Groundwater heat pumps and aquifer heat storage

Research Report SD/90/1
Hydrogeology Series

British Geological Survey

Research Report SD/90/1

Groundwater heat pumps and aquifer heat storage

R Kitching, T R Shearer and B Adams

BRITISH GEOLOGICAL SURVEY

RESEARCH REPORT SD/90/1

Hydrogeology Series

Groundwater heat pumps and aquifer heat storage

R Kitching, T R Shearer and B Adams

Cover photos

Groundwater heat pumps installed in glasshouses at Reach, Cambridgeshire

Geographical index

United Kingdom

Subject index

Groundwater, hydrogeology, aquifers, heat pumps

Maps and diagrams in this report use topography based on Ordnance Survey mapping

Bibliographic reference

KITCHING, R, SHEARER, T R, and ADAMS, B. 1992. Groundwater heat pumps and aquifer heat storage. *British Geological Survey Research Report* SD/90/1.

ISBN 0 85272 195 1

Keyworth, Nottingham British Geological Survey 1992

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available through the Sales Desks at Keyworth and at Murchison House, Edinburgh, and in the BGS London Information Office in the Natural History Museum Earth Galleries. The adjacent bookshop stocks the more popular books for sale over the counter. Most BGS books and reports are listed in HMSO's Sectional List 45, and can be bought from HMSO and through HMSO agents and retailers. Maps are listed in the BGS Map Catalogue, and can be bought from Ordnance Survey agents as well as from BGS.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG
☎ Nottingham (0602) 363100 Telex 378173 BGSKEY G
Fax 0602–363200

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 031–667 1000 Telex 727343 SEISED G
Fax 031–668 2683

London Information Office at the Natural History Museum Earth Galleries, Exhibition Road, South Kensington, London SW7 2DE
☎ 071–589 4090 Fax 071–584 8270
☎ 071–938 9056/57

19 Grange Terrace, Edinburgh EH9 2LF
☎ 031–667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ Exeter (0392) 78312 Fax 0392–437505

Bryn Eithyn Hall, Llanfarian, Aberystwyth, Dyfed SY23 4BY
☎ Aberystwyth (0970) 611038 Fax 0970–624822

Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HB
☎ 091–281 7088 Fax 091–281 9016

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ Belfast (0232) 666595 Fax 0232–662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ Wallingford (0491) 38800 Telex 849365 HYDROL G
Fax 0491–25338

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ Swindon (0793) 411500 Telex 444293 ENVRE G
Fax 0793–411501

Printed in England for the British Geological Survey by Derry and Sons Limited, Nottingham

FOREWORD

Dwindling fossil fuel resources leading to recent rises in the price of fossil fuels have highlighted the need for energy conservation and the requirement to investigate energy-efficient methods of space heating. Furthermore, increased concern for the environment dictates that advances in this field should be non-polluting and environmentally acceptable.

Recent studies commissioned by the Department of Energy have indicated that by the year 2000 the most energy-efficient means of generating electricity and providing space heating for our major cities is likely to be Combined Heat and Power Stations linked with Large Scale District Heating Schemes. Such schemes will need energy storage components which could be provided by aquifer heat storage.

The work reported on in this investigation has concerned the role of aquifers in improving energy efficiency. Two aspects have been investigated, namely the use of groundwater heat pumps in making use of renewable energy resources and the use of aquifers for energy conservation by storing waste heat and useful heat produced at times when there is no demand. The report covers fieldwork and modelling studies undertaken by the British Geological Survey Hydrogeology Research Group during the period 1980–1988 relating to trials of groundwater heat pumps and storage of energy in aquifers.

The research was funded from NERC/BGS Science Budget. Numerous individual reports and papers have been produced on different aspects of the work. This final report covers the total activity during the project.

We wish to acknowledge the valuable assistance afforded by the South of Scotland Electricity Board, Eastern Electricity Board, Irvine Development Corporation and many private industries and companies together with colleagues from the British Geological Survey who have provided geological and hydrogeological background information.

EXECUTIVE SUMMARY

This report covers fieldwork and modelling studies undertaken during the period 1980–1988 relating to trials of groundwater heat pumps and storage of energy in aquifers.

Groundwater and ground-coil heat pump systems were tested in a glasshouse environment. They performed reliably and maintained adequate temperatures with high efficiency. In particular the directly pumped groundwater system yielded a coefficient of performance (C.O.P.) of greater than 2.5. When used with a diurnal energy store the efficiency was further increased. In a second investigation, a groundwater heat pump was installed in a terraced house in Scotland and yielded a C.O.P. of 2.8.

The high efficiency of groundwater heat pumps together with their energy conservation potential are features that will commend them at a time when protection of the environment is becoming increasingly important.

The results of a trial energy storage experiment in East Anglia are reported together with computer simulations. Additional modelling studies indicate that energy recovery rates of 60–80% may be possible in large-scale energy storage schemes. Although Aquifer Thermal Energy Storage is only used at present experimentally at a few locations throughout the world, it is likely that it will be seen increasingly as an environmentally sound method of increasing the efficiency of energy use whilst significantly decreasing the necessary investment associated with power generation.

1. SCOPE OF THE REPORT

This report covers field work and modelling studies undertaken by the Hydrogeology Research Group of the British Geological Survey during the period 1980–1988 relating to trials of groundwater heat pumps and storage of energy in aquifers.

1.1 Introduction

Rapid rises in the price of fossil fuels in the early 1980's necessitated a reappraisal of the methods of space heating in industry, horticulture and the home. The use of heat pumps, which are energy efficient, has become more economically viable and with the advent of models that can be used with groundwater, field trials were required to evaluate the use of aquifers to supply these devices. Shallow groundwater has the advantage of being available in many parts of the UK and remains at a usable temperature throughout the winter, when heating is most needed.

Furthermore the need for energy conservation has indicated the requirement for research into new and improved methods of storing waste heat and diurnal heat produced out of phase with demand. Thermal Energy Storage (TES) offers the opportunity for the recovery and reuse of heat currently rejected to the ambient environment. By matching a waste energy supply with a thermal energy demand, TES improves the efficiency and capacity factor of generation plant. The storage of hot water in aquifers is a system that offers considerable potential in the energy conservation field. The work described in this report is the first step towards application of the technique on a larger scale.

2. GROUNDWATER HEAT PUMP TRIALS

2.1 The Use of Groundwater Heat Pumps to Heat Glasshouses at Reach, near Cambridge

2.1.1 *Introduction*

The use of heat pumps has now become economically viable in some circumstances. Such heat pumps extract heat from a low temperature source such as ambient air or water and supply that heat at a higher temperature suitable for space heating. The heat pump requires some input energy (e.g. electrical) to achieve the transfer of heat to the higher temperature level but in general the total heat output is greater than the electrical input.

The domestic refrigerator is a good illustration of the practical application of the heat pump principle. In this case, the low temperature source of heat is the food within the refrigerator and the higher temperature sink is the radiator usually at the back of the cabinet which radiates warmth while the compressor is working. Electrical energy is supplied to the compressor to achieve this transfer of heat from the inside to the outside.

Figure 1 shows the layout and basic components of a groundwater heat pump used for space heating. The refrigerant fluid (typically freon) flows around a closed circuit between the compressor and expansion valve via the two heat exchangers. These heat exchangers have large surface areas to achieve efficient transfer of heat between the input and output media. Groundwater at about 10°C flows through the primary circuit of the first heat exchanger (evaporator) and is cooled by the cold refrigerant vapour in the secondary coil. After receiving heat from the groundwater, the refrigerant fluid is compressed, which raises its temperature and causes it to condense in the second heat exchanger (condenser). Heat given out during the condensation process passes to the space heating medium (air or water) in the secondary coil of the condenser. The refrigerant then passes through the expansion valve which cools and vaporizes it in the evaporator ready to begin the cycle again.

The ratio of total heat output to total electrical energy input is known as the coefficient of performance or

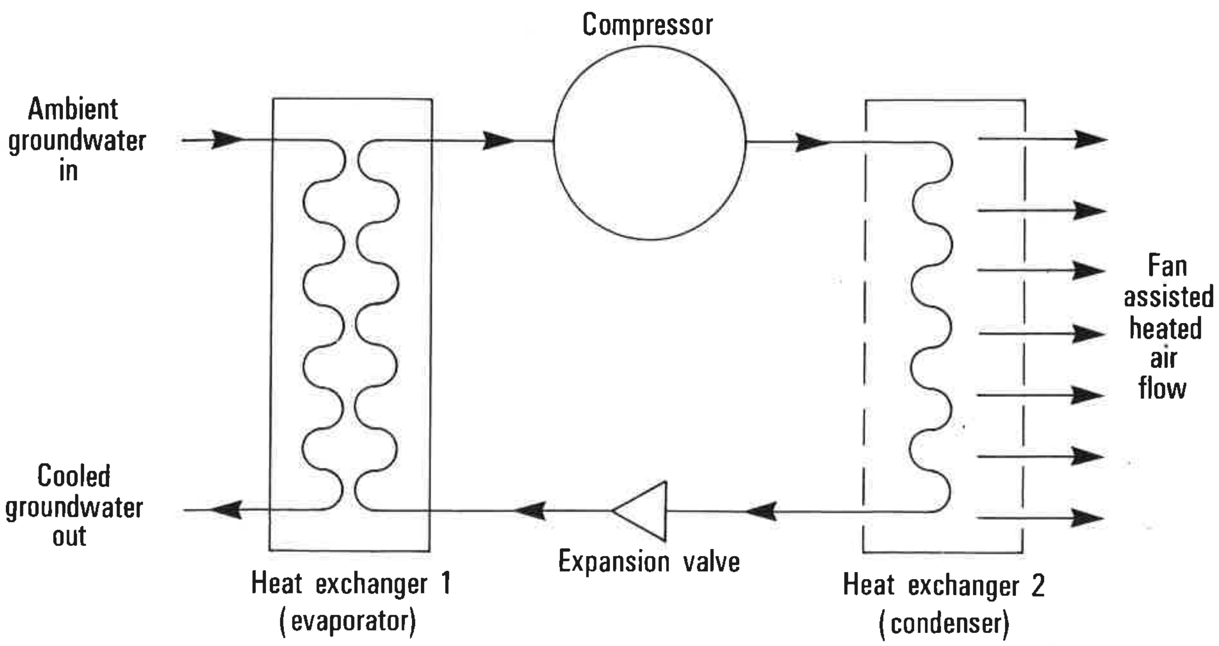


Figure 1 The principle of the groundwater heat pump.

C.O.P. A typical value of C.O.P. is 3, so that for every three units of heat supplied only one unit of electricity is used.

The C.O.P. or efficiency of the heat pump is inversely proportional to the temperature difference between the source and the sink of heat. Thus an air source heat pump becomes less efficient as the ambient air temperature falls and the efficiency is lowest at the time of peak heat demand. Furthermore, air source heat pumps require regular defrosting at lower ambient temperatures, which reduces their efficiency considerably.

Groundwater source heat pumps do not suffer these disadvantages as groundwater temperatures are almost constant throughout the year. It is therefore possible to achieve high efficiencies (C.O.P. = 3) even when the ambient air temperatures are low.

The availability of off-peak electricity to drive a highly efficient groundwater heat pump at night when glasshouse space heating demand is greatest led BGS to set up a small project to investigate the feasibility and economics of groundwater heat pumps in glasshouses.

2.1.2 *Experimental details*

Three glasshouses (Robinson Model 1024) approximately 7 m × 3 m each were erected at a site near Reach, Cambridgeshire (Figure 2). The geological profile here is represented by the borehole section shown in Figure 3. Two aquifers suitable for supplying groundwater to heat pumps are available on this site.

1 The Lower Chalk within about 5 metres of the ground surface, with a water table at about 2.5 metres below surface.

2 The Lower Greensand located at approximately 35 – 48 metres below ground surface.

For the first heat pump project at the site, the shallow but prolific Chalk aquifer was selected as drilling and pumping costs were minimal. A supply borehole was drilled to a depth of 6 metres at a diameter of 24 cm in a trench 6 metres long and 3 metres deep, backfilled with gravel, to act as a collector.

The heat pumps installed in the glasshouses were TETCO type HECWE-042 Water to Air units with a nominal output of 10/12 KW. They were fitted with variable speed fans and ducting capable of supplying air at 1000 cubic feet per minute at approximately 35°C. The heat pump installed in glasshouse A was supplied directly with groundwater from a submersible pump in the adjacent borehole at a rate of approximately 30 litres/minute. In passing through the evaporator of the heat pump the groundwater was cooled by approximately 3°C and was discharged on the hydraulic downstream side of the aquifer.

The heat pump installed in glasshouse B was identical to that in A but was fed from a closed loop groundcoil system installed at a depth of 3.0 metres below ground surface and at least 0.5 metres below the water table. The coil was constructed of 25 mm. internal diameter, 33 mm. external diameter class C alkathene pipe 300 metres long and covering a ground area of 300 m². A Grundfoss GP2/70K pump was used to circulate 25% ethylene glycol antifreeze solution in the groundcoil/heat pump circuit, the rate of flow being approximately 40 litres/minute with a 2°C temperature drop across the evaporator.

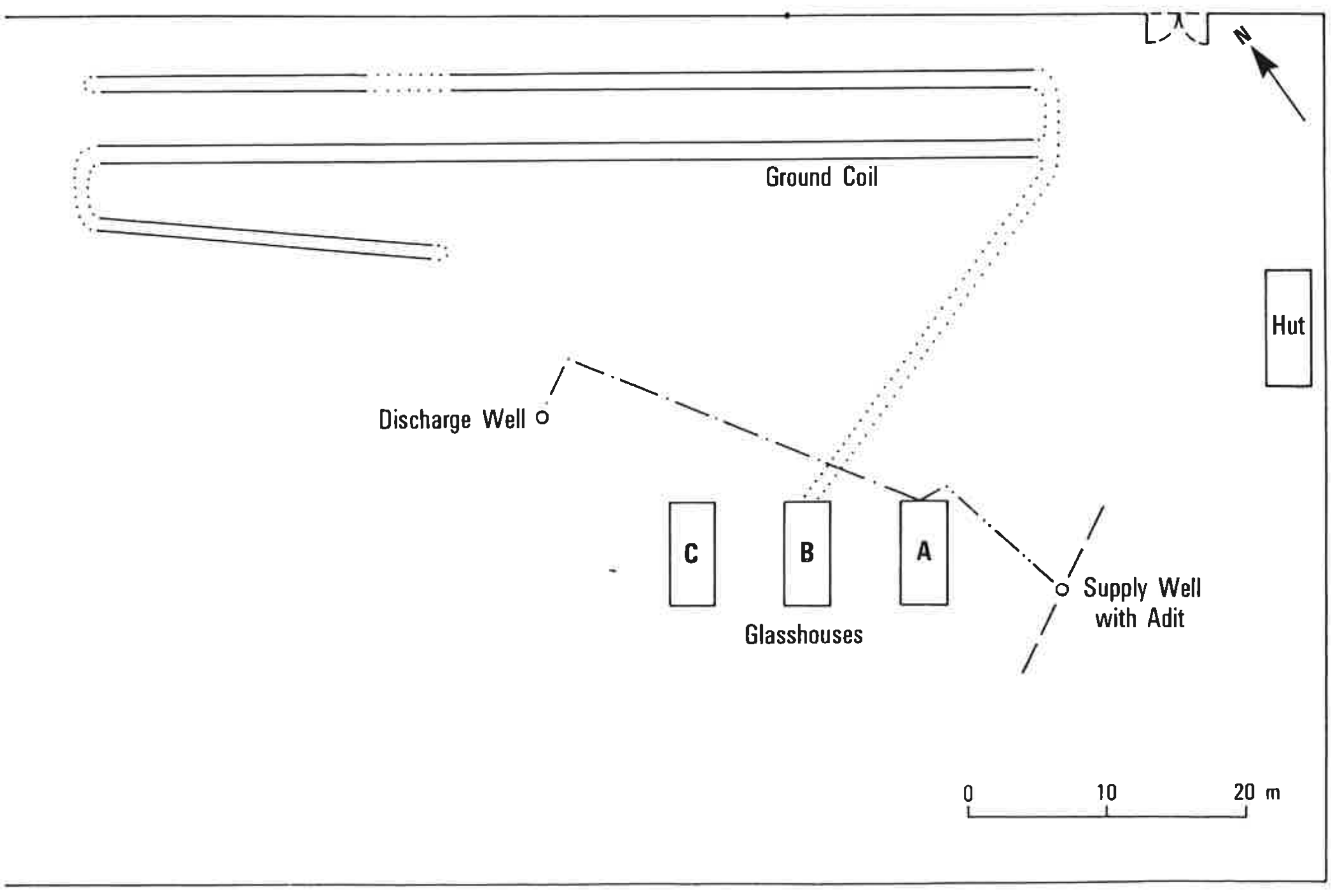


Figure 2 Reach heat pump project site plan.

