding produce grown at the nursery until it is ready for dispatch. The target temperature varies throughout the season but averages between 10 and 11^{o}C. Floor area of the packhouse is 1,200m^{2}.

An air cooled refrigeration unit was installed when the packhouse was built. This is a Technibel CSAGV-80 with a remote evaporator (situated in the packhouse) and has a cooling capacity of 80kW. A second remote evaporator was installed when the packhouse was built because it was envisaged that another refrigeration unit would be required.

Figure 6 Tecnibel CSAGV -80 air cooled unit

Figure 7 Clivet MCH292 water cooled unit

For the project, a Clivet MCH 292 water cooled refrigeration unit was installed alongside the existing air cooled unit. This had a cooling capacity of 108kW and was sourced to be as close as possible in design and size as the Technibel. The second evaporator was already in place and was connected to the water cooled unit which simplified its installation. The water cooled unit used identical compressors to the air cooled unit.

An existing borehole supplied the nursery with irrigation water. This borehole produced a sufficient quantity of water for cooling of the refrigeration unit. By connecting to this borehole the water cooled refrigeration system effectively became a ground sink cooled refrigeration unit (GSRU). Because there was an existing water supply license to provide enough water for the ground sink cooling it was not necessary to go through the licensing procedure for the abstraction and discharge of water that may be required on other sites. This helped to keep the cost of the project to a minimum.

Water from the borehole was pumped into a header tank and from here piped to the GSRU. Once the water had passed through the heat exchanger it was returned to a header tank and then used for irrigation. A. Pearson & Sons have heated their irrigation water for some time, so the warm water from the GSRU helped to reduce the amount of energy used for this purpose.

Figure 8 Borehole water tank

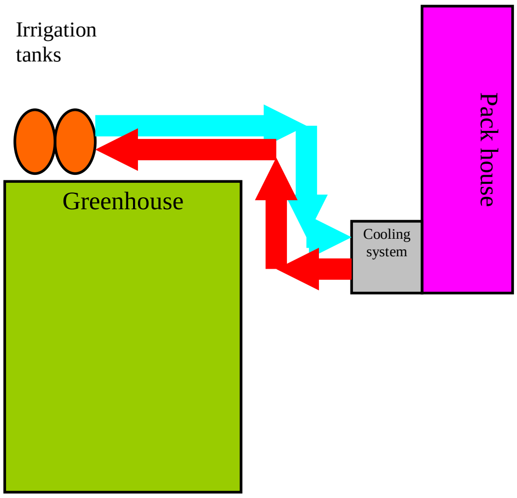


Figure 9 Schematic representation of the installation

Data collection

Both refrigeration units were fitted with additional sensors at requisite points in the refrigeration cycle, these were:

- Temperature and pressure of refrigerant at the condenser.
- Temperature and pressure at the inlet and outlet of the compressor.
- Temperature and pressure at the evaporator.

These sensors were used alongside the displacement of the compressors and the enthalpy of the refrigerant to calculate the CoP. Other instrumentation was also fitted to monitor:

- Reject water flow rate and temperature.
- Ambient temperature.
- Packhouse temperature.
- Electricity consumption.

The installation of these sensors allowed the calculation of efficiency by a variety of other methods to give confidence in the results.

A building management system – Priva Compri HX and Priva Top Control, was already in place to manage the packhouse and the air cooled refrigeration unit. This was expanded to include control of the GSRU and to provide all the data collection necessary through the data management add-on Priva Top Control History. Top Control allowed the user to easily see what was happening in the packhouse and change settings or investigate problems.

Top Control was programmed to allow each refrigeration unit to run on an alternate day basis. In practice this meant that for each day either the air cooled or the water cooled unit was nominated as the lead refrigeration unit and the other would only be allowed to operate should the conditions in the packhouse require greater refrigeration capacity. This ensured that both units were operated in a variety of ambient conditions and for different refrigeration requirements. Below are example screenshots from the Top Control computer.

A copy of the Top Control history database was downloaded at regular intervals. This allowed calculations of CoP to be made and also gave the electricity consumption figures.

