‘Energy Comparison of a Ground Source Heat Pump Using Hydrocarbon Refrigerant’

by

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1. Abstract

The purpose of this paper is to show that the benefits of ground source heat pumps can only be optimised through the very careful design of all the components including the refrigerant selection.

This paper describes an innovative scheme whereby a ground source heat pump draws heat from a nearby field to heat a school. The heat pump system replaces electric night storage heaters, which were noisy, bulky and difficult to control, particularly during the spring and autumn. The suitability of this installation was assessed through cost analysis and energy measurements of the old and new system.

The installation consists of a water to water heat pump connected to MDPE pipework arranged in ‘slinky coils’ laid horizontally at the bottom of trenches dug in a field adjacent to the school. Glycol solution is circulated to extract low grade heat from the ground. This heat is upgraded to a useful temperature by the heat pump before being distributed to fan coil units. This system was commissioned in October 2003.

The energy consumption of the old system has been estimated from the electricity billing records. Additionally, we now have local metering recorded weekly by the school staff for greater accuracy. Digital readouts of the ground loop and building loop temperatures are also monitored.

This project has resulted in significant energy savings relative to direct electric heating. The plant now runs for only five days per week instead of seven due to upgraded time clock controls with ‘day omit’ functions. The heat pump is expected to reduce running costs by over 58%, energy consumption by over 79% and to reduce CO_2 emissions by 18 tonnes per annum. We calculate that we would need to plant 165 trees to achieve the same CO_2 reduction as our heat pump. We conclude that ground source heat pumps can be a cost effective method of reducing green house gas emissions relative to less efficient combustion or resistive heating technologies.

2. Introduction

I am honoured to have been invited by The International Refrigeration Committee of the UK Institute of Refrigeration to address you on the application of hydrocarbon refrigerants in a ground source heat pump recently installed by my company, Earthcare Products, at Buntingsdale Infant School in Shropshire. The project was joint-funded by Shropshire County Council's Energy Conservation and Sustainable Construction Unit and the UK Government's Carbon Trust. The newly installed system demonstrates the cost, logistical and technological issues that surround the use of heat pump systems in non-domestic applications.

3. The Problem

Buntingsdale School is located next to an Army helicopter airfield. It is a raised pre-fabricated building of a frame and panel type construction as shown in figure 3.1. There are three large classrooms with associated staff and ancillary areas. The school caters for the children of service families living at the base and boasts a strong teaching practice: the latest OFSTED report stated that the school "provides good value for money."[1]

Figure 3.1: Buntingsdale Infant School, Shropshire

However, Shropshire County Council, which maintains Buntingsdale School, had been concerned at the cost of heating the school. The high cost was in part due to the building's method of construction but mostly due to the presence of electrical night storage heaters. These were noisy, bulky, uneconomic and difficult to control. The school suffered many days where teaching was difficult due to excessive heating, especially on mild days in spring and autumn.

[1] *OFSTED Inspection Report* (Inspection number: 248449)

4. Possible Solutions

In most areas of the country, the solution to this problem would have been the installation of a gas-fired central heating system. However, large areas of Shropshire – including Buntingsdale – do not enjoy the provision of a mains gas supply. As a result, the Council considered other means of heating, some of which it had been studying for several years within the remit of its environmental policy. Amongst the options available to the Council were an air source heat pump and a ground source heat pump. After some discussion and cost analysis, summarised in table 4.1, it was decided to purchase the latter – a ground source heat pump.

Heating System	*CO_2 emissions per kWh fuel (Kg CO_2/kWh)*[2]	*Efficiency %*	*CO_2 emissions per kWh useful heat (Kg CO_2/kWh)*[3]	*Price per useful heat output p/kWh*
Coal boiler	0.34	70	0.41	2.57
Oil boiler	0.28	80	0.34	2.21
LPG Condensing Boiler	0.25	90	0.28	3.26
Mains gas Condensing boiler	0.19	90	0.21	1.64
Air source heat Pump	0.47	250	0.16	1.99
Typical ground source heat pump	0.47	320	0.13	1.56
Optimised hydrocarbon refrigerant ground source heat pump	0.47	430	0.10	1.16