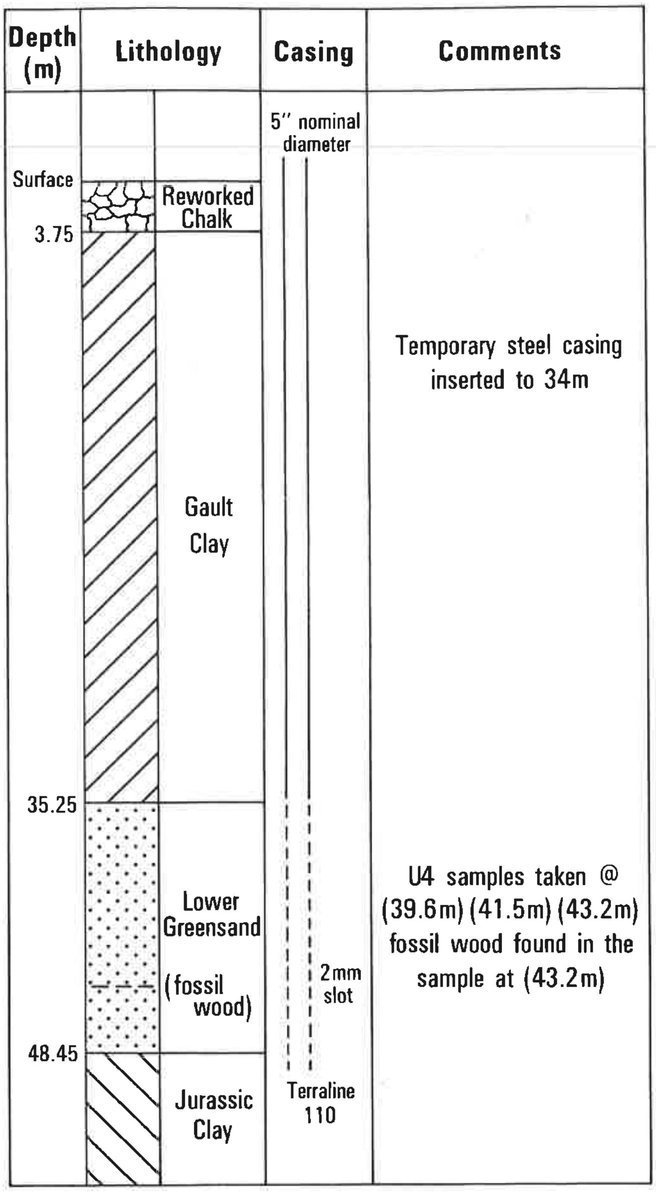


Figure 3 Borehole log at Reach research site, Cambridgeshire.

Glasshouse C was fitted with an electrical resistance heating system plus fan to simulate the air flow distribution in the other glasshouses and to provide a control for comparison of energy consumption with the heat pumps.

For the period December 1980–October 1981 the glasshouses were fitted with thermostats to control the temperature at approximately 19°C. From November 1981 a microcomputer system was introduced to control the operation of the heat pumps and to log the results of the experiment. The following parameters were monitored:

i Internal temperatures of all three glasshouses.

ii External air temperatures.

iii Groundwater temperatures.

iv Flow and return temperatures for the evaporators of the heat pumps.

v Water and antifreeze flow rates to the heat pumps.

vi Times of operation of the heat pumps.

The above parameters were logged at one minute intervals, hourly and daily summaries being produced by the microcomputer and stored on disk.

Manually read KWH meters and water flow meters provided a ready check on the total power and water use of the heat pumps over longer periods.

2.1.3 *Results*

The data logger was commissioned in November 1981 and difficulties with the computer caused some breaks in operation in the first few months. Figure 4 shows the performance of the systems in the three glasshouses for the continuous period 29 January to 14 April 1982. This period included cold spells with minimum temperatures well below zero. The mean daily internal air temperature in glasshouse A was maintained at about 20°C throughout the period without difficulty. The groundwater input temperature during this period was about 9°C and the drop across the heat pump was 2–3°C.

The lower drop of 2°C during the period 6 February to 11 March 1982 was due to the use of a submersible borehole pump with a higher pumping rate, the rate of extraction of heat from the groundwater being nearly constant for the whole period.

The groundcoil heat pump in glasshouse B was also able to maintain a temperature approximately 20°C for most of the period but during the cold spells it had to work very hard and the flow and return temperature of the antifreeze solution declined to a minimum at the end of February.

The electrical resistance heating system in glasshouse C proved incapable of maintaining and simulating accurately the temperature distributions in A and B for the whole of the period. It also suffered breakdowns due to overheating of the fan.

Table 1 compares the performance of A and C for the period 23 March to 6 April 1982, when similar mean temperatures were maintained and a direct comparison was possible. The C.O.P. of the heat pump using direct groundwater (A) has been calculated in two ways. Firstly by a direct comparison with the power consumed by electrical resistance heating (C) giving a C.O.P. of 2.5. Secondly from the equation:

$$\text{C.O.P.} = \frac{\text{Heat extracted from water} + \text{total power consumed} - \text{submersible pump power consumed}}{\text{total power consumed}}$$

which yields a C.O.P. of 2.67.

Table 2 shows the performance of glasshouse A for the longer period 29 January to 14 April 1982, covered by Figure 4. The C.O.P. of A for this period calculated from the power consumed and heat extracted from the water was 2.52. Direct comparison with C was not possible for this period due to the glasshouse temperature not being comparable.

Table 3 compares the performance of glasshouses B and C for the period 23 March to 6 April 1982, when reasonably similar mean temperatures were maintained. The C.O.P. of the groundcoil heat pump in B is 1.71 by direct comparison with the electrically (resistance) heating house C. This figure is not as reliable as for glasshouse A as it has not been possible to check it by a second method.

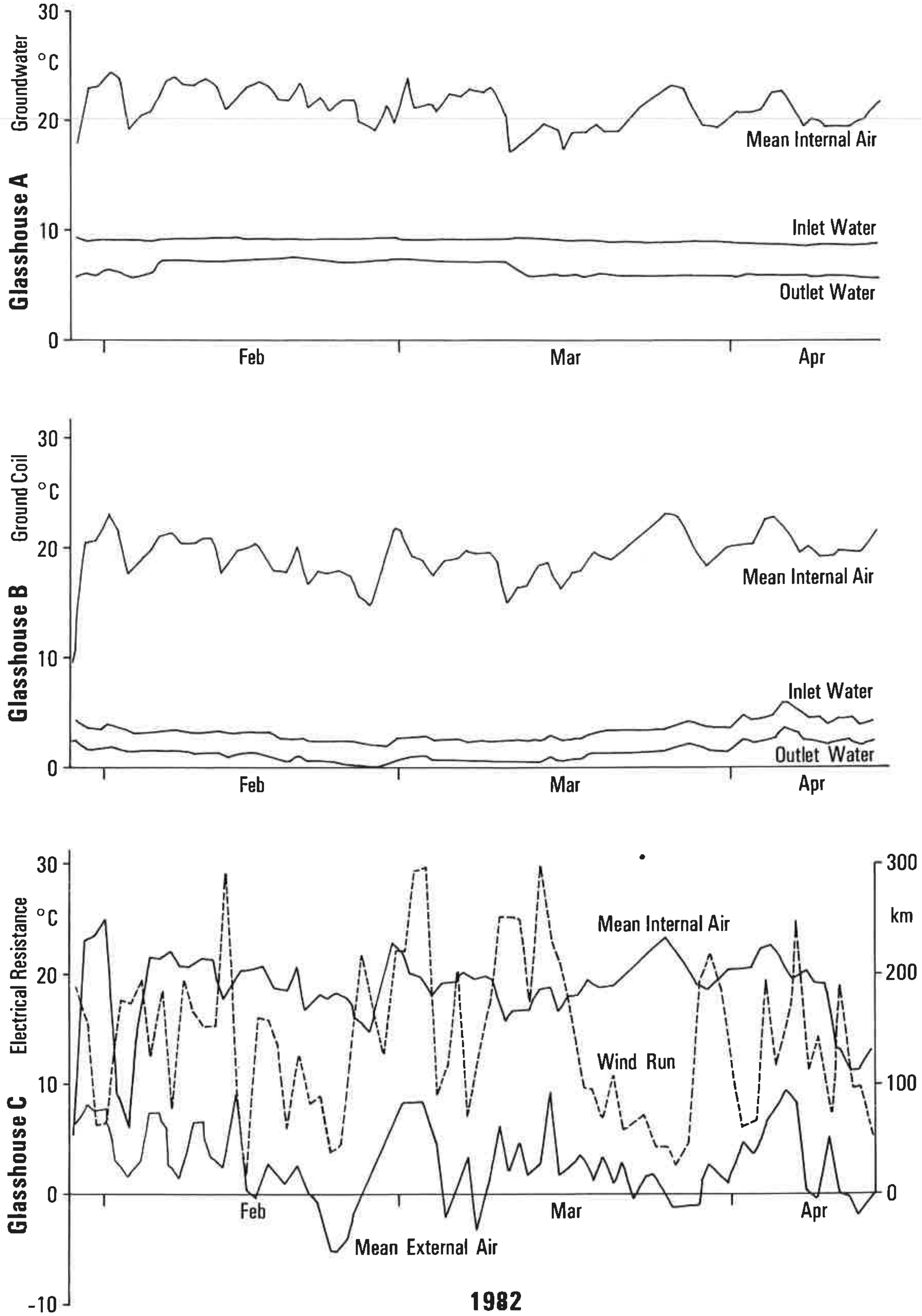


Figure 4 Glasshouse temperatures at Reach heat pump research site for the period 29 Jan – 14 April 1982.

Table 1 Comparison of glasshouses A and C at the Reach heat pump site for the period 23 March to 6 April 1982

Glasshouse	A	C
System	Heat pump plus direct ground-water	Electrical resistance
Total power consumption KWH	412	1022
Mean temperature °C	20.95	20.95
Submersible pump Consumption KWH	69	—
Total water flow m³	221	—
Total hours running	135	168
C.O.P.	2.67	1.00

Table 2 Performance of glasshouse A at the Reach heat pump site for the period 29 January to 14 April 1982

Glasshouse	A
System	Heat pump plus direct groundwater
Total power consumption KWH	4083
Submersible pump consumption KWH	968
Total water flow m³	2664
Total hours running	1266
Heat from water KWH	7165
C.O.P.	2.52

Table 3 Comparisons of glasshouses B and C at the Reach heat pump site for the period 23 March to 6 March 1982

Glasshouse	B	C
System	Heat pump plus groundcoil	Electric resistance
Total power consumption KWH	596	1022
Mean temperature °C	20.90	20.95
Total antifreeze flow m³	2664	—
Total hours running	166	168

2.1.4 *Conclusions*

Both the groundwater and the groundcoil heat pump systems have performed reliably and maintained adequate temperatures in the glasshouses; they have yielded good values of C.O.P. (efficiency). In particular the directly pumped groundwater system has operated at a C.O.P. of greater than 2.5 checked by two methods. Further improvements in C.O.P. of the groundwater-fed systems are to be expected from the use of high efficiency submersible pumps which are now becoming available, and it is thought that enlargement of the diameter of the groundcoil and the use of a more efficient circulating pump might likewise improve the C.O.P. of the groundcoil system.

2.2 The use of a groundwater/water heat pump with diurnal energy storage

2.2.1 *Introduction*

Following the successful trials of the water/air heat pumps in the glasshouses at Reach, one of these was replaced with a similar water/water machine of comparable capacity together with a large hot water storage tank which permitted the daily heating requirements to be largely met by heat pump operations at night utilising cheap rate electricity. This was expected to return an even greater economic efficiency.

2.2.2 *Experimental Details*

The heat pump used was a TETCO HEWTW-050-C water-to-water unit manufactured by the Thermal Energy Transfer corporation of Powell, Ohia, USA. It operated from a 240 v, 50 Hz, single-phase electricity supply. The nominal power consumption was 3 kw and the nominal heat output was 10 kw.

The heatpump was a water-to-water unit. The output heat exchanger (the condenser) provided hot water for a secondary plumbing system. This included a circulating pump and a system of valves that allowed the heat to be pumped either directly to a network of conventional domestic hot water radiators or to the hot water storage tank. The same pump and valves permitted heat to be supplied to the radiators from the storage tank with the heat pump off (Figure 5).

There were six radiators in the secondary circuit, arranged in two rows, three along each side of the glasshouse. They were mounted on the inner sides of white melamine clad panels situated 50 cm from the walls to minimise heat loss by direct radiation through the glass. Each radiator was a Warmastyle Ltd DD/C10 double panel convector 700 mm high and 1944 mm long with a nominal output of 4.27 kw. This rating assumed however a mean water temperature of 80°C and a mean room temperature of 20°C. As it was known that high output temperatures from the heat pump have an adverse effect on the C.O.P., the heating system was sized for a temperature difference of 25°C when the rating of the radiators was reduced to one third. Thus together with the heat likely to be given off by the electrical components of the system the heat output was expected to total around 10 kw. This had proved adequate to heat the glasshouse during the previous experiment with air output heat pumps except in extreme conditions.

The hot water storage tank had a nominal capacity of 2.7 m³. It was supplied by Cambrian Plastics Ltd of Bridgend, Wales, and consisted of a 1.2 m diameter filament wound GRP cylinder, 2.3 m long including the

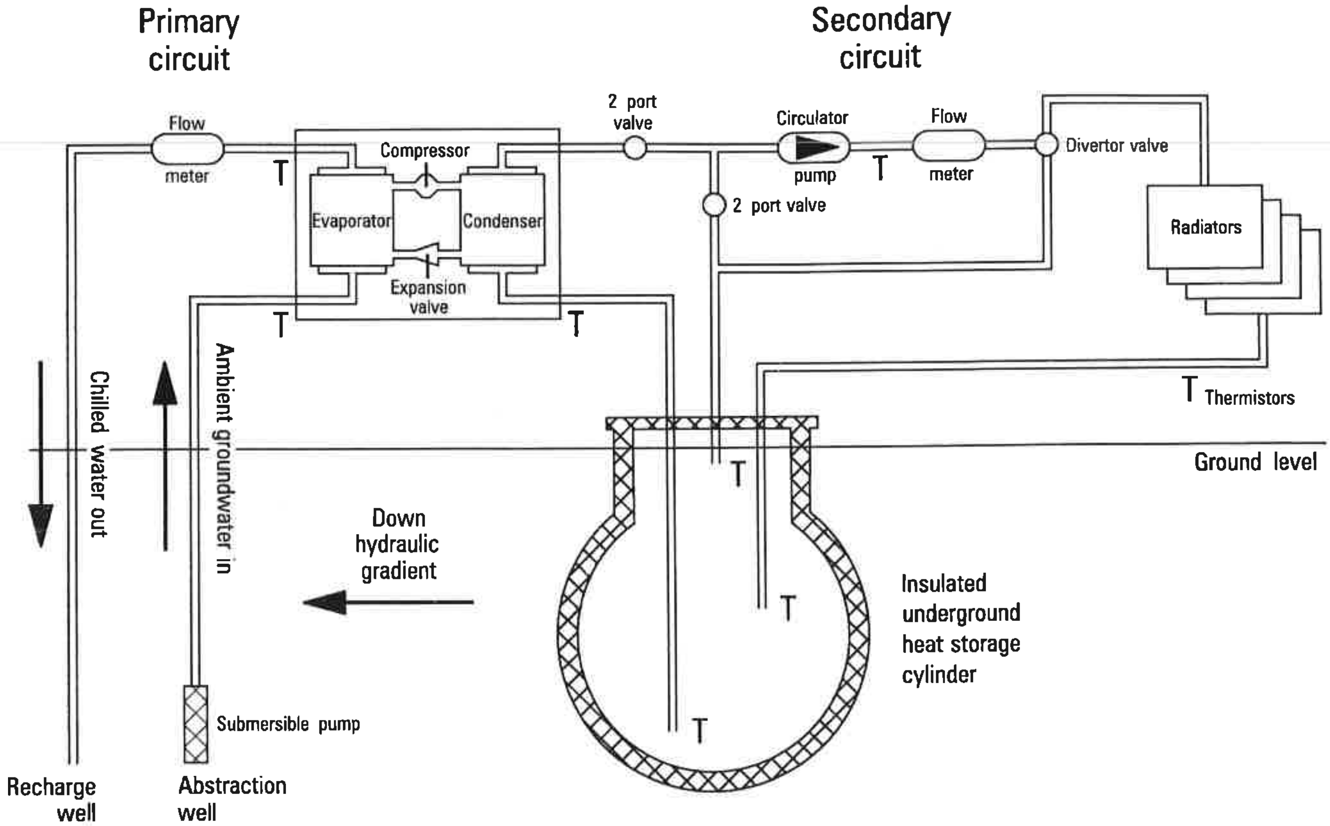


Figure 5 Water to water heat pump with heat storage cylinder.

domed ends. It had 50 mm of polyurethane foam insulation encapsulated in the laminate. This limited the thermal transmittance ('U' value) to 0.43 W/m^2 °C/hr. The cylinder was buried adjacent to the glasshouse with the top of its 600 mm diameter, 800 mm long, access shaft flush with ground level. The secondary plumbing circuit had connections at the top, middle and bottom levels of the heat store so that water could be added or removed from the warmest and coldest part as appropriate to the particular heating mode in use (Figure 6).

As the site was not normally manned the operation of the heat pump was controlled by an Apple II + microcomputer which also logged the various operating parameters. The computer was fitted with two Aughton ADC 1612 (16 channel, 12-bit) analogue-to-digital interfaces to measure variables such as temperature, water flow and power consumption and control was effected by an Interactive Structures DI09 32-channel digital input/output port which also monitored the status of several heat pump interlocks.