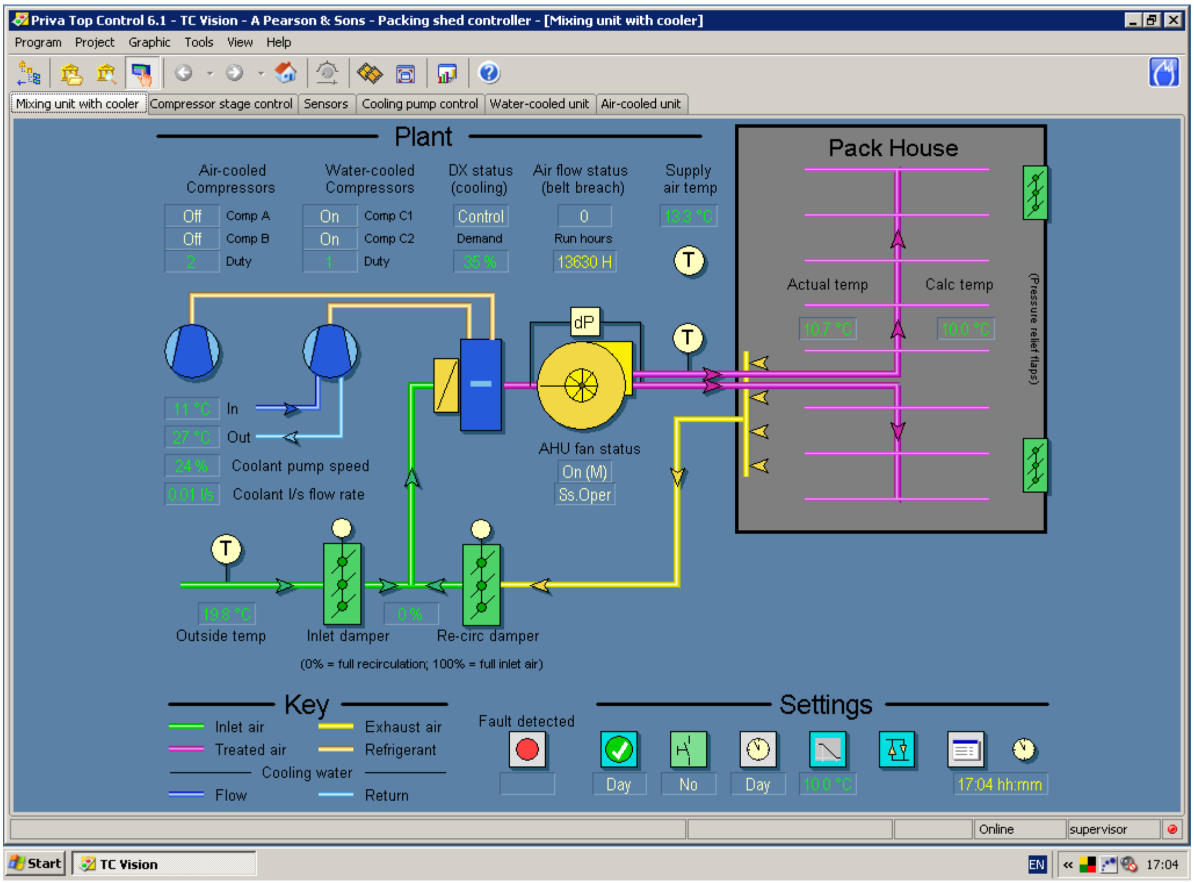


Figure 10 Overview page of the packhouse control

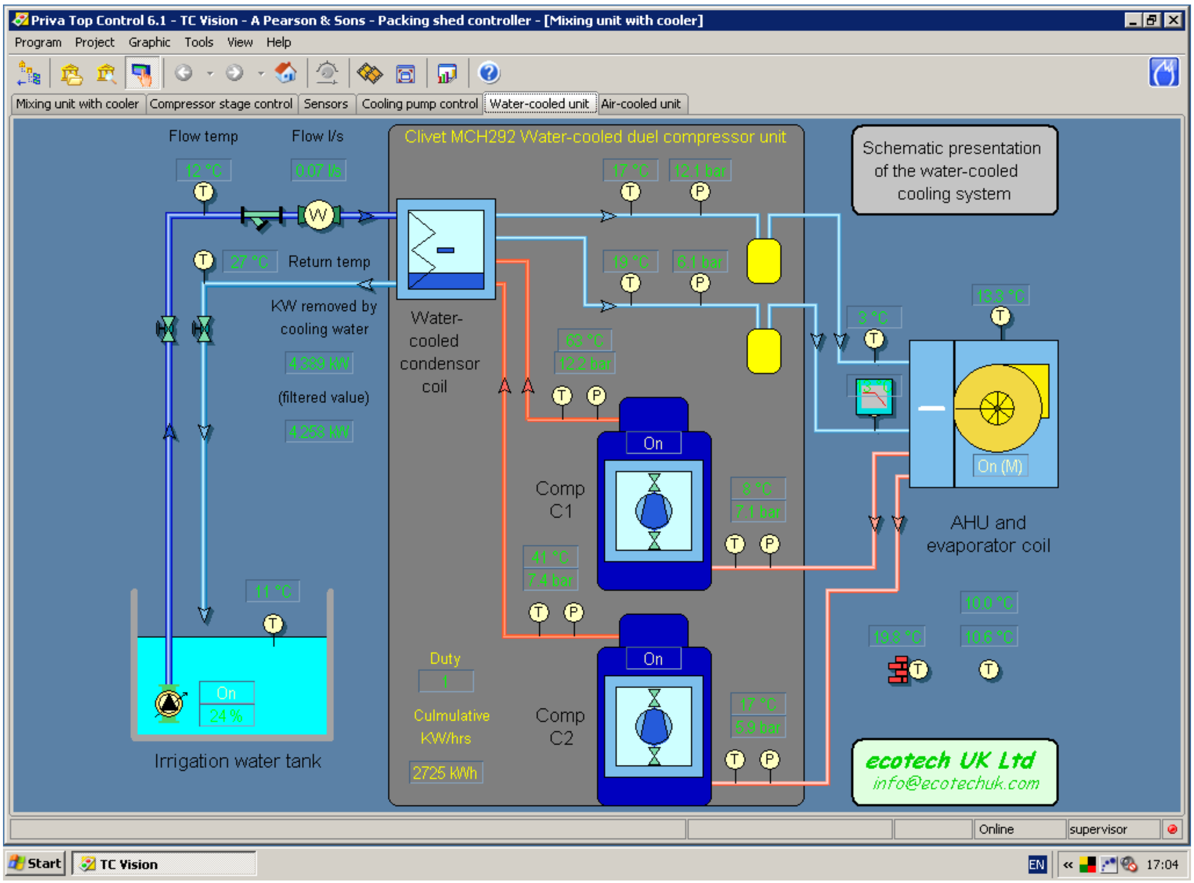


Figure 11 Detailed page showing GSRU control

Performance evaluation

The efficiency of both the conventional air cooled refrigeration unit and the water cooled refrigeration unit were compared by calculating their Coefficient of Performance (CoP). For a refrigeration system the CoP is the ratio of the amount of cooling delivered to the amount of electricity used by the system.

$$\text{CoP} = \frac{\text{Cooling delivered (kWh)}}{\text{Electricity consumed (kWh)}}$$

The electricity consumed is the sum of all electrical loads drawn by the refrigeration unit (the compressors, the condenser fans, the evaporator fans and any pumps). Electricity meters were fitted to both units to allow the energy consumed to be ascertained. In calculating the CoP for comparison purposes, the evaporator fans were omitted because they were equal in both cases.

The cooling delivered is the amount of cooling energy delivered by the system. This can be (and was) calculated by a number of different methods including interpretation of pressure/enthalpy charts related to the system and by monitoring the temperature and flow rate of the water (in the case of the water cooled unit) or the air coming out of the condenser (in the case of the air cooled unit).