Table 4.1: Comparison of Different Heating Systems

5. Chosen System

Two types of ground source were considered, boreholes or so-called "slinky-loops", which are laid under the surface of the ground below the plough-line. Local geological conditions did not permit the use of a borehole so a slinky-loop was opted for. This was only made possible by kind loan of an adjacent field by a local farmer. In this system, a water to water heat pump would be connected to MDPE pipework arranged in 'slinky' coils laid in trenches dug in the field. A glycol solution would be circulated to extract low-grade heat from the ground. This heat would be upgraded to a useful temperature by the heat pump unit before being distributed to 18 local fan coil units of varying sizes. The budget for the entire project was around £70,000.

The heat pump chosen was one Earthcare Wesper CWP21 reversible heat pump chiller, as shown in figure 5.1, providing 36.4 kW heating output as water at 46°C. The power input is 8.46kW, giving a COP of 4.3 when using propylene glycol at 0°C as the heat source. Noise levels were specified to be suitable for classroom / meeting room / lecture theatre applications.

[2] *John Willoughby's Domestic Fuel Price Guide No. 27*, April 2003
[3] *SAP*, 2001

Figure 5.1: Earthcare Wesper CWP21

It was intended that this solution would deliver a number of benefits:

- the fan coil units would smaller, less intrusive, more controllable and quieter than the electric night storage heaters they replaced;
- overall system efficiency would be higher;
- energy savings would be matched by similar carbon savings;
- the school would enjoy comfort cooling in the summer months.

6. Refrigerant Selection

In addition to using a ground source heat pump, which has inherent energy efficiency and environmental advantages, further performance gains were brought with the use of hydrocarbon refrigerant coupled with the optimisation of the heat pump chiller unit itself. Most heat pumps currently use synthetic refrigerants with a high global warming potential. Table 6.1 illustrates the comparative environmental impact of different Refrigerants. Quite apart from the environmental problems inherent in the use of these refrigerants, they make far-from-ideal heat pump working fluids. For example, the critical temperature of HFC R410A is only 72°C, far less than for the previous generation HCFC R22, which has a critical temperature of 96°C. However, by using hydrocarbon refrigerants, it is possible to attain similar critical temperatures to those achieved by R22. The hydrocarbon R290, for instance, has a critical temperature of 97°C, making it the ideal replacement for heat pump applications that would previously have used R22. Our two preferred hydrocarbons for heat pump applications are propane (R290) and propylene (R1270). Both refrigerants have zero Ozone Depletion Potential (ODP) and a negligible Global Warming Potential (GWP) of only 3. R1270 offers the same heating capacity as R22, whereas R290 offers higher sink temperatures (65°C instead of 55°C), meaning it can be used with conventional radiators and those domestic hot water applications where many R407C heat pumps must use electric resistance booster heaters to raise the water temperature above the Legionella risk zone. In this case, propylene (R1270) was used as the refrigerant, as it was more suited to this application, giving higher thermal output capacity at the design conditions:

Heat Output (R 1270)	B0/W46	36.4 kW
Heat Output (R290)	B0/W46	30.6 kW
Heat Output (R407C)	B0/W46	31.3 kW

Ten years of experience has taught us that apart from the safety issues, which will be dealt with shortly, standard components work better with hydrocarbon refrigerants than with R22 or R407C. In particular, compressors run quieter and cooler. The expansion valve requires only slight adjust to compensate for the 60% reduction in mass flow rate. If the heat pump is to operate at temperatures above 50°C then the compressor oil should be changed to an SP100 mineral type grade 4, but at lower temperatures the original oil, whether mineral or ester, will be suitable.