The air temperature within the glasshouse was measured by three thermistors mounted along the axis of the house at 1.5 m above floor level. The microcomputer controller was set to maintain a mean air temperature of 19°C throughout the 24 hours. How this was achieved was determined by the time of day, i.e. which electrical tariff applied. During the night (the economy electrical tariff period) if the air temperature fell below the set point the heat pump was switched on and the valves and pumps actuated to supply the hot water produced directly to the radiators.

The heat pump was supplied with the coldest water from the bottom of the tank and the still somewhat warm water leaving the radiators was re-injected into the middle level of the tank. When the temperature was restored to above 19°C the heat pump continued in operation but the valves were re-set so that the hot water was input to the top of the storage tank. No water flowed through the radiators. If the heat pump was in this mode of operation at the end of the economy tariff period it was switched off.

During the day (the standard electrical tariff period) if the glasshouse air temperature fell below 19°C the heat-pump was not switched on immediately. Instead the valves and circulation pump were actuated so that hot water was drawn off at the top of the storage tank and passed through the radiators before being returned to the middle level of the tank. Only if the temperature fell below 18°C was the heat pump switched on during the day for directly heating the radiators.

Once an operating mode had been initiated by the computer it was maintained for a minimum of 5 minutes to prevent adverse short-cycling effects. This simple operating logic was overridden by a software cut-out which switched the heat pump off until the end of the tariff period if the output temperature of the heat pump rose above 50°C. At this point either the whole storage tank was full of hot water or the flow rate in the secondary had unexpectedly reduced and there would be a danger of the heat pump's refrigerant pressure lock-outs tripping out. This would have de-activated the system until the next manned visit.

The operating logic was kept deliberately crude as the storage capacity of the computer's disks did not permit a sufficiently detailed record of the system working to be kept to allow adequate analysis of more sophisticated functions. However, it was clearly not ideal that the system generally permitted more heat to be stored on warm nights (which are likely to be followed by warm days) than on cold nights when more of the heat pump's capacity was required immediately. This led to heat being stored for longer periods than originally envisaged and because the insulation of the tank was not absolute some

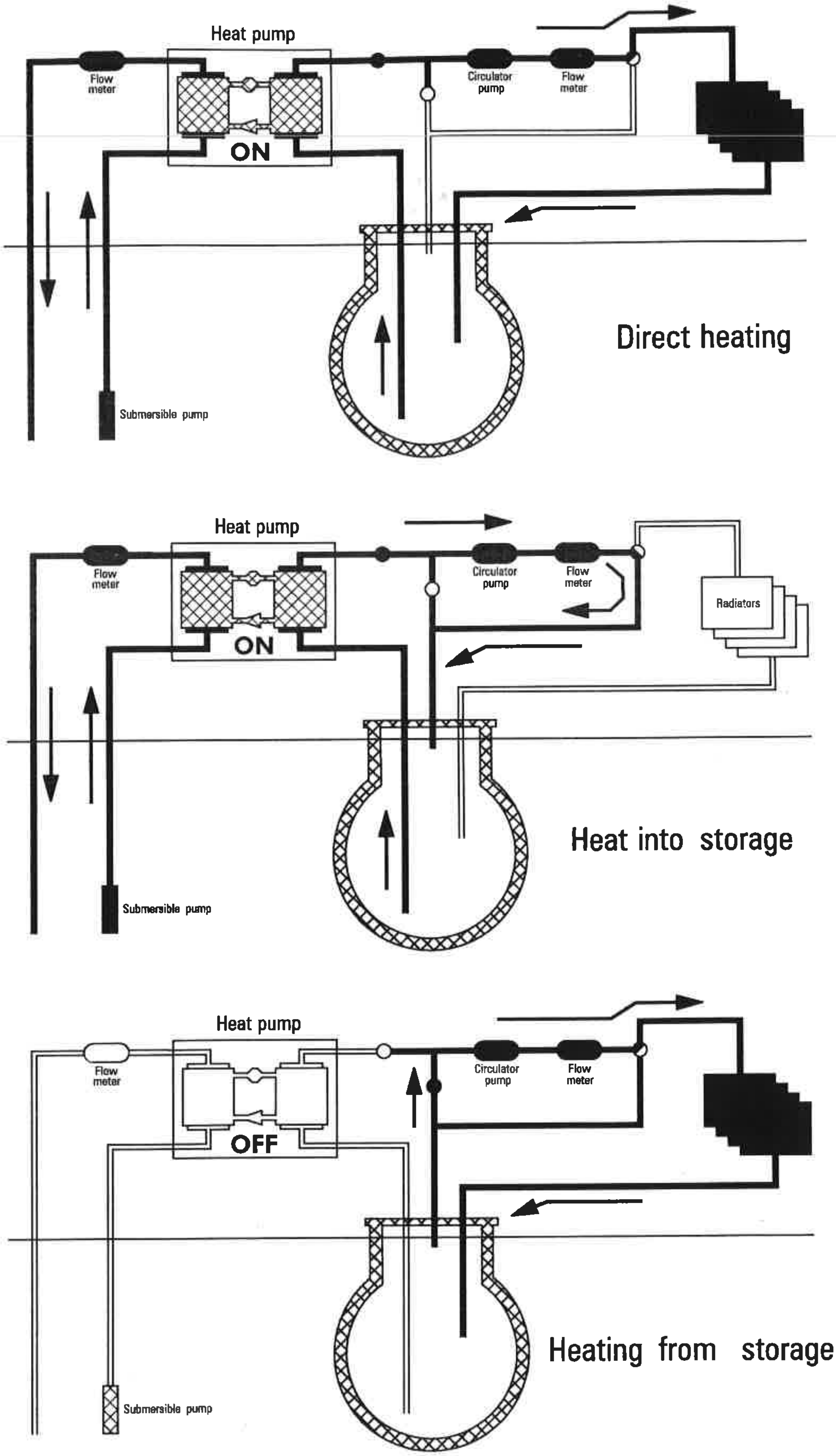


Figure 6 Operating modes for water to water heat pump with heat storage cylinder at Reach, Cambridgeshire.

of this heat was lost to the environment. It would be much better if it were possible to incorporate some means of anticipating fairly precisely the heat requirements of the heatload for the following day. Predicting the heat demand of a glasshouse is particularly difficult. They have little insulation, minimal thermal mass, and generally an inadequate degree of air-tightness which renders them very vulnerable to meteorological variations, particularly at such an exposed site as Reach at the edge of the Fens. This problem was exacerbated by the innate ability of glasshouses to capture large amounts of solar radiation by the greenhouse effect. Much could be gained in circumstances that permitted daily manual control related to short term weather forecasts.

The heat pump was installed during the winter of 1984/85 and was first operated in February 1985. It then ran until May when it was switched off for the summer. Heating was restarted in late September but a number of minor problems with the secondary plumbing circuit prevented normal operations until the beginning of December. It then performed reliably until the end of May when it was again switched off for the summer.

The early operating experience indicated that the insulation on the heat storage cylinder was inadequate, particularly around the manhole shaft and cover. Extra insulation was added in mid-November 1985 in the form of 75 mm (approx) polyurethane foam cast in-situ around the shaft and 100 mm (approx) glassfibre blanket over the manhole shaft which was also housed in a wooden enclosure. These measures reduced the heat loss throughout the water in the tank to one third of the original with a particularly noticeable effect at the top of the tank thereby conserving the highest grade energy in the system.

After the addition of the extra insulation the heat loss from the tank was 5 watts/°C above ambient groundwater temperature. It was likely that this would reduce as the ground in the immediate vicinity of the tank was warmed by the escaping heat. However, it was obvious through the winter of 1985/86 that heat was still being lost to the atmosphere immediately above the tank and that it would be preferable to install the heat store directly below the heat load.

2.2.3 *Results*

When the heat pump was supplying heat directly to the radiators, it consumed a total of 2.96 kw of electricity: 2.52 kw of this were used by the compressor and the circulating pump and valves of the secondary plumbing circuit. As these are housed within the glasshouse their power was eventually dispersed as useful heat within the heat load.

The remaining 0.44 kw was taken by the submersible pump mounted in a borehole outside the glasshouse. Some of this energy was, however, recovered in the form of a raised groundwater input temperature. The primary input water was generally 1°C hotter than the ambient groundwater temperature. The primary flow rate was 18.25 l/min and the temperature drop across the evaporator averaged 4.3°C. Thus, energy was abstracted from the groundwater at a rate of 5.43 kw. This indicated that the basic coefficient of performance of the heat pump (the ratio of potentially useful heat produced to energy consumed) was 2.7.

However, the water in the secondary plumbing system, rather than being returned directly from the output of the radiators to the input of the heat pump, was also circulated through the heat storage tank. When the system was designed it was envisaged that there would be a significant temperature gradient down the height of the tank and that the coldest water would collect at the bottom. The system was therefore planned to draw off this coldest water for the heat pump feed. This would enable the heat pump to work against the minimum temperature head which is beneficial to the C.O.P. However the flow in the secondary produces enough turbulence in the tank to ensure fairly even mixing of the water. Consequently, for much of the heating season, the water taken from the tank was hotter than that being returned from the radiators. Thus, there was a net abstraction of heat from the store to the load and consequently the apparent C.O.P of the system was raised to almost 3.0 in this mode.

During the night, once the heat pump had satisfied the immediate heating requirements of the glasshouse, the radiators were by-passed and the heat output of the heat pump was directed to the store: the hot water being fed to the top of the storage while the heat pump evaporator was supplied with cold water from the bottom.

The electrical consumption, primary flow rate and primary temperature drop remained virtually the same as when the heat pump was heating the radiators and consequently so did the basic C.O.P. However, not all the heat produced was transmitted to the heat store. The equivalent of about 20% of the electrical input was dissipated within the glasshouse. For most of the heating season this dissipated energy in fact performed a useful role in maintaining the temperature of the glasshouse just above the set point and deferring the time at which the heat pump had to revert to direct heating. However, towards the end of the heating season as the store became warmer the proportion of dissipated energy increased to two-thirds the input electricity and this had the effect of raising the glasshouse temperature significantly above the set point. Consequently some of this energy should perhaps be considered to have been wasted although this has not been done in the following analysis.

Table 4 lists the monthly totals for the electricity used in the standard and economy tariff periods alongside the actual heat consumed by the glasshouse in KWH. Also listed are theoretical figures for the electricity that would have been used by the heat pump to generate the heat directly at the time of use assuming the basic C.O.P. of 2.7.

In September 1985, the standard electricity tariff was 7.93 p/unit and the economy tariff was 3.09 p/unit. The costs for the 1985/86 winter seasons heating totalled £348.33 for the heat pump with storage compared to £1206.91 if the glasshouse has been heated directly by electricity thus the economic efficiency was 346%.

The use of the storage tank increased the economic efficiency of the theoretical directly used heat pump by 28% giving a saving of almost £100 in the year. Thus, it would take 12 years to recover the purchase and installation costs.

Table 4 Electricity Consumption and Heat Production for a water to water heat pump with heat storage cylinder at Reach, Cambridgeshire

	Electricity consumed by heat pump with storage kWH		Heat supplied to glasshouse kWH		Theoretical direct Heat pump COP = 2.7 Electrical consumption	
	Standard	Economy	Standard	Economy	Standard	Economy
December 1985	321	1079	1959	2554	725	946
January 1986	669	1106	2616	3160	969	1170
February 1986	528	977	2002	2815	741	1046
March 1986	276	1171	1418	3030	525	1122
April 1986	140	1108	978	2531	362	937
May 1986	19	820	180	1469	67	544
Sub Total	1953	6261	9153	15569	389	5765
TOTAL	8214		24722		9154	
Pence/unit	7.93	3.09	7.93	3.09	7.93	3.09
Tariff totals	£154.87	£193.46	£725.83	£481.08	£268.74	£178.13
TOTAL	£348.33		£1206.91		£446.87	

2.3 The use of a groundwater heat pump to heat a house at Irvine New Town, Scotland

2.3.1 *Introduction*

Previous work by BGS using groundwater to air heat pumps for space heating in horticultural glasshouses had shown that high coefficients of performance could be maintained throughout the year and that fuel costs were considerably lower than when oil was used.

Irvine Development Corporation was approached with a view to instigating experimental projects in houses within the New Town area as hydrogeological conditions were particularly suitable. This chapter describes the first experimental installation of a groundwater heat pump in one of the I.D.C. houses.

2.3.2 *Experimental details*

A hydrogeological investigation was undertaken for the Irvine area and indicated where groundwater was likely to be available within 5 metres of the surface and therefore exploitable at reasonably low costs. The survey showed that a considerable area of the Irvine New Town was likely to be able to supply groundwater suitable for operation of heat pumps.

The Development Corporation consulted with BGS on the design and execution of suitable projects to demonstrate the feasibility of heating normal domestic premises by utilising a water to air heat pump to transfer energy from groundwater to air as the heating medium. The existing method of heating on the housing estate was by electric convectors using full rate electricity. For the heat pump installation warm air was circulated throughout the dwelling by a mechanical ventilation system operating on a recirculation basis. Figure 7 indicates a schematic layout of the installation.

In order to exploit the groundwater, a 200 mm diameter borehole was drilled in the rear garden of the house. The geological profile is shown in Figure 8. The borehole was fitted with 200 mm diameter perforated plastic casing inserted to 7.5 metres with gravel pack. Rest water level was 2.3 metres below ground level. A pumping test on the borehole gave a drawdown of 0.6 metres after pumping at 52 litres/minute for 88 minutes. The temperature of the pumped water was 11.1 degrees Centigrade on 12 November 1981.

The groundwater heat pump selected for the project was a TETCO type HECWE-042 water to air unit with a nominal output of 10/12 KW. It was fitted with a variable speed fan and ducting system to all rooms of the house. The air output was rated at approximately 0.47 cubic metres/second at 35 degrees Centigrade.

The heat pump was fitted in the kitchen of the house together with monitoring equipment to measure the groundwater flow rate and temperature. Ambient outside temperatures and room temperatures were also measured at one minute intervals and all results were logged on a P.E.T. microcomputer and hourly summaries were listed on a printer installed in an upstairs room.

The heat pump thermostat was installed in the main downstairs room and controlled the house temperature to 21 degrees Centigrade between the hours of 7 am and 11 pm. The groundwater was pumped from the borehole in the garden through the evaporator of the heat pump and discharged to a surface water drain. The rate of pumping was approximately 25 litres/minute and the drop in temperature across the evaporator was approximately 3–4 degrees Centigrade. Manually read KWH meters and water flow meters provided a ready check on the total power and water used of the heat pumps over long periods.

Air was drawn into the heat pump and across the condenser coil where it gained energy from the refrigerant and was then circulated throughout the dwelling. Air was recycled by filtration through the dwelling back to the unit where it was reheated. On this particular project the heat loss (fabric) was approximately 7.6 KW when ambient is – 1 degrees Centigrade. Heat pump maximum rated output was 12 KW, which was probably slightly higher than required for the total of fabric and infiltration losses for the dwelling. As the coefficient of performance was affected by secondary circuit differentials, there were facilities on the system to vary the supply air volume (between 0.6 cubic metres/sec at 32 degrees Centigrade and 0.35 cubic metres/sec at 43 degrees Centigrade) thus

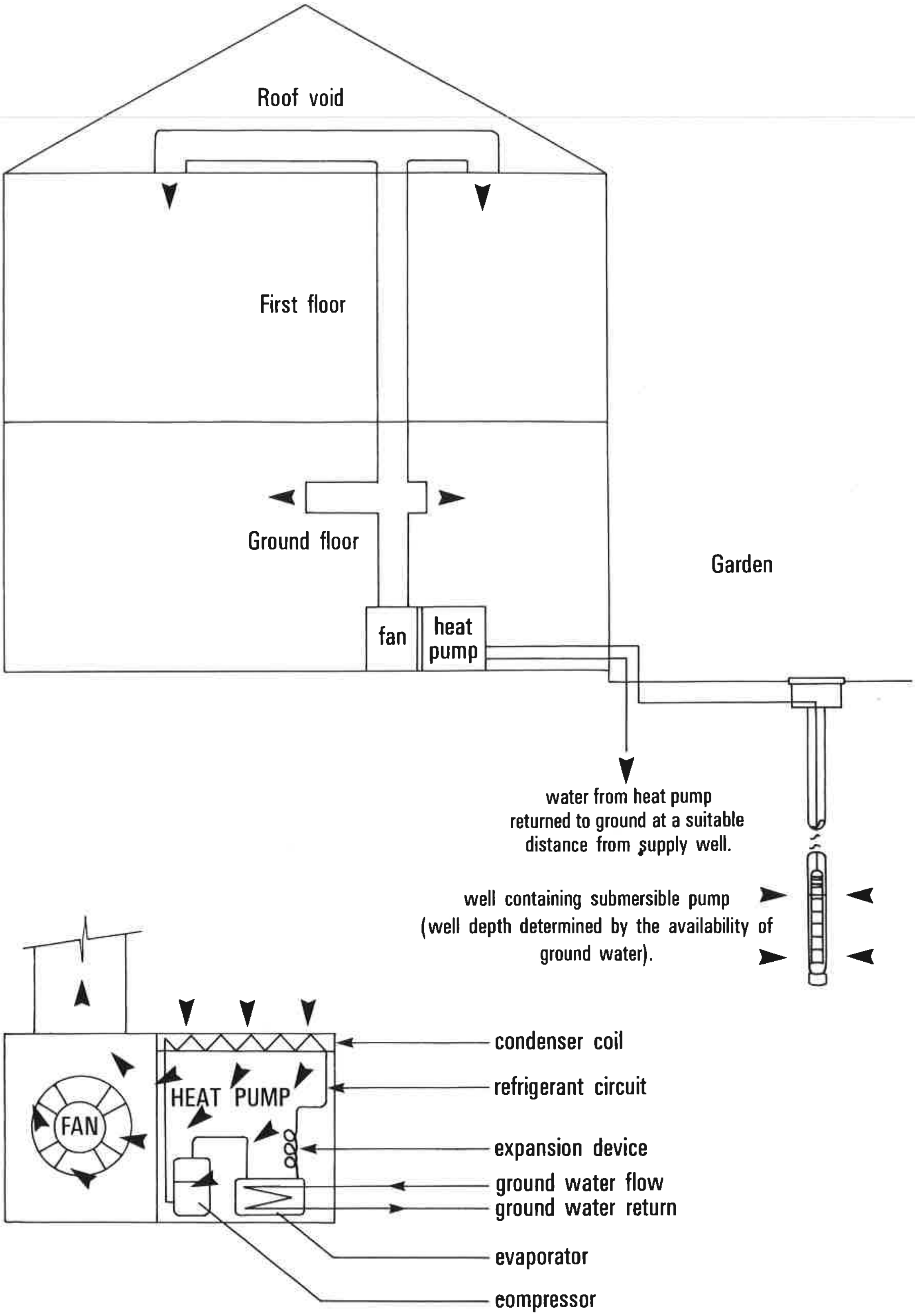


Figure 7 Groundwater to air heat pump installation at a house in Irvine, Scotland.