Results

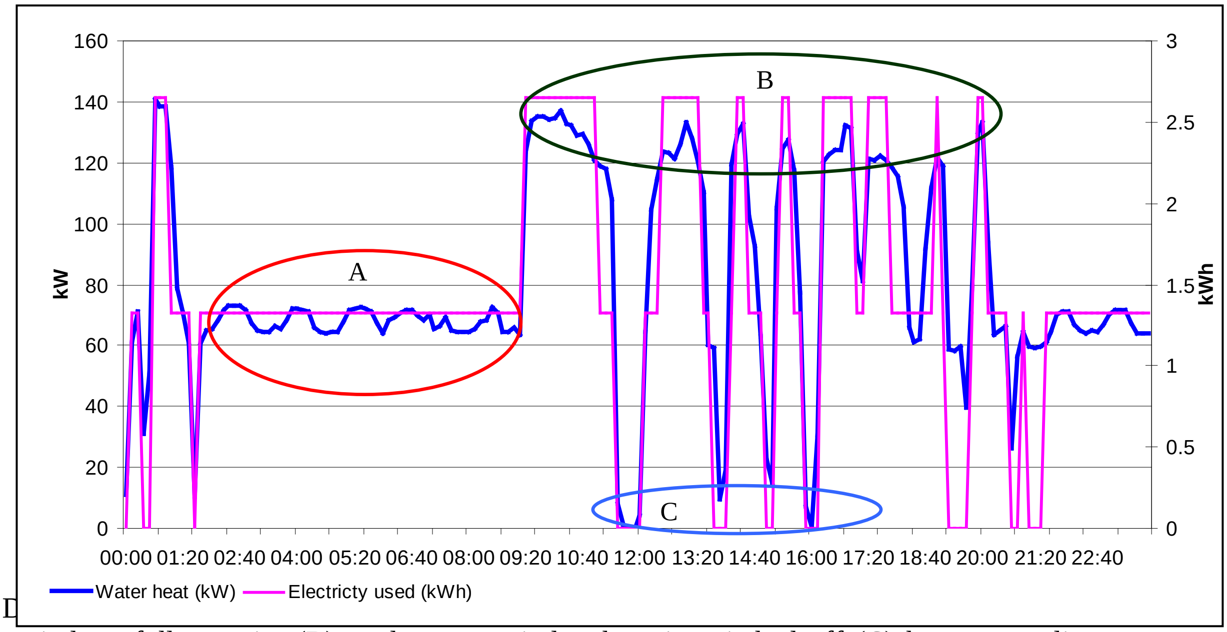
Water cooled unit CoP

The CoP of the water cooled unit was easily calculated from the metering of the electricity used by the unit and the monitoring of the flow rate and water temperature leaving the unit. The calculation is shown below.

$$\text{CoP} = \frac{\text{Heat of cooling water (flow rate * temperature difference) - Electricity input}}{\text{Electricity input}}$$

The cooling CoP was calculated under various conditions (different outside and packhouse temperatures) producing a seasonal average of 5. In other words, for every 1kWh of electricity used by the refrigeration plant 5kWh of useful cooling was delivered to the packhouse and for every 1kWh of electricity used, 6kWh of heat was rejected to the water.

The graph below shows a day's operation of the GSRU in the height of summer.



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periods at full capacity (B), and some periods where it switched off (C) because cooling was not needed. In this period a total of 1,900kWh was recovered in the form of hot water and electricity consumption was 300kWh. This gave a water heating CoP for this day of 6.3.

Air cooled unit CoP

Calculating the CoP of the air cooled unit was more complicated because it is difficult to ascertain the airflow and temperature coming off the evaporator. The temperatures and airflows through the condenser were measured during a site visit and the results compared to the CoP derived from the pressure/enthalpy charts. By cross checking these calculations at different outside temperatures an average CoP of 3 was demonstrated (3kWh of cooling delivered per 1kWh electricity used).

Use for other applications

There are many potential applications for GSRU's in agriculture and horticulture. These include vegetable crop stores and any other refrigerated packhouse regardless of the specific produce being packed.

Figure 12 A typical crop store/packhouse building

The energy consumptions/heat recovery potentials associated with the fitting of a GSRU to potato and other vegetable stores was assessed using a specially developed spreadsheet simulation tool. Various user modifiable inputs were built into the tool to allow a wide range of different applications to be specified.