Refrigerant type	*Refrigerant*	*Ozone depleting potential* [4]	*Global warming potential*	*Number of trees required to offset the release of 1kg of refrigerant*[5]
Hydrochlorofluorocarbons (HCFCs)	R22	0.034	1,700	15.3
Hydrofluorocarbons (HFCs)	R134a	0	1,300	11.7
	R404a	0	3,800	34.2
	R407C	0	1,600	14.4
	R410A	0	1,900	17.1
Hydrocarbons (HCs)	R600a	0	3	0.027
	R290	0	3	0.027
	R1270	0	3	0.027

Table 6.1: Comparative Refrigerant Environmental Impact

7. System Optimisation

Further optimisation was achieved by employing the following:

a) Low energy refrigerant

The use of hydrocarbon refrigerants reduces energy consumption relative to R22 and other synthetic alternatives, due to more favourable thermodynamic characteristics.

b) Fully flooded evaporator

Normally only available via expensive electronic expansion valves, zero superheat was achieved by the application of a plate suction liquid heat exchanger with the phial of the expansion valve located downstream of the heat exchanger. The lower condensation temperature relative to R22 improves the efficiency of the internal heat exchanger. Heat transfer is increased between the liquid upstream of the expansion valve and the vapour upstream of the compressor, thus improving the COP further.

[4] IPCC 3rd Assessment Report, 2001
[5] The Edinburgh Centre for Carbon Management, 'Estimation of Carbon Offset by Trees', *ECCM Technical Document No. 7*, March 2000

c) Compressor motor control

The compressor motor control modulates the voltage and current to the compressor at part load conditions. This reduces the motor core and winding losses and reduces power input. The effectiveness of compressor motor control is enhanced by the fact that the lower mass flow rate, density and viscosity of hydrocarbon refrigerant reduces the load on the motor.

Further work was carried out on the heat pump chiller to minimise possible global warming emissions:

a) Refrigerant charge

By careful design and the fact that hydrocarbons weigh approximately 60% less than HFCs, this is restricted to less than 100g per kW.

b) Refrigerant emission rate

Leakage was minimised by the elimination of on-site refrigeration pipe work, copper-to-copper flared joints and copper capillary lines. We also utilise conventional mineral oils, thus eliminating the higher risk of leakage from gaskets and shaft seals when using synthetic ester oils.

It was intended that the combined effect of these energy efficiency measures would result in a potential energy saving in excess of 75% relative to direct electric heating. In addition, the plant would only be running during weekdays, making a further saving of 28%, raising total savings to some 79%.

8. System Description

A single pumped fan coil circuit provides either heating or cooling. A 2-pipe fan coil installation was designed, with the fan coils being oversized relative to traditional heating systems providing due allowance for the lower flow temperatures of the heat pump. Insulated plastic pipework was used throughout, run at low level under the floor. A buffer tank with a nominal 500 litres internal capacity was included to minimise compressor cycling and to allow for the inclusion of low cost electric immersion heaters for back up. In winter, the heat pump heats and in summer provides comfort cooling as required. A system schematic is shown in figure 8.1 below.