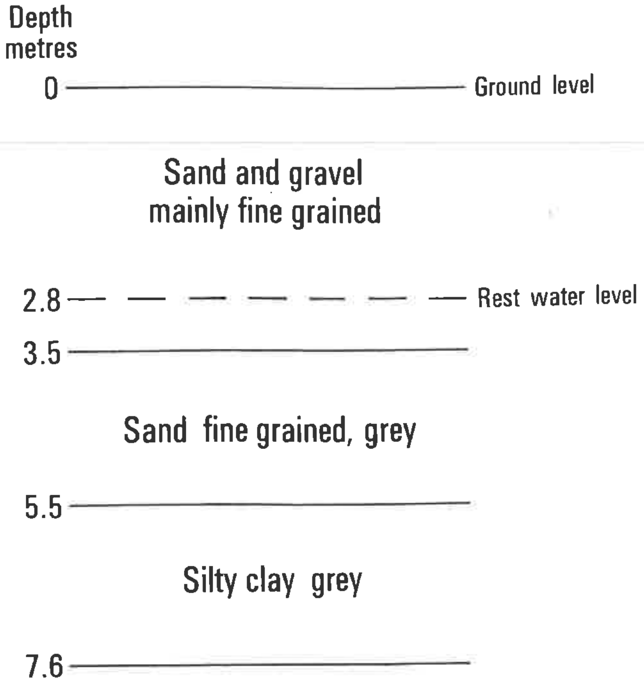


Figure 8 Geological profile at Irvine borehole site.

enabling an optimum setting to be obtained. The reliability of the system (and indeed other research systems) has been relatively good. The American manufactured heat pump used on this particular project was relatively cheap although its noise level was high.

2.3.3 *Results and conclusions*

The groundwater heat pump was commissioned in February 1982 and the full data logging facilities were brought into operation in March 1982. The heating system proved very satisfactory maintaining room temperatures in the range 18–22 degrees Centigrade over the period February to June 1982. Input groundwater temperatures were approximately 10 degrees Centigrade with a fall of 4 degrees Centigrade across the evaporator. Values of coefficient of performance ranged from 2.7–2.9. A slight problem was experienced at the end of March when the water flow filter became blocked because of pumping of sand grains from the borehole through the system. Regular cleaning of the filter has overcome this problem. Table 5 summarizes the measured operating conditions of the system during the period 27/3/82 to 22/6/82.

The effective running costs of the heat pump system were 1.62 p/KWH which compared with running costs of gas at 1.21 p/KWH and oil at 2.3 p/KWH. The use of off peak electricity and the installation of heat storage facilities would further reduce the running costs of the heat pump system.

The viability of heat pump installations depends upon both running costs and capital costs. As the heat pump and associated equipment is generally operated by electricity, the running cost viability can be assessed by obtaining the applicable electrical tariff and dividing by the coefficient of performance. Thus if the coefficient of performance is 3.0 and the electrical tariff is 4.5 p/KWH then the comparative running cost can be approximated at 4.5 divided by 3.0 that is 1.5 p/KWH. The capital costs of installations are currently fairly high in comparison with alternatives. This is particularly so in the domestic market where gas fired low pressure water is the major opposing type of system. Apart from the current cost of the heat pumps themselves, which would appear to be unrealistically high (primarily due to limited production and the fact that most units currently available are imported), system installation costs are also high due to the requirement for low emission temperatures. The key factor governing system designs is that the coefficients of performance are highest when the secondary transmission medium temperatures are at their lowest. For example, the coefficient of performance for a water to water pump system utilising groundwater at 10 degrees Centigrade as a primary source varies from 2.5 with secondary flow at 49 degrees Centigrade to 4.0 with secondary flow at 27 degrees Centigrade. This of course means that with a wet system a larger emitter surface area would be necessary to achieve a high coefficient of performance. In view of this the adoption of heat pump systems may well mean that it will be necessary to adopt underfloor or similar types of emission systems which offer large surface area at relatively low mean temperatures. The acceptance and application of these unusual design parameters will obviously affect capital costs until suitable type systems have been developed. For example, it may be possible to design and install low cost underfloor heating systems which utilise plastic tube, as most plastics should not be adversely affected by the relatively low mean water temperatures associated with this type of system.

Table 5 Measured operating conditions of a groundwater heat pump system at Irvine, Scotland

27/3/82 to 22/6/82

Electricity consumed	1317 KWH
Groundwater flow	568.6 cubic metres
Operating hours	408.4 hours
Mean input water temp.	10.54 degrees Centigrade
Mean output water temp.	6.6 degrees Centigrade
Mean difference	3.88 degrees Centigrade
Groundwater flow rate	23.20 litres/minute
Mean power	3.22 KW
Mean C.O.P.	2.79
Domestic tariff	4.52 p/KWH
Heat pump effective cost	1.62 p/KWH

2.4 Current Status of Groundwater Heat Pumps in the U.K.

Apart from the experimental installations described in this report a number of trial systems have been introduced in offices, schools and private houses in the U.K. They have in general been reliable and produced C.O.P.'s in the region of 3.0. However, they have usually been expensive to install as the cost of available heat pumps in the U.K. is relatively high compared to say the United States where the economies of larger scale production help to keep costs lower. Furthermore, heat pumps in the U.S.A. are often used in dual mode for heating and air conditioning which is not the case in the U.K.

Recent reductions in the price of fossil fuels have reduced the running costs of heating systems which has not helped the case for heat pumps which are capital intensive with lower running costs. However in the longer term it is likely that fuel prices will rise making the use of groundwater heat pumps more viable. Furthermore the high efficiency of groundwater heat pumps together with their energy conservation potential are features that will commend them at a time when protection of the environment is becoming increasingly important.

3. HEAT STORAGE IN AQUIFERS

3.1 Introduction

In many industrial processes waste heat is produced as a by-product either in medium or low grade form. Similarly the generation of electricity is usually only about 30% efficient, with the remaining 70% being rejected as waste heat, most of it at the power station and in relatively low grade form. If there is a demand for process or space heating near the source of waste heat and if the demand is in phase with the supply and the grade of waste heat is high enough then energy will be conserved and heating costs will be low.

However, frequently the demand for space heating will be out of phase with the supply of waste heat. This can occur on a diurnal basis for example due to high domestic space heating demands during the evening or on a seasonal cycle. More waste heat will be available during the summer but the maximum space heating demand will occur during the winter.

Storage of hot water in tanks at the ground surface is very expensive and impractical in many urban situations. Recent estimates of the cost of pre-stressed concrete thermal storage vessels with insulation suitable for storing 40 000 m^3 of hot water at up to 100°C are in the region of £1.2 million. If cheaper methods of heat storage could be developed greater flexibility in the use and conservation of waste heat would be achieved. In addition there would be the possibility of using cheap night-rate electricity to produce heat which could be stored for subsequent use at times of peak demand during the day.

The possible storage of heat in suitable aquifers merits consideration for the following reasons:

1. Permeable geological formation are widely available and are natural stores and transmitters of water.

2. Water is a readily available material of high thermal capacity ideally suited for transport of heat at temperatures up to 100°C or higher if under pressure.

3. Suitable aquifers are present beneath many industrial and urban areas where scope for even low cost storage facilities (if the technology were available) at ground surface would be extremely limiting.

4. The storage and re-use of waste heat would reduce thermal pollution at present caused by the discharge of surplus heat.

It should be noted that the volumes of aquifer required for energy storage are very small in relation to the extent of these natural geological systems. For example a spherical zone of sandstone 5.5 m diameter with a porosity of 32% could store 2.0 MWH of heat at a temperature of 60°C in excess of the natural formation. Provision of thermal insulation would be impractical under these conditions so that some heat loss would have to be tolerated. The ratio of heat losses to heat stored would decrease markedly as the amount of heat stored increased.

Some theoretical and experimental research into ATES has already been undertaken mainly in the USA but also in some other parts of the world. Since 1965 Shanghai, Peoples Republic of China has been using aquifer storage of cooled natural water in winter for subsequent summer air conditioning (Yan, 1981). In the west, ATES was first proposed in the early seventies (Kazmann, 1971; Meyer et al., 1973). Recent work by Auburn University in a confined aquifer near Mobile, Alabama, has achieved thermal recovery of up to 68% after a storage period of 9 weeks (Molz et al., 1983).

3.2 Trial Project at Reach, Cambridgeshire

This report describes some practical and theoretical work undertaken by the British Geological Survey in East Anglia on the storage and recovery of heat in the Lower Greensand Formation.

3.2.1 *The experimental equipment*

The purpose of the field experiment was:

(i) to gain first hand experience of the problems and procedures involved in ATES field work;

(ii) to obtain experimental data which could be used to develop and calibrate a mathematical model of an ATES system. This model to be used to plan further ATES schemes and to predict their performance.

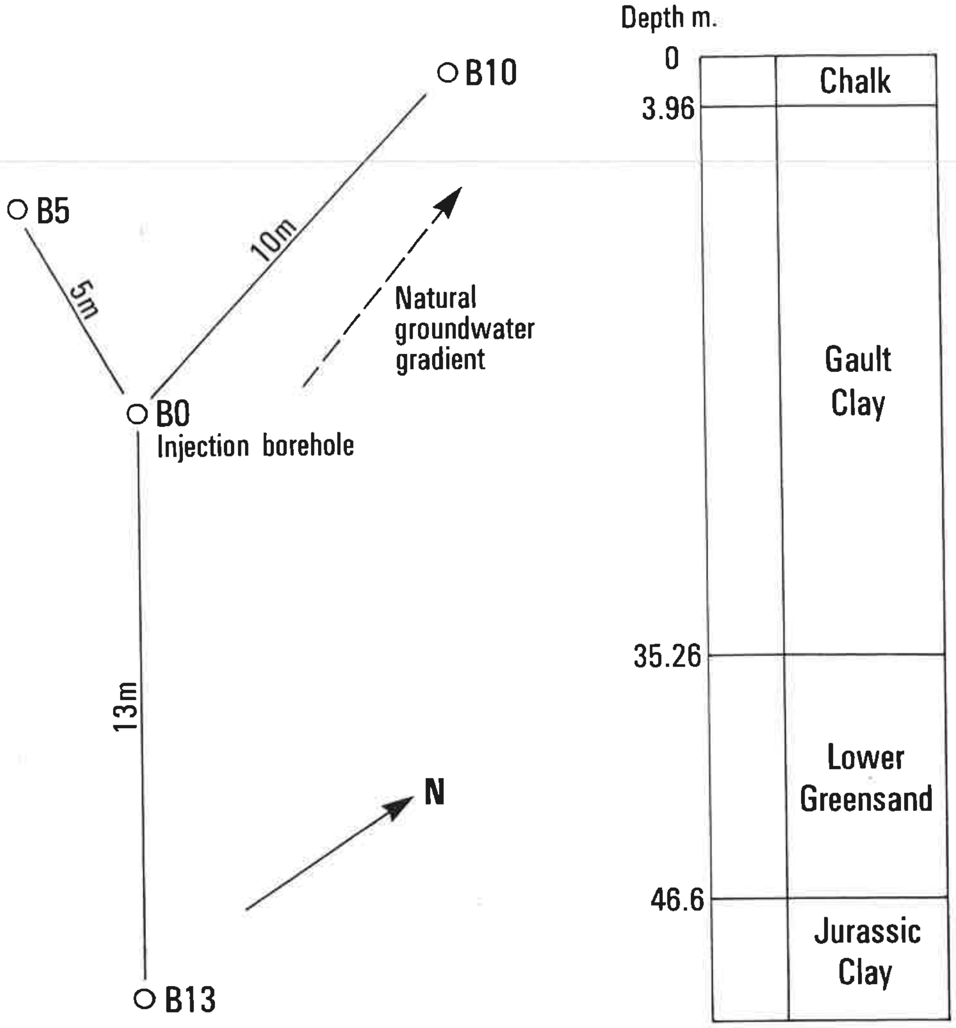
A preliminary study of possible locations for ATES work in the UK indicated that the Lower Greensand aquifer in the Cambridge area and the Permo-Triassic sandstones of the Midlands might be suitable areas. An existing experimental facility at Reach, 12 miles north east of Cambridge (NGR TL 558 659) was finally selected for this ATES project. In this site the Lower Greensand aquifer is approximately 13 m thick, is underlain by Jurassic Clay and confined by 31.5 m of Gault Clay which in turn is overlain by about 3–5 m of Chalk. The water in the Lower Greensand is confined with a piezometric level approximately 2.5 metres below ground surface.

In order to provide access to the Lower Greensand aquifer for injection/abstraction and monitoring of the hot water, four boreholes were drilled as shown in Figure 9. The central injection borehole was drilled 6" diameter to a depth of 46.6 metres. The adjacent boreholes were drilled at 4"/5" diameter to a similar depth. The boreholes were completed with Demco Terraline 110 thermoplastic casing and Terrascreen with 2 mm slots opposite the LGS. This material has a low heat conduction (0.22 watts.m.deg°C), a temperature range of −10°C to 110°C, is non-corrosive and has a high resistance to regenerative chemicals.

It was required to monitor the spread of the temperature anomaly around the injection hole and for this purpose temperature sensors were located both in the injection borehole and in the three observation holes at different distances and orientations from the central hole. Accurate thermistors supplied by the Yellow Springs Instrument Company were used as temperature sensors as they possessed the required sensitivity and were readily interfaced to the data logging system.

These thermistors were mounted on probes constructed from 6 m lengths of 1" diameter ABS plastic pipe connected by flanged joints. Over the screened section of the borehole, thermistors were mounted at 1 m intervals separated by neoprene washers (located by a flange) of slightly larger diameter than the casing. The purpose of the neoprene washers was to minimize convection effects within the boreholes so that the sensors truly measured

Figure 9 Location and lithology of boreholes at Reach aquifer energy storage site.



the temperature in the adjacent aquifer. In the Auburn experiment (Molz et al., 1979) convection was significant and had to be controlled by the drastic measure of backfilling the observation holes with a clean medium sand. The advantage of the technique used at Reach to control convection over that used at Auburn is that both the instrument strings and the boreholes can be recovered. A pressure transducer was also mounted upon each probe. Additionally in the central borehole (the injection/abstraction hole) an inflatable packer was inserted just above the top of the LGS. The hot water for injection was produced by three liquid propane gas boilers connected in parallel and fed with water from a storage tank filled from the Chalk aquifer. A lagged hot water storage tank was connected in the pipeline immediately after the boilers and hot water was injected down the borehole from this tank by means of a small pump. The hot water tank served two purposes:

(i) as an air trap to minimize the injection of gas into the aquifer;

(ii) as a stabilization reservoir to overcome short term differences between production and injection of hot water.

Water flow regulation valves were incorporated in each boiler feed and the flow rate was metered both before the boilers and before injection. The meter on the cold water feed pipe provided electrical output pulses for the data logging system. Float switches in the hot and cold water storage tanks were used to control the injection and boiler feed pumps. Additional thermistors were mounted at the well head and above the packer to monitor the temperature of the injected water and the column of water above the packer.