Model inputs were:

- Store dimensions – height x width x length.
- Thermal insulation values for the roof, walls & floor (u-values in W/m^2/Deg C).
- Air leakage (changes/hr)

Plant considerations:

- Compressor size (kW).
- Compressor efficiency (CoP)
- Fan size (kW).
- Air flow rate (m^3 / S / Tonne).
- The ability to use ambient air for cooling.

Crop details:

- Crop type (potatoes, tomatoes, onions etc.)
- Quantity (tonnes)
- Respiration rate (Watts/tonne)
- Specific heat (J/kg/deg C).

Settings:

- Store temperatures.
- Temperature strategy.

The packhouse/crop store spreadsheet simulation was created to ascertain the impact that a more efficient refrigeration system would have on the cold storage and packhouse energy required for a variety of crop types.

The spreadsheet simulation was based on a number of real crop stores and packhouses and used a full twelve months weather information from Hull, in Yorkshire. Operation of refrigeration plant to provide cooling for target conditions was calculated for each half hour in the year. The sections below summarise the crop details and the storage/packhouse results obtained from this simulation.

It should be noted that in all cases a well insulated and well maintained building has been assumed. Clearly, facilities of a lower standard would use more refrigeration and so the savings delivered by GSRU would be greater. In practice, this may make investment in GSRU more attractive.

Crop stores

The table below summarises the crop type details used in the crop store simulation.

Crop type	**Store season**	**Target temperature**	**Tonnes**
Onions	August – June	0 Degrees C	1100
Potatoes (processing)	September – June	9 Degrees C	1100
Potatoes (pre-pack)	September – June	3 Degrees C	1100
Carrots	October – June	0 Degrees C`	1100
Cabbage	October - June	0 Degrees C	1100
Apples	September - June	3 Degrees C	11*100 tonne stores

Table 6 Crop store details

All of the crops in the store are assumed to be stored in one tonne boxes. In the store the refrigerated air delivery is assumed to be ‘overhead throw’ where the cold air is blown over the stacks of boxes and then has to pass through the produce to return to the evaporator. All crops except apples are stored in a single air space. Apple storage has been considered as consisting of eleven adjacent 100 tonne controlled atmosphere stores.

Target temperature was taken as a single figure appropriate to the crop. The effect of ‘pulldown’ i.e. removal of field heat, has been taken into account in all cases within the first months operation of the store.

The following table gives an indication of the potential energy savings and the value of recovered energy. Examples of the output from the spreadsheet simulation can be found in Appendix 1.

Crop store type (1100 tonnes stored per annum)	**Compressor energy used for normal refrigeration (kWh)**	**Compressor energy used for ground sink refrigeration (kWh)**	**Energy saving (kWh)**	**Hot water energy available (ground sink cooling only) (kWh)**
Onions	76,846	46,108	30,738	276,646
Potatoes (processing)	14,976	8,986	5,990	53,916
Potatoes (pre-pack)	48,168	28,901	19,267	173,406
Carrots	150,858	90,515	60,343	543,090
Cabbage	64,008	38,405	25,603	230,430
Apples	83,740	50,244	33,946	301,464

Table 7 Crop store results

The results given in the table above shows only the reduction in energy consumption of the compressor. All other energy requirements such as circulation fans, lighting, occasional heating, etc will remain the same. The energy consumption of the store as a whole would therefore be greater than that indicated in the table.

Recovery energy in the form of hot water is given as a guide although in some cases it may not be possible to use it. The economics of installing a GSRU will be significantly improved if this warm water can be used displacing the use of heating fuel. The water temperature achieved during the trial was up to 40°C. This means that for each 1000kWh of hot water there would be 2.86m^3 of water at 40°C.

Packhouse crops

The table below details the main inputs used in the packhouse simulation.

Crop type	Packing season	Input temperature	Target temperature	Tonnes/year
Lettuce	April – September	20 Degrees C	2 Degrees C	1500
Strawberries	May – September	20 Degrees C	3 Degrees C	500
Tomatoes	March – September	20 Degrees C	10 Degrees C	1400

Table 8 Packhouse details

The quantity of crop put through the packhouse is shown as tonnes per month as a seasonal average. The likely impact of the energy saving will be greater if there is more produce put through in the warmer mid summer months than in the early and late months.

The following table gives an indication of the potential energy savings and the value of recovered energy.