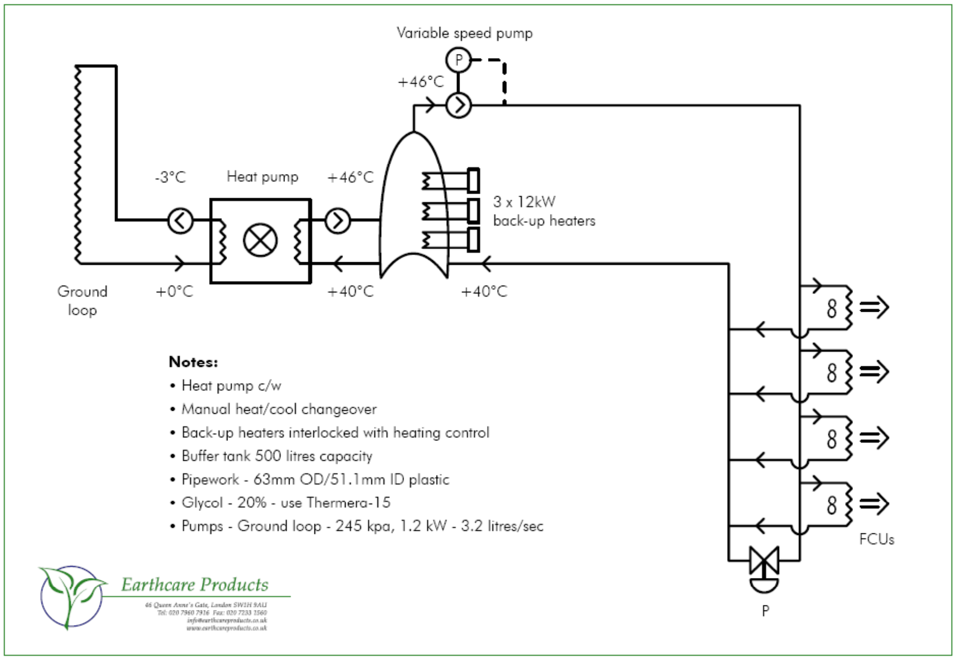

Figure 8.1: System Schematic

9. Control Scheme

Each fan coil has a factory fitted four port valve and controller suitable for two pipe heating application, i.e. one stage heating, one stage cooling, with strap-on heat pump sensor to prevent heating in cooling mode and vice versa.

The control panel in the plant room includes a time clock facility and frost protection to run the system when internal ambient temperatures drop below 10°C.

10. System Installation

Externally, it was intended that fifteen 50m long, deep slit trenches to accommodate vertical slinky coils be dug in the adjacent farmer's field. In practice, the trenches had to be dug shallower and wider than originally intended (1.2m deep and 1m wide) because the soil type meant that the trenches had a tendency to collapse. The pipework was arranged into ‘slinky coils’ 1m in diameter, as shown in figure 10.1, and laid horizontally at the bottom of the trenches, as shown in figure 10.2.

Figure 10.1: Slinky coils prior to installation

Figure 10.2: Slinky coils laid horizontally in trench

Inside the building, the heat pump was installed in the cleaner's storeroom, which allowed the pumps, electrical and heat pump plant to be housed in one self-contained plantroom. The fan coils were installed where the night storage heaters had previously been situated.

11. Safety Issues

The flammability data for propene is shown in Table 11.1, as a consequence, it was necessary that the heat pump complied with relevant safety standards affecting the use of hydrocarbon refrigerants, namely:

- Highly Flammable liquids and Liquefied Petroleum Gases Regulations (1979);
- UK HSE Guidance Booklet HS (G) 3 – Highly flammable materials on construction sites;
- ACRIB Guidelines for the use of Hydrocarbon Refrigerants in Static Refrigeration and Air Conditioning Systems.

The heat pump itself already included several specific safety measures:

- all electrical components adjacent to the heat pump chiller sealed to IP54 standard and isolated from the refrigeration system;
- safety labelling applied to the heat pump and compressor;
- all heating element thermal cut outs set below the flash point of the refrigerant;
- pressure relief devices commissioned so as not to cause additional hazards to fire fighting personnel;
- the overall design of the system avoided dead spaces where a leaked heavier than air refrigerant could accumulate.

In addition, the following procedures were adhered to:

a) The system was pressure tested to 400 PSIG using oxygen-free nitrogen and then triple evacuated down to 1 Tore pressure prior to refrigerant being introduced to the system.
b) Commissioning was carried out by a hydrocarbon registered refrigeration engineer, in compliance with:
    - BS 4434 (withdrawn)
    - BS EN 378
    - Institute of Refrigeration Code of Practice for A3 Refrigerants
c) Safety labelling was put in clear and visible locations in the plant room.
d) A leak detector was fitted in the plantroom.
e) A transfer grille was fitted through the floor of the plantroom to prevent the build up of any heavier than air gas.
f) Permanent ventilation was fitted to the case of the heat pump using a spark proof extract fan.

Substance	*Refrig. No.*	*Flammability limits*		*Toxicity (exposure limits)*		*Practical limit (kg/m^3)*
		Lower	*Upper*	*LTEL*	*STEL*	
Propene	R1270	2.5	10.1	1000	1250	0.008

Flammability limits as % volume in air.
Toxic exposure limits given in PPM, LTEL = Long-term exposure limit (8-h Time Weighted Average) STEL = Short-term exposure limit (10-min).
Classified as an asphyxiant.