A potential problem with aquifer thermal energy injection boreholes is clogging from air entrapment, particulate deposition, chemical and biological causes. Some problems relating to aquifer and borehole clogging have been described in the literature (Molz et al., 1979; Molz et al., 1981; Adams et al., 1980; Meyer and Hauz, 1980; Tsang (Ed.) 1978; Yan, 1981). In the Reach experiment it was felt that as the total quantity of water to be injected was relatively small, expensive or complex provisions (such as treatment plant and backwashing facilities) could not be justified. However, some consideration was given to the potential problem. Part of the reason for installing the hot water storage tank after the boilers was to act as an air trap to minimise injection of gas into the aquifer, and the cold water tank whilst acting as a reservoir for the boilers also served as a settling tank to decrease particular content of the injected water.

Chemical incompatibility of the Chalk and Lower Greensand waters was not felt to be a major problem. The initial Chalk water would be saturated or oversaturated with respect to calcite, the solubility of which decreases with rising temperature. Depending upon the kinetics of the heating and injection system, the calcite could precipitate out, probably in finely divided particulate form. As the Chalk water cools slightly, following injection, the solubility of calcite would increase which, coupled with the probability that the Lower Greensand aquifer contained high CO_2 would result in the resolution of any remaining particulate $CaCO_3$. Additionally if the Lower Greensand were anoxic then the injection of aerated water would create a redox front causing precipitation of iron (and possibly manganese). However, Van Beek (1980) has shown that such precipitation has no serious effect upon aquifer permeability. Thus, while deposition in the boiler, pipes and hot water tank may have been a potential problem, it was felt that chemical clogging of the well and/or aquifer was not likely to be. Biochemical clogging was assumed not to be a problem on such a short time scale.

As it was intended that the system should operate at a remote site for long periods continuously (day and night) it was necessary to provide a reliable data logging system and an appropriate alarm system if problems occurred.

A reliable and economical solution to this problem was found by the use of an Apple II Microcomputer together with four Kratos "Analog Link On" units. The temperature sensing thermistors were interfaced to the Analog Units by voltage stabilised resistor networks. The measuring accuracy achieved was better than 0.2°C. Water flow rates and pressures were logged on other channels of the Analog unit. All the parameters were logged at approximately 1 minute intervals and hourly summaries were recorded on floppy disks. Some data analysis was undertaken on site by the microcomputer and presented on the VDU so that the state of the experiment could be readily assessed during site visits to change the disks (at 10-day intervals). The system could also be programmed to provide digital outputs which could be used to control the experiment (by closing or opening valves or switching pumps on or off when specified conditions were met); in practice this facility proved to be unnecessary. Additionally a backup power supply was provided to enable the computer to operate normally for several hours in the even of mains power failure and also an alarm system was included which would telephone BGS headquarters in the event of a system crash.

3.2.2 *The operation of the experiment*

The experiment involved a single injection/storage/recovery cycle over 279 days in 1982. Following sporadic injection tests over a period of a few days (in order to check equipment) full injection commenced on 24 February and continued for 77 days until 12 May with only a few minor interruptions due to equipment failure in the early stages. An average injection rate of 19.74 m^3/day resulted in a total injection volume of 1520 m^3. At a mean injection temperature of 57°C this corresponds to a total energy injection of 86.64 MWH at a rate of 46.8 KW.

The energy was stored for 105 days from 13 May until 26 August while measurement of the temperature in all the boreholes was continued. Abstraction of the hot water commenced on 26 August and lasted for 97 days until 1 December. The mean rate of abstraction was 20.21 m^3/day.

The operation of the single injection/storage/abstraction cycle proceeded relatively smoothly without any major problems. However a few minor difficulties were experienced.

Injection was temporarily stopped on days 7 and 8 in order to change the pressure transducer below the packer in the injection borehole. This resulted in a decrease in the temperature recorded by the well head thermistor although it should be noted that no injection actually occurred at this temperature. The increase in injection temperature at day 29 was caused by the installation of improved regulator valves which permitted finer balancing of individual boilers. Failure of one of the boilers caused the temperature decrease recorded at day 38 and its replacement by a new boiler resulted in an improved temperature from day 43 onwards.

By the end of the injection phase all of the thermistors mounted below the packer in the injection borehole had failed, thus preventing analysis of the temperature profile at the injection point. Molz and Melville (1982) report similar thermistor failure in the ATES experiment at Mobile, Alabama. They concluded that "the problem was chemical in nature, probably due to unexpectedly rapid water migration through the epoxy barrier used to insulate the thermistor from the surrounding groundwater. Evidently, such migration is significantly accelerated by temperatures above 60°C. Only 3 thermistors failed, apart from the 8 in the injection borehole out of a total of 45 in the whole of the Reach experiment and, apart from within the injection borehole, temperatures were significantly lower than 60°C.

During the testing period prior to the main injection, problems were encountered with the use of the packer. On initial injection tests the packer split and the combination of partial deflation of the packer and the introduction of nitrogen gas (used for inflating the packer) into the column of water above the packer caused water to rise within the injection borehole—for this reason a float switch was inserted into the top of the injection borehole, which, if activated would switch off the injection pump. When the packer had been repaired it was resited just above the top of the aquifer. However, on initiating injection, water again rose in the borehole above the packer. Repeated testing of the packer and logging of the borehole under injection and static conditions using a temperature/conductivity probe and downhole TV failed to positively identify the cause. However the problem was solved by raising the packer to be central within the next section of casing. It is assumed that cavities in the Gault Clay immediately behind the casing had not filled by natural slumping and that injected water was rising up behind the casing and re-entering the injection borehole at the next casing joint upwards. If the casing joints above the suspect one had greater integrity then repositioning the packer in the next length of casing above would prevent the leakage—as was the result.

In order to check whether hot injected water was leaking vertically upwards behind the casing to the Chalk aquifer, temperature measurements were taken in a specially constructed borehole in the Chalk adjacent to the injection hole but 1 metre downstream. From these measurements and a calculation of the heat loss expected from the borehole itself it was concluded that no significant leakage of hot water occurred behind the casing up to the Chalk.

3.2.3 *Results and discussion*

The temperature as measured by the well head thermistor is shown as a function of time in Figure 10. The reasons for the fluctuations have already been discussed in the previous section. Figure 11 shows the temperature of the abstracted water against time. It will be seen that the abstraction temperature had fallen to 30.5°C after 10 days and to 19°C after 90 days.

Figure 12 shows typical vertical temperature profiles in an observation borehole during the injection phase. The

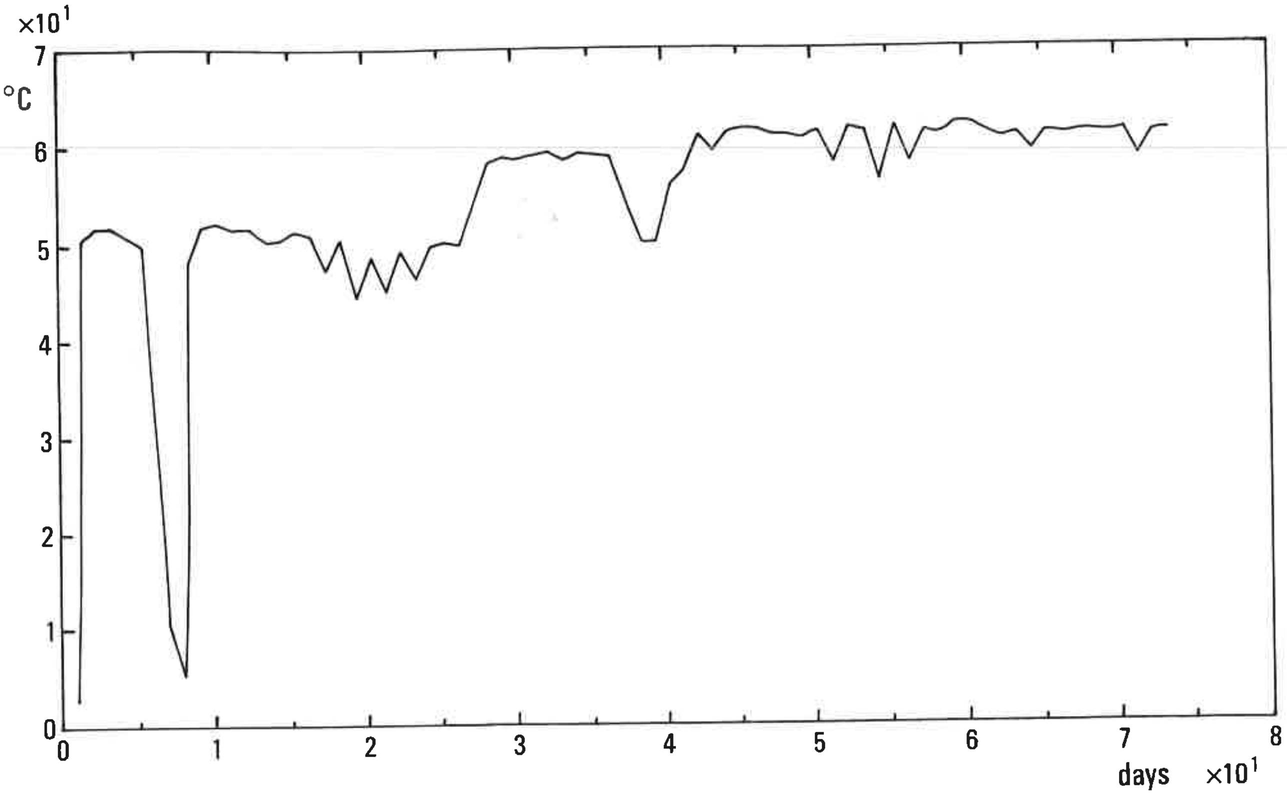


Figure 10 Injection temperature at well head against time.

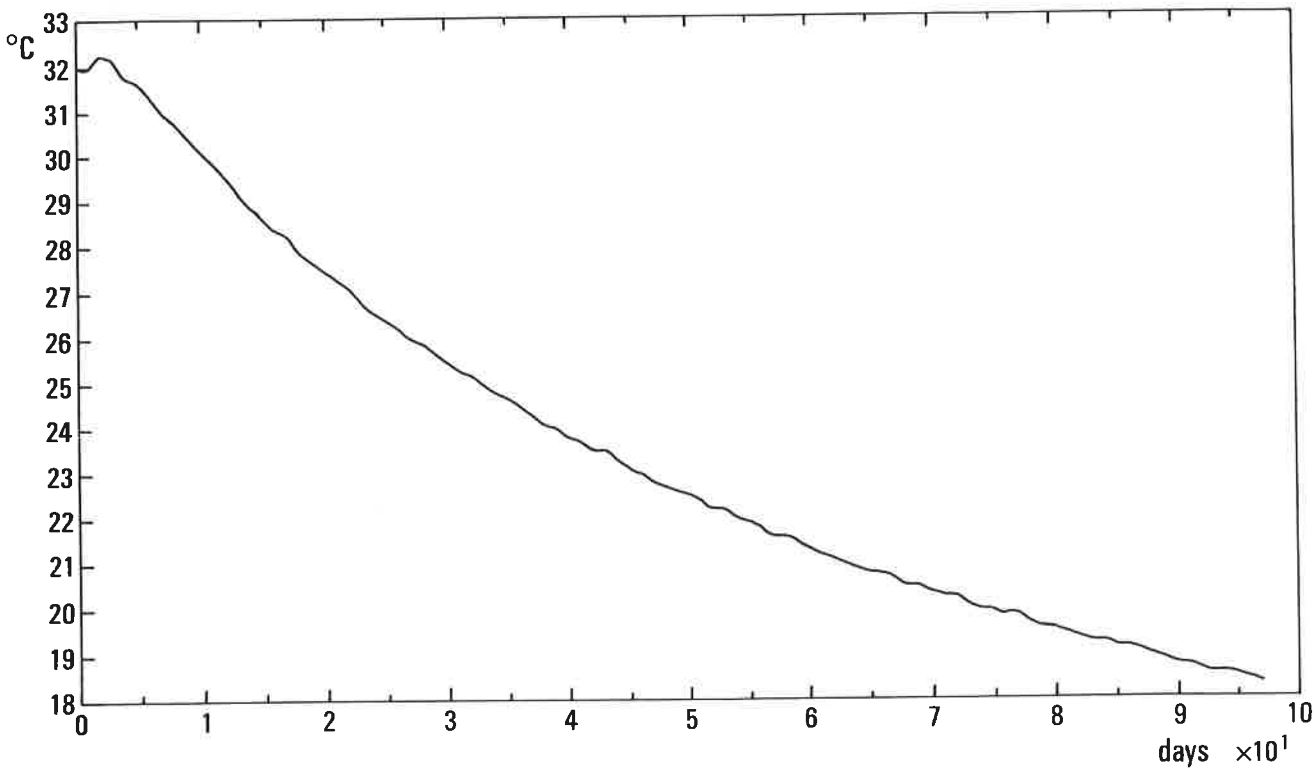


Figure 11 Temperature of abstracted water against time.

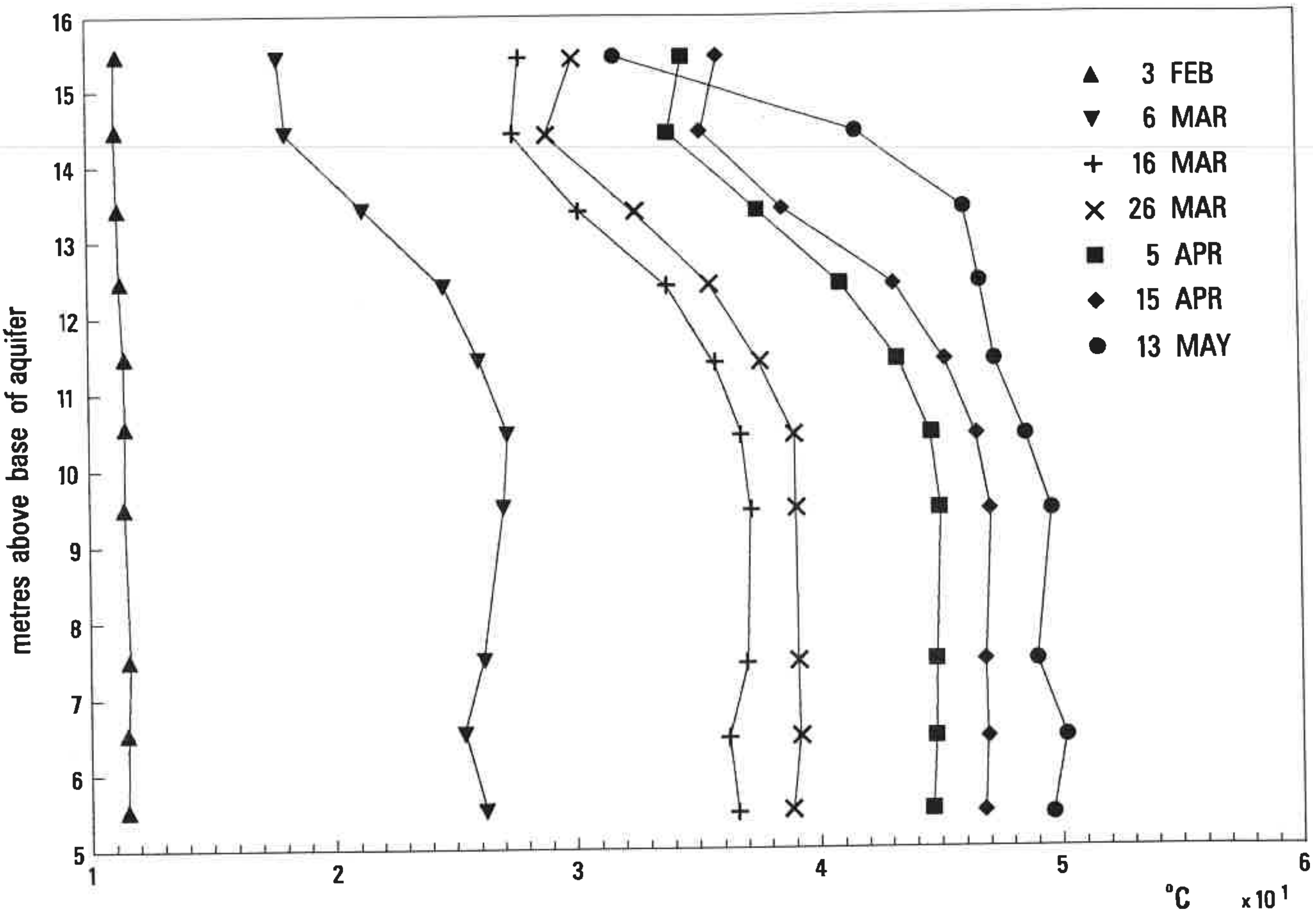


Figure 12 Vertical temperature profile at 5 m radius (injection phase).