Crop type	Compressor energy used for normal refrigeration (kWh)	Compressor energy used for ground sink refrigeration (kWh)	Energy saving (kWh)	Hot water energy available (ground sink cooling only) (kWh)
Lettuce	69,178	41,525	27,653	249,150
Strawberries	53,464	32,057	21,407	192,343
Tomatoes	23,875	14,321	9,554	85,927

Table 9 Packhouse results

Economics

Savings

Crop stores

Crop type	Electricity saved (kWh)	Cost saving (@ 12p/kWh) (£)	Hot water available (kWh)	Value of hot water (@ 3.75 p/kWh) (£)
Onions	30,738	3,688	276,646	10,374
Potatoes (processing)	5,990	718	53,916	2,021
Potatoes (pre-pack)	19,267	2,312	173,406	6,502
Carrots	60,343	7,241	543,090	20,365
Cabbage	25,603	3,072	230,403	8,640
Apples	33,946	4,073	301,464	11,304

Table 10 Crop store results

Packhouses

Crop type	Electricity saved (kWh)	Cost saving (@ 12p/kWh) (£)	Hot water available (kWh)	Value of hot water (@ 3.75p/kWh) (£)
Lettuce	27,653	3,318	249,150	9,343
Strawberries	21,407	2,568	192,343	7,213
Tomatoes	9,554	1,146	85,927	3,222

Table 11 Packhouse results

Value of electricity saved has been calculated based on a cost of 12p/kWh slightly inflated to allow for future price increases. The hot water value has been calculated by ascertaining the equivalent cost of the hot water if provided by a gas boiler operating at 80% efficiency – gross cost per kWh of heat produced of 3p.

Capital costs

The complexity and cost of the installation of a water cooled refrigeration will be very site specific. In this example, the installation costs at the trial site are detailed below for guidance. If a water cooled refrigeration is being seriously considered then a full cost benefit analysis would need to be carried out for the specific installation.

Item	**Cost**
Air cooled unit (80kW)	£10,000
Water cooled unit (100kW)	£13,000
Electrical connections for substitute unit	£500
Electrical works for each new unit	£5,000
Sinking borehole	£10,000
Pump and pipes	£5,000

Payback scenarios

Three payback scenarios have been created to show the impact of various site specific issues like the utilisation of recovered heat and the availability of borehole water.

Scenario 1

This is based on the update of an air cooled unit which is due for replacement, a use for the hot water and an existing borehole.

Additional cost of water cooled unit versus air cooled unit	£3,000
Extra electrical installation cost	£500
Borehole cost	£0
Pipes installation and connections	£5,000
Value of electricity savings	£1,150
Value of hot water	£3,200
Payback period	2 years

Scenario 2

This is based on the update of an air cooled unit which is due for replacement, an economically viable use for the hot water and no borehole.

Additional cost of water cooled unit versus air cooled unit	£3,000
Extra electrical installation cost	£500
Borehole cost	£10,000

Pipes installation and connections	£5,000
Value of energy savings	£1,150
Value of hot water	£3,200
Payback period	4.25 years

Scenario 3

This is based on the full cost of replacement of a functioning refrigeration unit with no need for additional cooling, no use for the hot water and no existing borehole.

Cost of water cooled unit versus air cooled unit	£13,000
Extra electrical installation cost	£500
Borehole cost	£10,000
Pipes installation and connections	£5,000
Value of energy savings	£1,150
Value of hot water	0
Payback period	25 years

Discussion

Water sources

Installation of a ground sink refrigeration unit requires access to a water source (if open loop is to be used) or the ability to install long lengths of pipe if closed loop is to be used. Neither option is particularly cheap. However the sinking of a borehole is the easiest and cheapest, albeit there is a requirement to have an abstraction license and in some cases a discharge license if the hot water is not to be used. Obviously in situations where a borehole already exists, and the pipework to connect it is short, then the additional cost is minimised. If a lagoon or lake is available that could be connected to the refrigeration unit the installation cost can be further reduced.