Table 11.1: Flammability & Toxicity Data

12. Operating Outcomes

The council have been very diligent in recording energy consumption at the school over the last few years. Unfortunately, a full comparison between the energy consumption of the old and new systems has not yet been possible due to a number of teething problems, namely:

- the time clock was not operational until the 24th January, 2004 – before this date, the heat pump was running 24 hours a day, 7 days a week;
- the immersion heaters had to be turned down slightly to avoid conflict with the heat pump;
- the fan coil thermostatic controllers had to be replaced in mid-April 2004 as the original integral controls were sensing cold drafts rising up through the uninsulated floor. The new controls should lead to better control of heating and cooling, therefore leading to reduced energy consumption.

Nonetheless, recent months have shown consumption figures in line with expectations so we look forward to studying full-year data in due course.

14. Environmental Outcomes

As mains electricity is only about 30% efficient as a means of transferring energy from the power station, a heat pump must achieve a COP of at least 3.3 before any net environmental benefit is gained, assuming no environmental disbenefit is incurred by the use of synthetic refrigerants such as HFCs. Using this logic, we can safely surmise that the COP of 4.3 achieved at Buntingsdale Infant School results in one unit of renewable energy for every unit of electricity consumed. When used with renewable power sources, heat pumps become energy amplifiers. Thus, this system would provide the equivalent thermal capacity of 4.3m^2 of solar PV panel for each m^2 utilised or 43kW of thermal output for every 10kW wind turbine utilized. Therefore, it is a viable alternative technology, which should not be overlooked in the quest for fossil fuel replacements.

15. Problems and Successes

Since eradicating initial snags, the project has been a resounding success. However, costs were higher than expected and as such form the most important criticism of the project. Horizontal slinky closed loop systems require a lot of land and the ground works can be expensive. Costs and programming would have been drastically reduced had the site been “new-build” and the ground works integrated within the whole project. Alternatively, an open loop system could be used, delivering even higher COPs, which in turn would help to improve the economic viability of the project. For example, the standing well column method requires the use of only one borehole rather than two, cutting costs significantly.

Where a closed loop is required and the project is “new build”, we would advocate energy piles, i.e. burying the closed loop in the building foundation piles, an approach frequently used in Austria.

Finally, there is still work to do on refrigerant optimisation, which might profitably use the beneficial properties of temperature glide with propane/ethane zeotropes to improve heat pump performance.

16. Conclusions

Old lessons have been re-learnt: commissioning complex heating systems is not a one off event but a reiterative process taking many months; a good controls system is crucial to a successful project; cost effectiveness is still a major barrier to be overcome in the majority of projects where this technology would be suitable.

However, this project has demonstrated that the technology is practical, feasible and can be improved further. For instance, if the COP can be raised to 5.3 then two units of renewable energy could be delivered for every unit of electricity consumed. This is a reasonable target given that COPs of up to 6.0 are achievable using currently available commercial technologies

In the next 15 years, worldwide demand for energy is forecast to increase by 75%[6]. Building services will account for around 45% of this figure. This scenario is wholly unsustainable using fossil fuel combustion technologies. In this short presentation, I

[6] Prof. James Lovelock, 24th May 2004

have sought to suggest one possible alternative technology, which could provide a sustainable heating solution in some applications. Although the concept of ground source heat pumps is not new, the fact that the emerging heat pump market relies heavily on environmental rather than economic drivers makes it difficult to see how a mass market in heat pumps can be achieved using HFC refrigerants, which are increasingly targeted as unsustainable by both environmentalists and governments. I hope, therefore, that I have outlined both the possible advantages and hurdles that are faced when using natural working fluids such as hydrocarbons in ground source heat pump applications.

17. References

1. OFSTED Inspection Report (Inspection number: 248449)
2. John Willoughby's Domestic Fuel Price Guide No. 27, April 2003
3. SAP, 2001
4. IPCC 3rd Assessment Report, 2001
5. The Edinburgh Centre for Carbon Management, 'Estimation of Carbon Offset by Trees', ECCM Technical Document No. 7, March 2000
6. Prof. James Lovelock, speech quoted in Daily Telegraph 24th May 2004