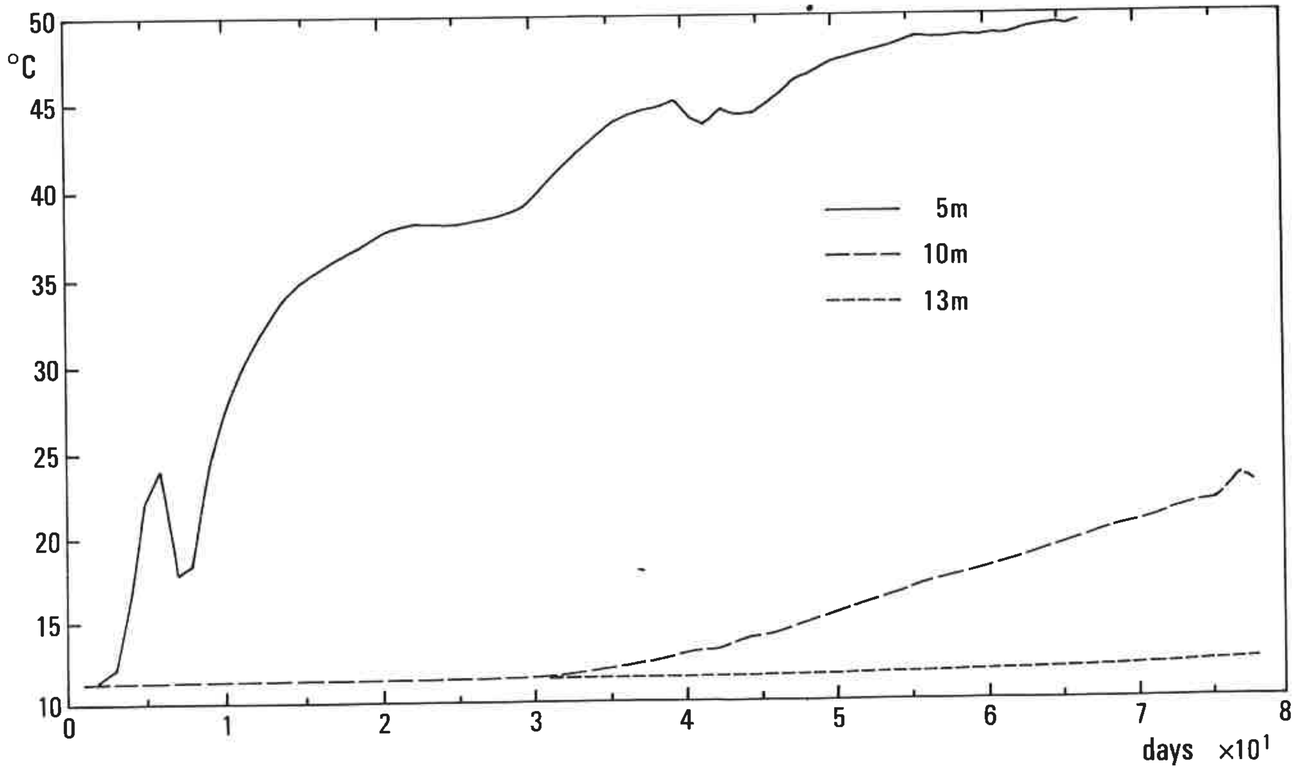


Figure 13 Maximum temperature against time (injection phase).

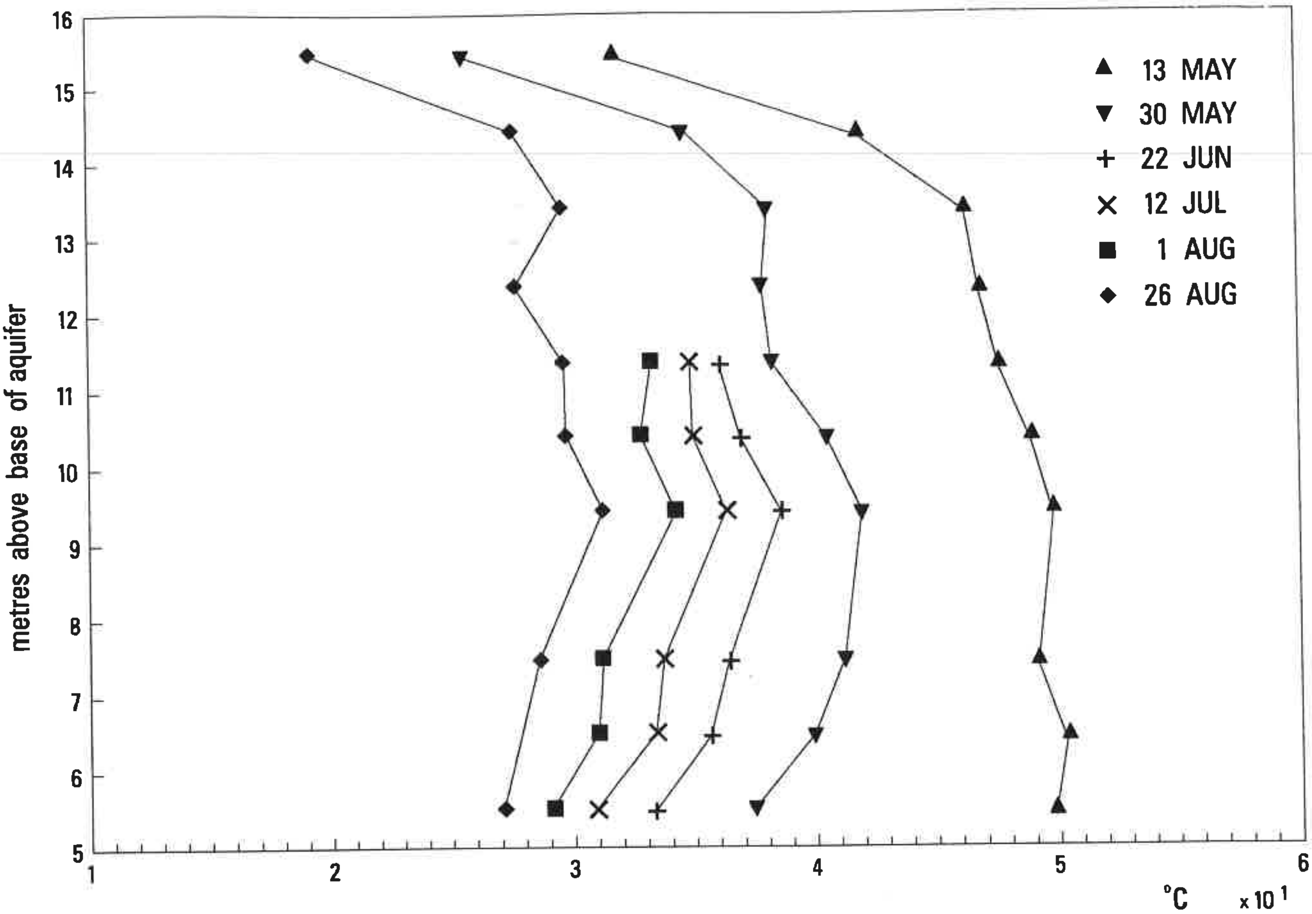


Figure 14 Vertical temperature profile at 5 m radius (storage phase).

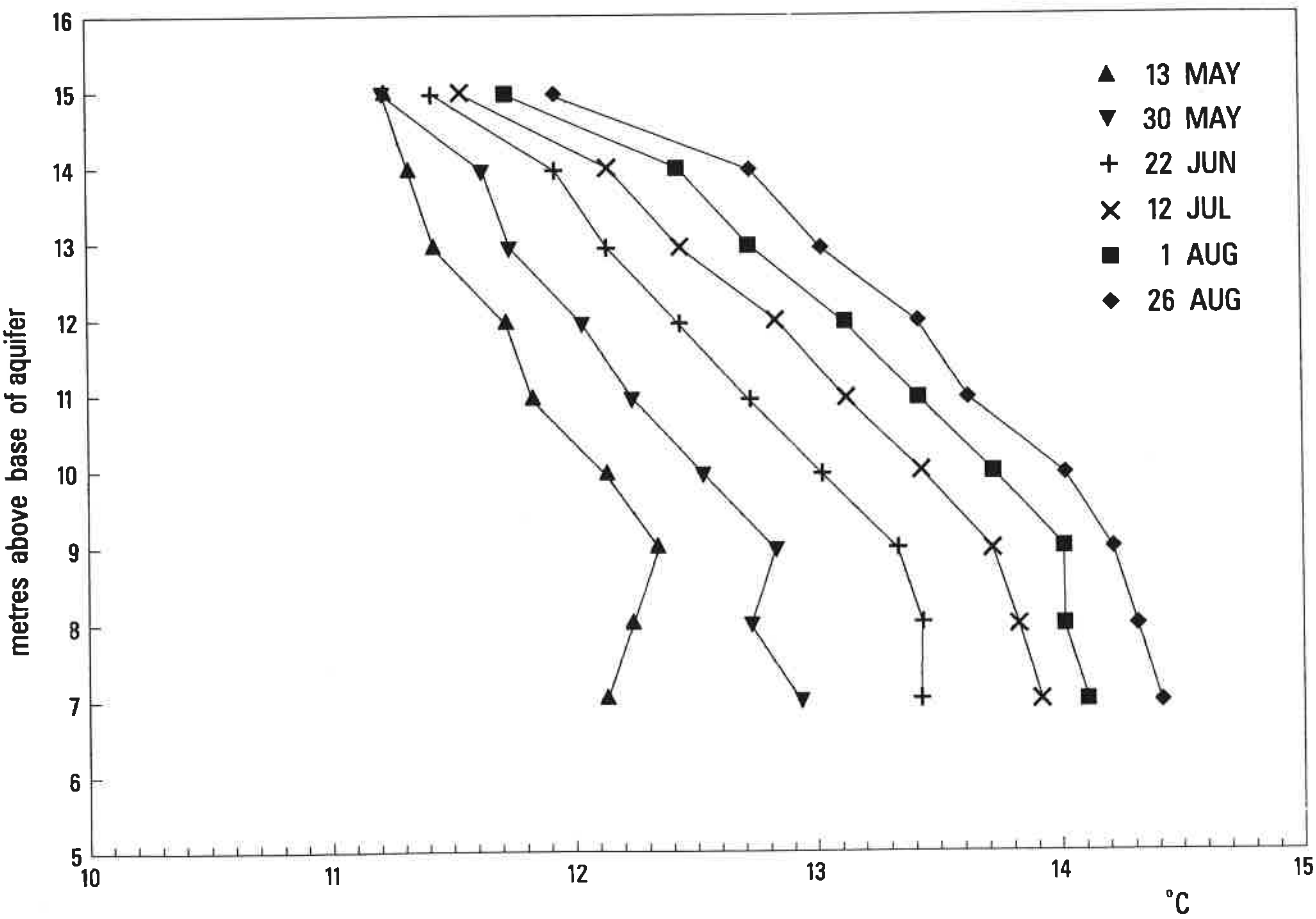


Figure 15 Vertical temperature profile at 13 m radius (storage phase).

maximum temperatures reached at 5, 10 and 13 m from the injection borehole were 50, 23 and 12.3°C. There is no apparent evidence of convection within the storage formation and the change in temperature of the profiles at the top of the aquifer suggests that the neoprene separators, installed to inhibit convection, were generally effective. The peak in some of the temperature profiles about 8–11 metres above the base of the aquifer may be due to variations in horizontal permeability with depth.

Figures 13 shows the maximum temperature against time for the 5, 10 and 13 m distance boreholes. It will be seen that the time after start of injection before the temperature begins to rise is 2, 30 and 50 days respectively.

Figures 14 and 15 show the temperature variations in the observation boreholes during the 105 day storage period. The temperatures in the boreholes within 5 and 10 metres from injection decline over this period whereas the temperature at 13 metres from injection continue to rise throughout the storage phase. This effect is thought to be a delayed response to the injected hot water. The contrary gradients of temperature against time are also indicated in Figures 16. it is not thought that the rise in temperature is due to the natural hydraulic gradient as this is in the direction from the 13 m borehole towards the injection borehole.

Figures 17 and 18 show the temperature as a function of depth and time in the observation boreholes. The temperatures decline with time.

Using the recorded temperatures and flow rates of the injected and abstracted water as functions of time, the amount of thermal energy injected and recovered can be calculated. A finite difference approximation of expression (1) is made to give equation (2) (Molz et al., 1979).

$$E_{in} = \int_{t_0}^{t_1} \varrho C\,[T_i(t) - T_a]\,I(t)\,dt$$

$$E_{out} = \int_{t_2}^{t_3} \varrho C\,[T_r(t) - T_a]\,R(t)\,dt \qquad (1)$$

Where E_{in} is the energy injected
E_{out} is the energy recovered
ϱ = water density
C = specific heat of water
$T_i(t)$ = temperature of injected water
$T_r(t)$ = temperature of recovered water
T_a = ambient groundwater temperature
$I(t)$ = injection rate
$R(t)$ = recovery rate

The limits t_0, t_1 and t_2, t_3 correspond to the time periods of injection and abstraction respectively.

$$E_{in} \approx \frac{\bar{\varrho}.\,\bar{C}}{2} \sum_n [T_i(t_n) + T_i(t_{n+1}) - 2T_a]\,(QI_{n+1} - QI_n)$$

$$E_{out} \approx \frac{\bar{\varrho}.\,\bar{C}}{2} \sum_m [T_r(t_m) + T_r(t_{m+1}) - 2T_a]\,(QR_{m+1} - QR_m) \qquad (2)$$

Where QI is volume of water injected
QR is volume of water recovered
$\bar{\varrho}$ is average ϱ
$\bar{C}$ is average C
indices n and m correspond to times when temperature and cumulative injection or recovery data were recorded.

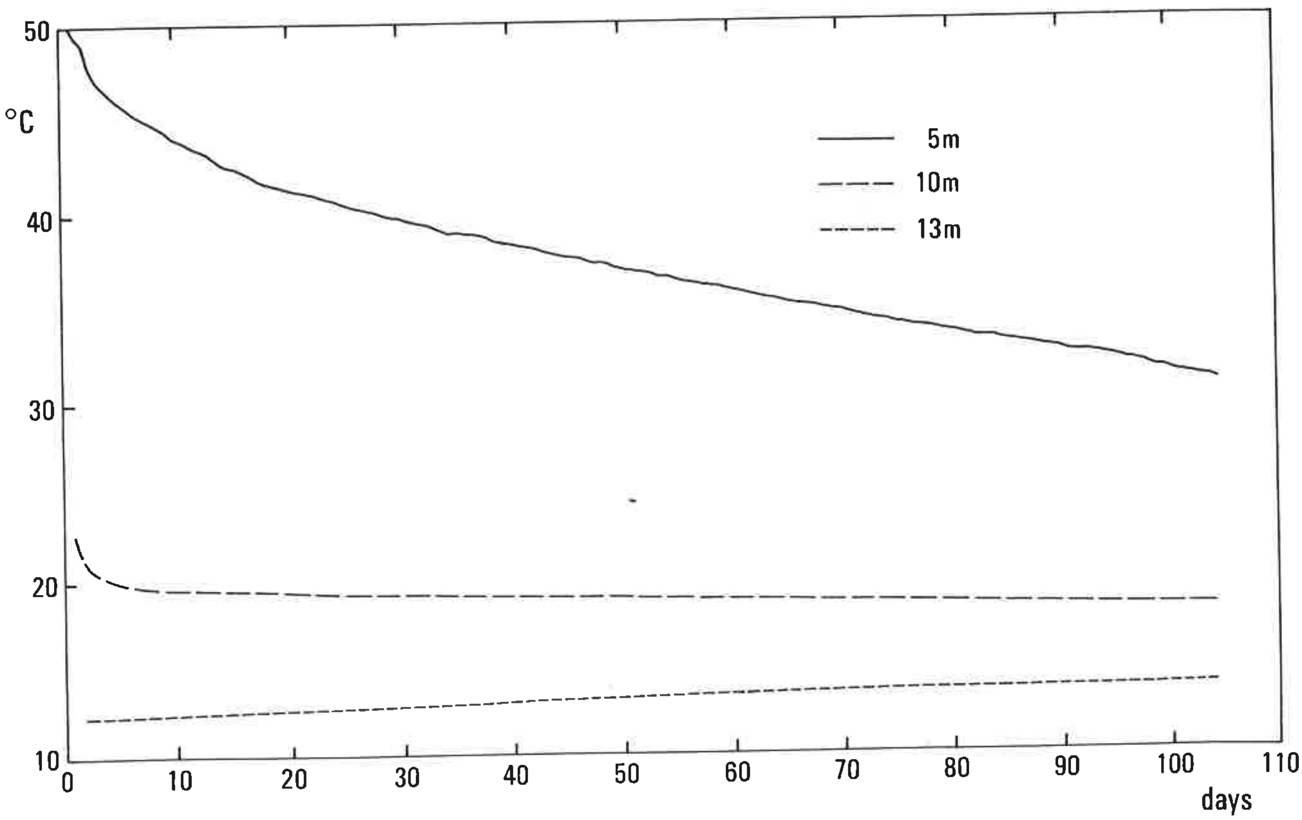


Figure 16 Maximum temperature against time (storage phase).