Hot water utilisation

The ability to use recovered heated water has a big effect on the economics of replacing air cooled refrigeration with a water cooled system. In all water cooled refrigeration systems the energy used to produce hot water and that produced for cooling is much greater than the electricity used. The value of the energy recovered in the form of hot water varied in the project spreadsheet simulation from £2,000 to £20,000 a year. This reflects the quantity of cooling required which is itself dependant on the cooling temperature and type of crop store or packhouse to which the technique is applied.

Technical barriers

Some technical problems with the installation were encountered which were largely due to poor matching of the water pump to the sytem. This resulted in higher than necessary water flows and ‘overcooling’ of the refrigerant. Detailed consideration of this in the planning stage should overcome this problem.

Technically the connection of the water cooled refrigeration unit is simple, albeit dependant on a water source being readily available. Side by side installation along with an air cooled unit will provide reassurances that cooling will always be available. However this should not be necessary as long as the planning and design of the installation is carefully thought through.

A direct replacement for an air cooled unit should involve few risks. However the economics look best where there is a need for additional cooling - a new building or replacement of where an existing unit is necessary. Paybacks vary considerably based on the amount of cooling required. Clearly when cooling use is high the potential for saving is greatest.

Conclusions

This project set out to show that water cooled refrigeration, specifically ground sink cooling has viable applications in the horticultural and agricultural sector. The installation at the trial site demonstrated that savings of 40% are possible.

Having ready access to a water source considerably reduces the payback periods and improves the economic viability. Other things that improve the economics are:

- A high cooling demand – the greater the demand the more viable the installation.
- A requirement for hot water – using the water can mean that in some cases the paybacks are 12 – 18 months.
- Requirement for investment in the cooling installation – clearly if investment in a refrigeration system is already required, for example for replacement of a faulty unit or the provision for additional cooling, then some of the cost of the GSRU can be set against what would have been spent on an equivalent conventional system.

In essence, the installation of a water cooled refrigeration unit should not be very much more complex or expensive than an air cooled unit. Additional complexity comes if long lengths of pipework are necessary to connect up a borehole or a closed loop system. Closed loop cooling itself is not really viable for packhouse/crop store applications because it does not allow the use of recovered heat in the form of hot water.

Glossary

Ground sink cooling	A specific type of water cooled refrigeration using the temperature of the earth to cool the refrigerant.
Coefficient of Performance	A measure of the efficiency of refrigeration systems, usually greater than 1.
Open loop cooling source	A source of cold water that is not recirculated, examples include abstraction of water from a borehole or a river.
Closed loop cooling source	A source of cold water that is recirculated through a matrix of pipes in the ground so that it can be cooled by the constant temperature of the earth.
Packhouse	A facility where crops are packed and held for short periods before dispatch for example for tomatoes, lettuce etc.
Crop store	A facility where crops are cooled and held at cold temperatures for long periods for example potato store, carrot store etc.

References

Refrigeration and Air Conditioning Technology, 6th Edition - Bill Whitman, Bill Johnson, John Tonczyk, Eugene Silberstein

Introduction to Thermodynamics – Keith Sherwin, Chapman and Hall 1995

Principles of Refrigeration – 2nd edition, Roy J. Dossat John Wiley and Sons 1981