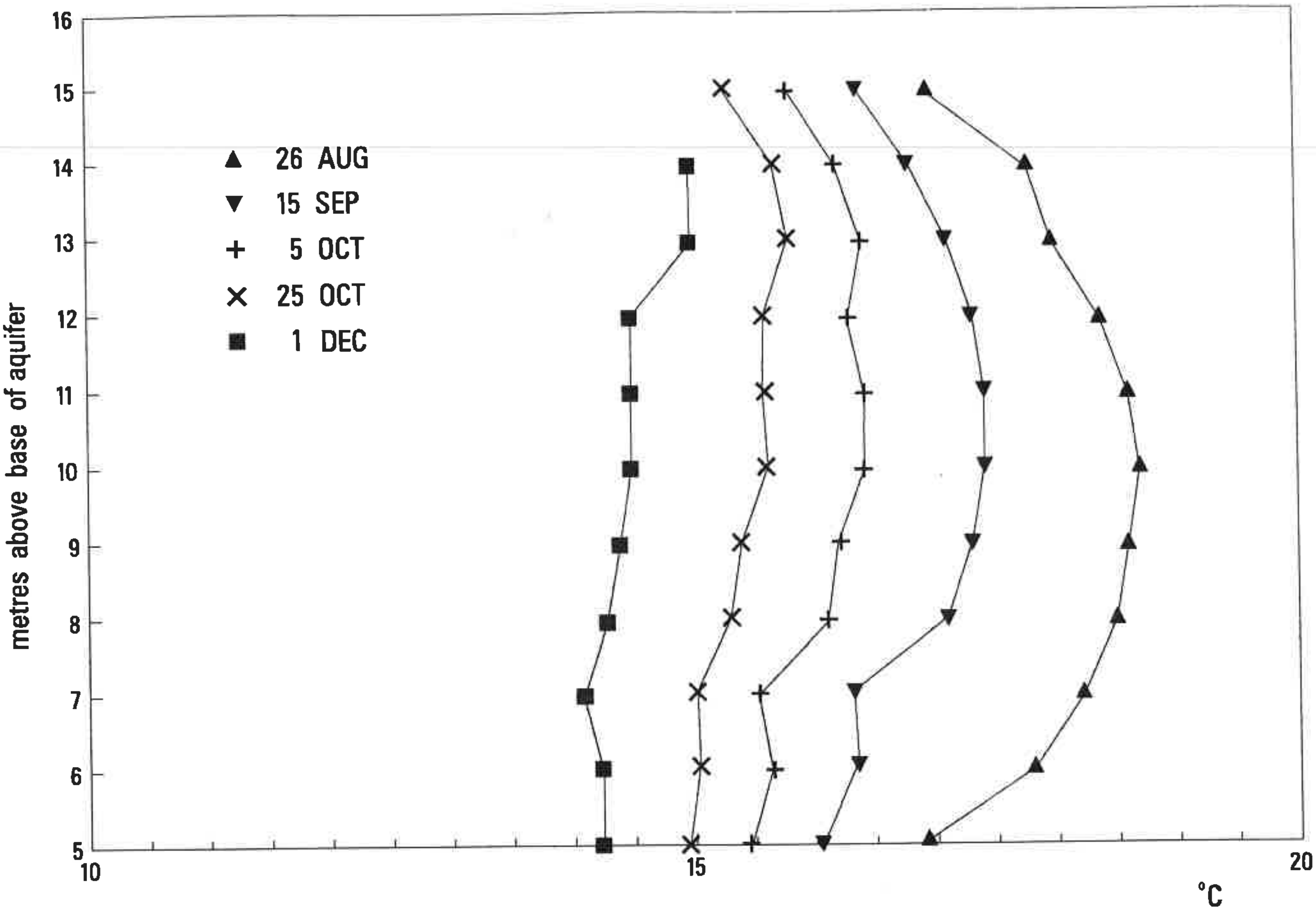


Figure 17 Vertical temperature profile at 10 m radius (abstraction phase).

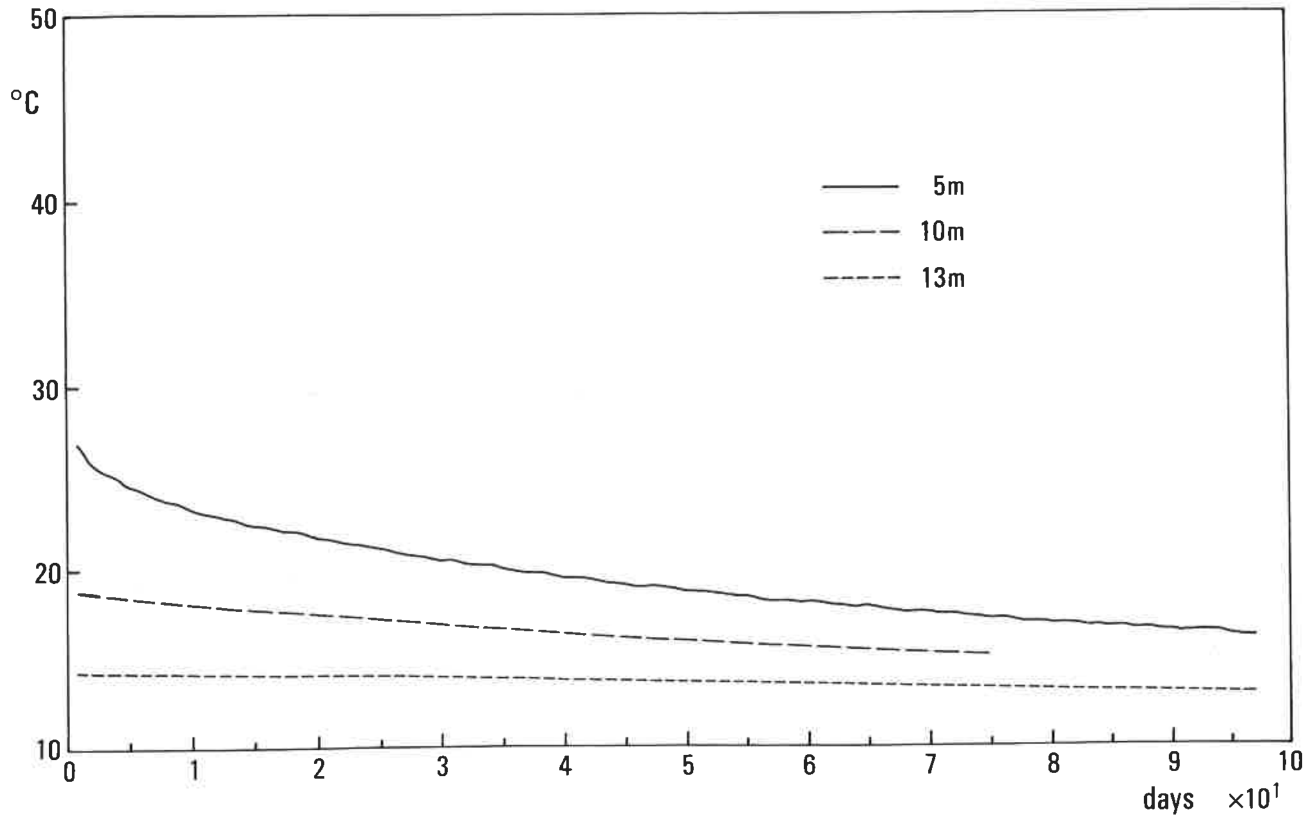


Figure 18 Maximum temperature against time (abstraction phase).

Using equation (2) it can be shown that a total of 86.64 MWH energy was injected and a total of 28.19 MWH abstracted—the total abstracted volume being greater than the injected volume by a factor of 1.29.

A thermal energy recovery factor can be defined as the ratio of total energy recovered (E_{out}) at any time during abstraction to total energy injected (E_{in}). Figure 19 shows this ratio plotted as a proportion of water recovered.

It can be seen that a total of 32.5% of the energy injected was recovered for 129% of the volume injected. An energy recovery factor of 27% was achieved for 100% volume recovery factor.

It was realised from the outset that an experiment of this size, bearing in mind the financial constraints was not likely to yield a high energy recovery factor. However the main purposes of the experiment were to gain experience in ATES techniques and provide data that could be used to calibrate a model of the system which could subsequently be used to predict the performance of other similar but larger systems.

In this experiment only a relatively small quantity of hot water (1520 m^3) was injected for one injection/storage/abstraction cycle only and an energy recovery factor about 30% was achieved. It is confidently expected that as the volume of hot water is increased the recovery factor will also increase significantly as the heat losses will be proportional to the radius of the sphere of influence squared and the volume stored to the radius cubed. Thus the ratio of heat stored to heat lost will increase proportional to the radius so that the energy recovery factor should increase with the size of the scheme.

Furthermore as the number of cycles of operation of an injection/abstraction scheme increases it is expected that the recovery factor will increase since some of the "lost" energy in a single cycle will have gone towards heating the aquifer matrix and that this energy will be "saved" in subsequent cycles.

3.2.4 *Mathematical modelling of results*

In ATES work it is highly desirable to develop mathematical modelling techniques to simulate the effects of heat injection and abstraction. In this way the limited results of expensive field experiments may be extended and extrapolated (within reason) to investigate the possible effects of further heat storage schemes in the same and similar aquifers. The first stage is always to calibrate the model as carefully as possible from the field experiment actually performed. The response of the model is assessed under these conditions and if differences between the model and field observations occur they must be investigated and appropriate corrections made to the model parameters to ensure agreement between model and field. When satisfactory agreement occurs it is then possible to use the model to predict the effect of different injection/abstraction schemes.

The model used in this work was a development of the Numerical Model CCC (conduction, convection-consolidation) constructed by the Lawrence Berkeley Laboratory (Mangold et al., 1980). This model solves numerically the heat and mass flow equations for a liquid saturated medium, and can compute one dimensional consolidation of the simulated systems. The model uses the Integrated Finite Difference Method in discretising the saturated medium and solves the equations by means of an iterative technique. The program was adapted to run on the Cray 1S machine at the University of London Computer Centre and a series of graphical routines were introduced to improve the output.

The finite difference equations used for the Reach simulation assumed radial symmetry. The Lower Green-

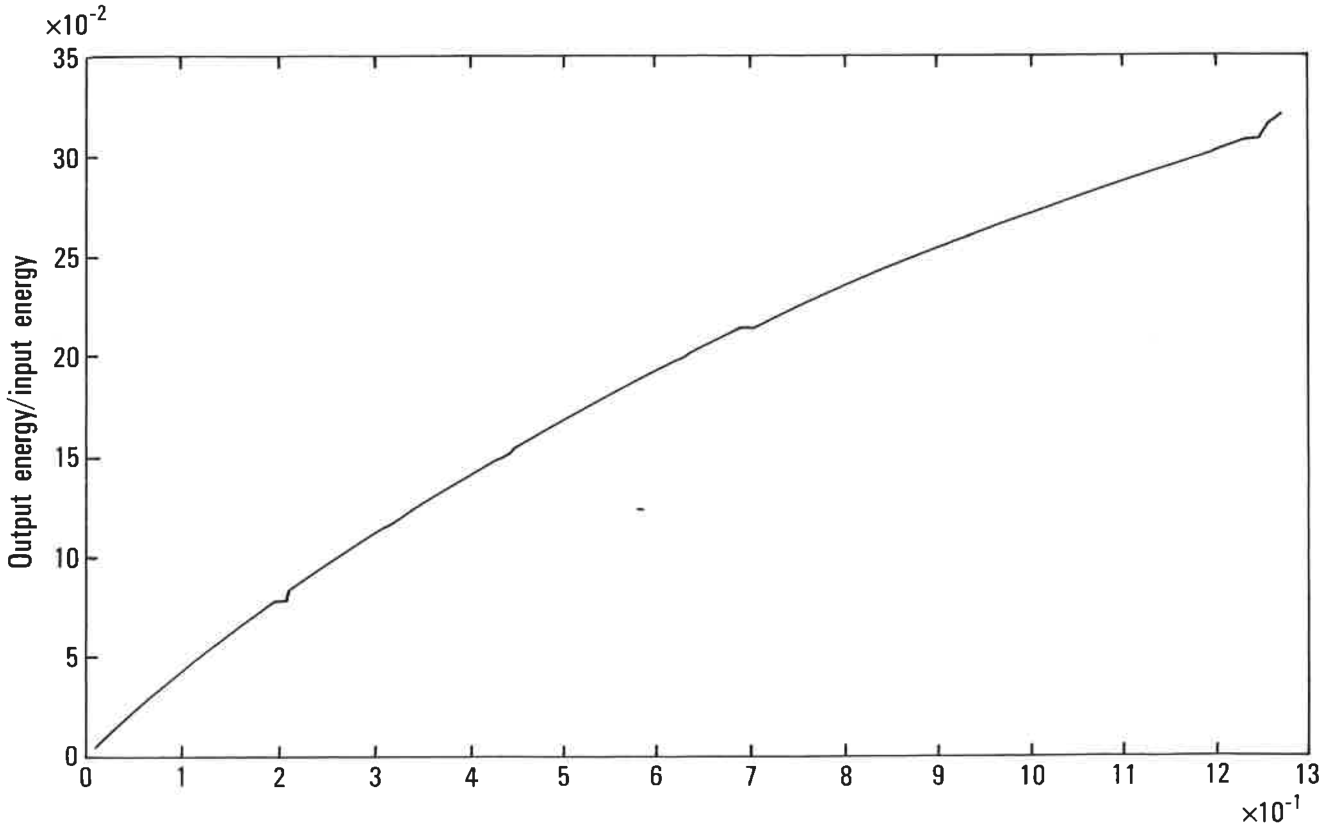


Figure 19 Energy recovered against proportion of injected water recovered.

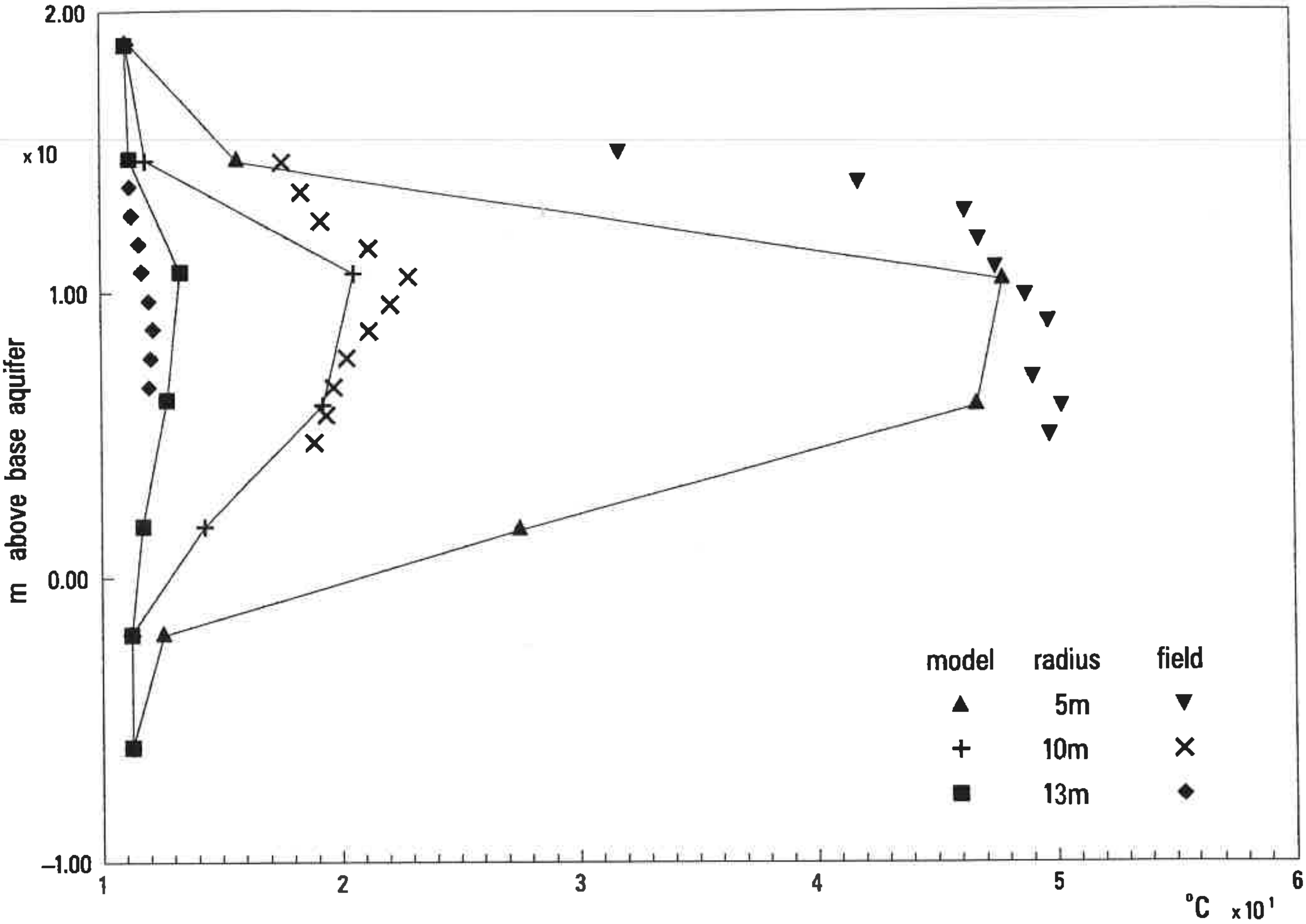


Figure 20 Comparison of model and field temperature/depth profiles (injection phase).