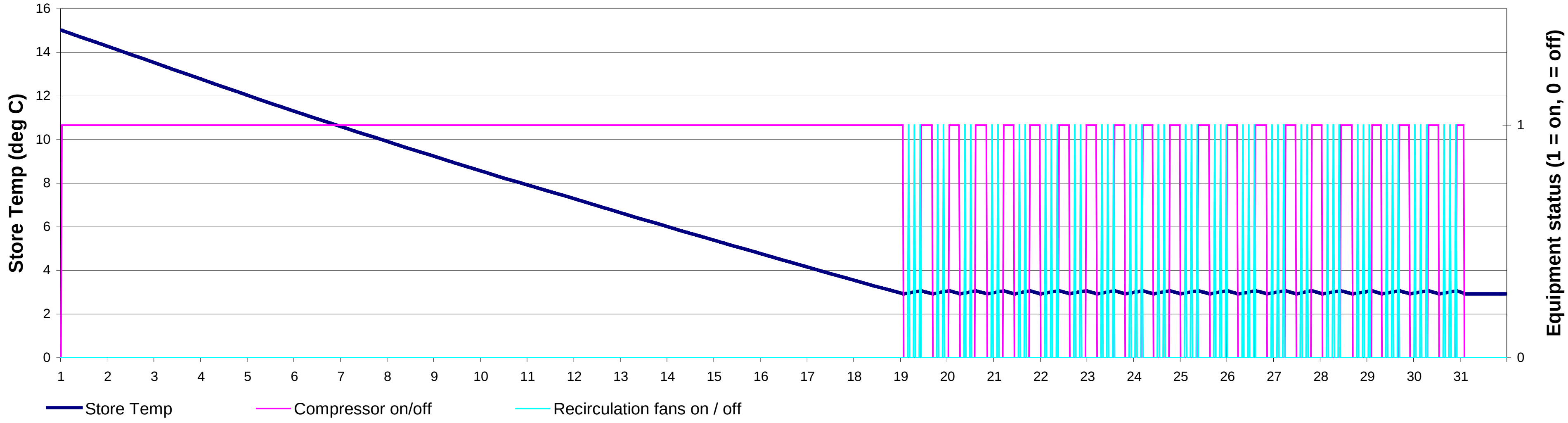
Appendix 1 Crop store model input page

Refrigerated Crop Store Model

Choose month	Jun							
Structural Details			**Insulation Details**			**Crop Details**		
						Crop	Potatoes (prepack)	
Length (m)	26.00	metres	Walls (W/m^2'C)	0.30	W/m^2'C	Crop quantity	1,100	Tonnes
Width (m)	23.00	metres	Floor (W/m^2'C)	0.35	W/m^2'C	Respiration Rate	9.00	Watts/tonne
Eaves Height (m)	5.50	metres	Ceiling (W/m^2'C)	0.30	W/m^2'C	Specific Heat	3,430	J'Kg'C
Ridge Height (m)	7.40	metres				Specific Heat Air	1,200	J/m^3
Total Store Volume m^3	3,857	Cubic metres	Air Leakage (changes/hr)	0.10	Changes/hr	Thermal Capacity	3,773,000,000	J/'C
						Respiration heat gain	9,900	Watts/deg C
Plant Details			**Total structural Heat Gain**					
Compressor Size (kW)	18	kW	Walls	161.70	Watts/Deg C			
C of P	3.0		Floor	209.30	Watts/Deg C			
Cooling Capacity (kW)	54	kW	Roof	181.83	Watts/Deg C			
Fan (kW)	12	kW	Leakage	128.57	Watts/Deg C			
Ambient capability	no							
Air flow rate	0.02	CMS/tonne	Total	681.40	Watts/Deg C			

Controller Settings			**Ambient strategy temperatures**		
Temperature at start of period	3	Deg C	Temperature difference at which ambient cooling becomes available	-2	Deg C
Target temperature	3	Deg C	Target temperature difference between store and cooling air	-2	Deg C
Temperature less than target allowed	3.125	Deg C	absolute minimum air temperature blown into store	1	Deg C
Temperature greater than target allowed	2.875	Deg C	maximum cooling rate allowed	-0.5	Deg C / day

Appendix 1 continued
Results from crop store model example of whole month



Month	Sep		
Temperatures			
Store start	15	deg C	
Store end	2.93	deg C	
Min temp	2.93	deg C	
max temp	15.0	deg C	
Hours run			
Compressor	543.5	hrs	
Ambient fans	0	hrs	
Recirc fans	26.5	hrs	

Energy consumed		
Compressor	5,870	kWh
Compressor fans	6,522	kWh
Ambient Fans	-	kWh
Recirc Fans	318	kWh
Total	12,710	kWh

Cooling delivered		
Compressor	29,349	kWh
Ambient Fans	-	kWh
Total	29,349	kWh
Heat delivered		
Respiration	7,128	kWh
Fans	6,522	kWh
store air leakage	683	kWh
store structural losses	2362	kWh
Total	16,695	kWh

COP	
Overall	2.3
Compressor	5.0
Ambient fans	
kWh / tonne	
Overall	11.6
Compressor	11.3
Ambient fans	-
Recirc fans	0.3

Appendix 1 continued
Results from crop store model example of day 18 of month