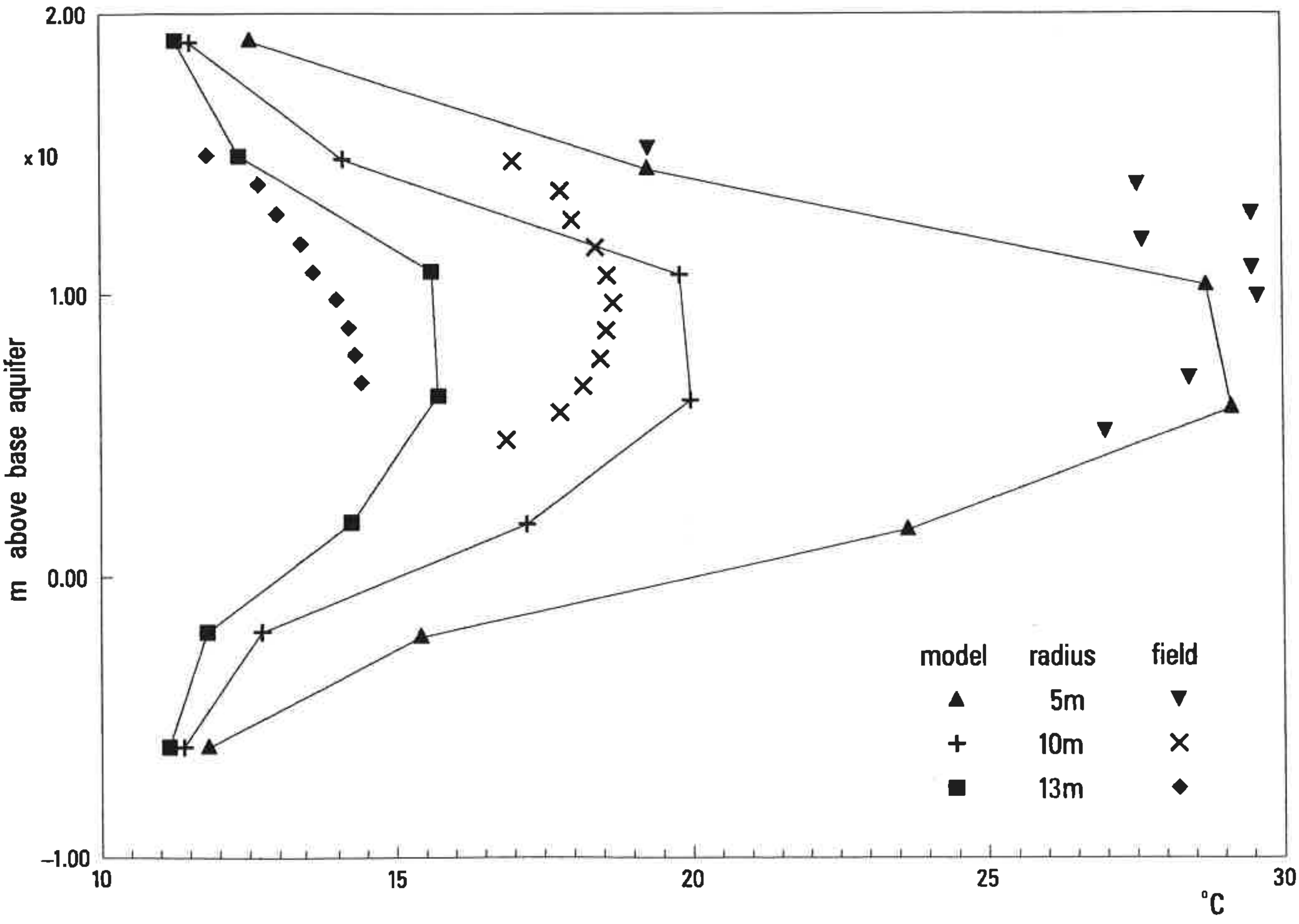


Figure 21 Comparison of model and field temperature/depth profiles (storage phase).

sand was simulated as three layers 4, 5 and 4 metres thick and a further 4 layers each 4 m thick above and below the LGS were incorporated in the nodal network used. Each layer was further divided into 28 radial nodes giving 196 total nodes.

The following thermal parameters were estimated for the Reach aquifer system:

Lower Greensand Thermal Conductivity 4.0 J/m/sec/°C
Heat Capacity 882 J/Kgm/°C

Gault & Jurassic Thermal Conductivity 1.4 J/m/sec/°C
Heat Capacity 1286 J/Kgm/°C

Good agreement was obtained between the model and field experiment for temperature/depth profiles using these parameter values (Figures 20 – 22). Slight discrepancies in different directions are probably due to aquifer inhomogeneity. Similarly the radial temperature profiles (Figure 23) show good agreement at the end of the injection stage and abstraction phases.

Having achieved good agreement between model and field results, the model was then used to investigate two larger schemes, one for diurnal and the other for interseasonal storage.

The diurnal scheme was based upon using an aquifer thickness of 5 metres and an injection rate of 405 KW at 80°C. Figure 24 indicates the fluctuations that might be expected on the output temperature. After 40 daily cycles of operation, the mean extraction temperature reaches 74°C with an energy recovery factor of 82%.

The interseasonal scheme was based upon using an aquifer thickness of 100 metres and an injection rate of 7.4 MW at 70°C. The output temperatures expected from such a scheme are shown in Figure 25. After 8 annual cycles of operation, the mean extraction temperature reaches 67°C with an energy recovery factor of 66%.

3.3 Current Status of Heat Storage in Aquifers in the U.K.

The studies undertaken for this project have demonstrated that it is possible to store and recover heat on an inter-seasonal basis. Additional modelling studies have shown that a large scale heat storage project might yield energy recovery ratios of 60 – 80%. Groundwater storage of energy on a shorter time scale(eg diurnal) is likely to be appropriate for Combined Heat and Power/District Heating Schemes where production of heat is usually out of phase with demand to some extent. The system is also likely to be appropriate where waste heat at an adequate temperature is available from industrial processes or refuse incineration.

Although Aquifer Thermal Energy Storage is only used at present experimentally in a few locations throughout the world, it is likely that it will be seen increasingly as an environmentally sound method of increasing the efficiency of energy use whilst significantly decreasing the necessary investment in cooling and backup systems associated with power generation.

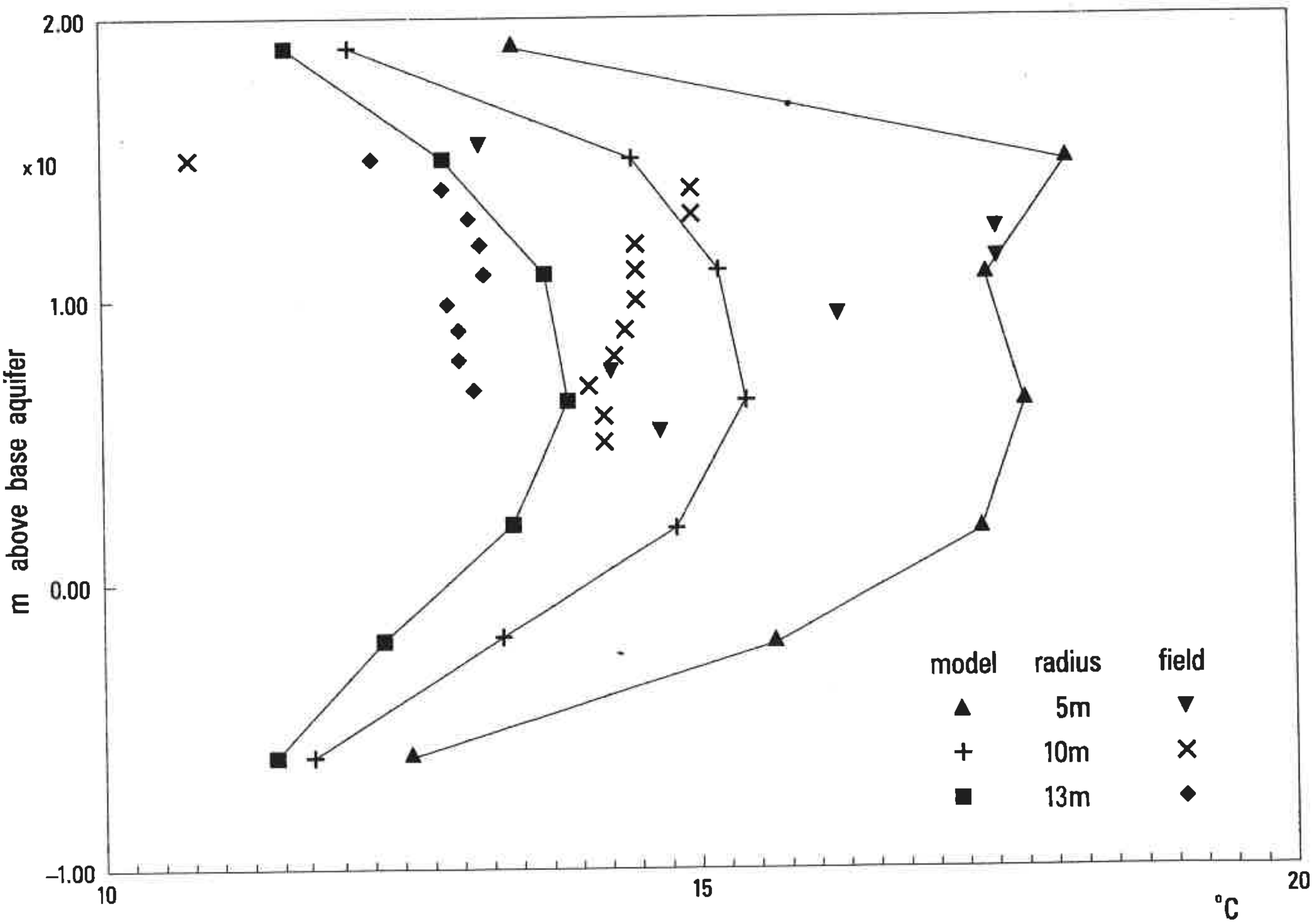


Figure 22 Comparison of model and field temperature/depth profiles (abstraction phase).

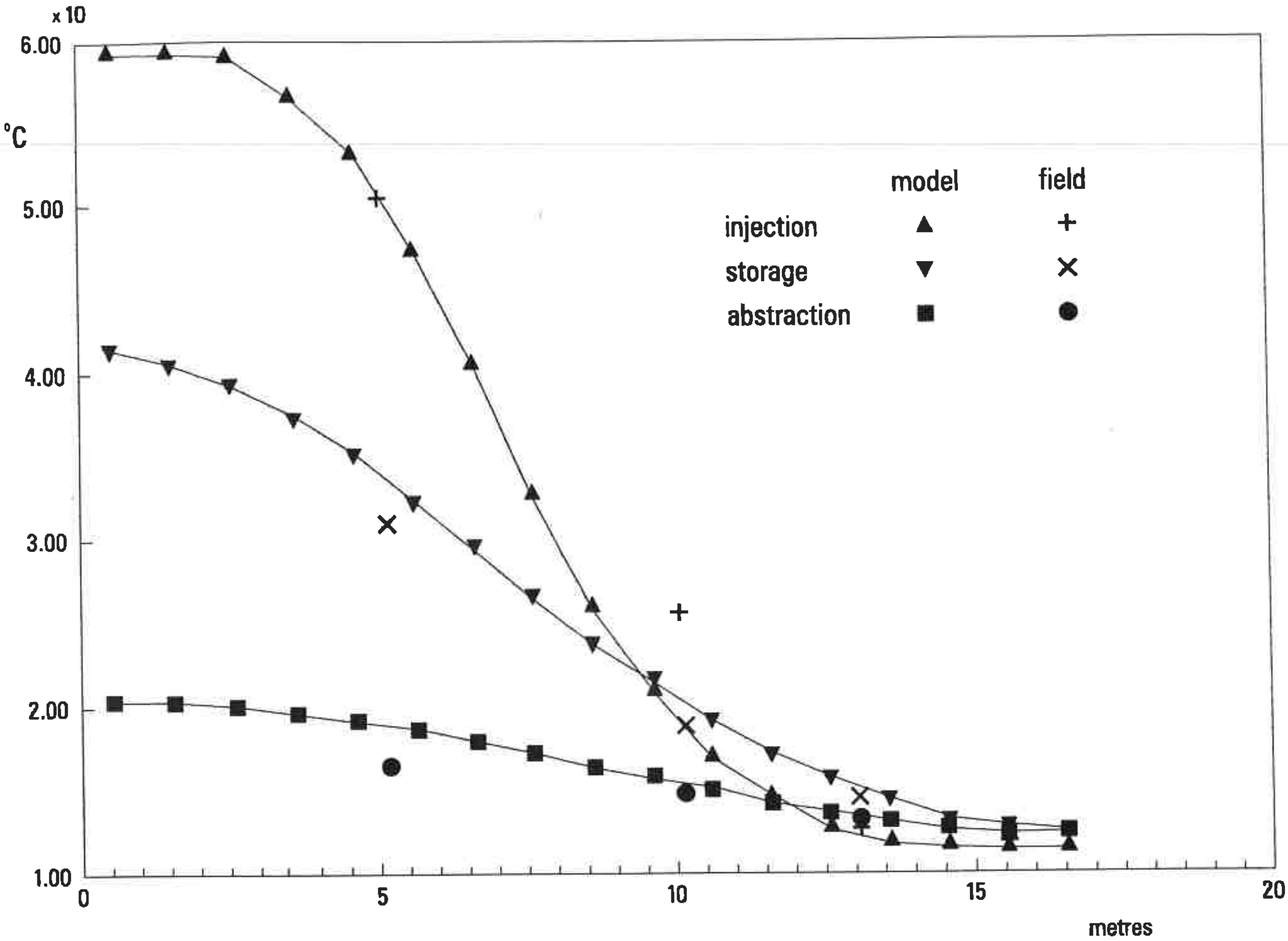


Figure 23 Comparison of model and field radial profiles.

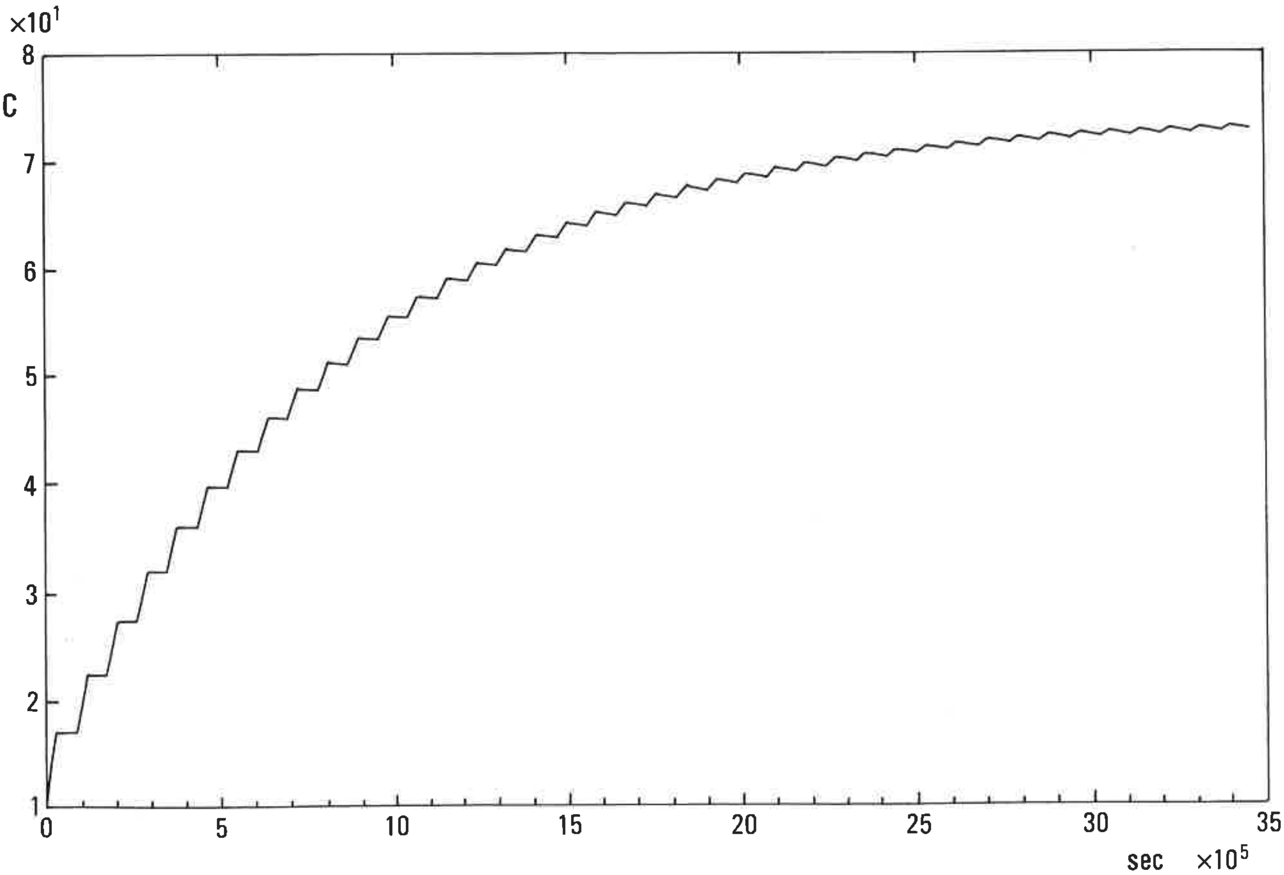


Figure 24 Abstraction temperature for proposed 405 KW diurnal storage scheme.

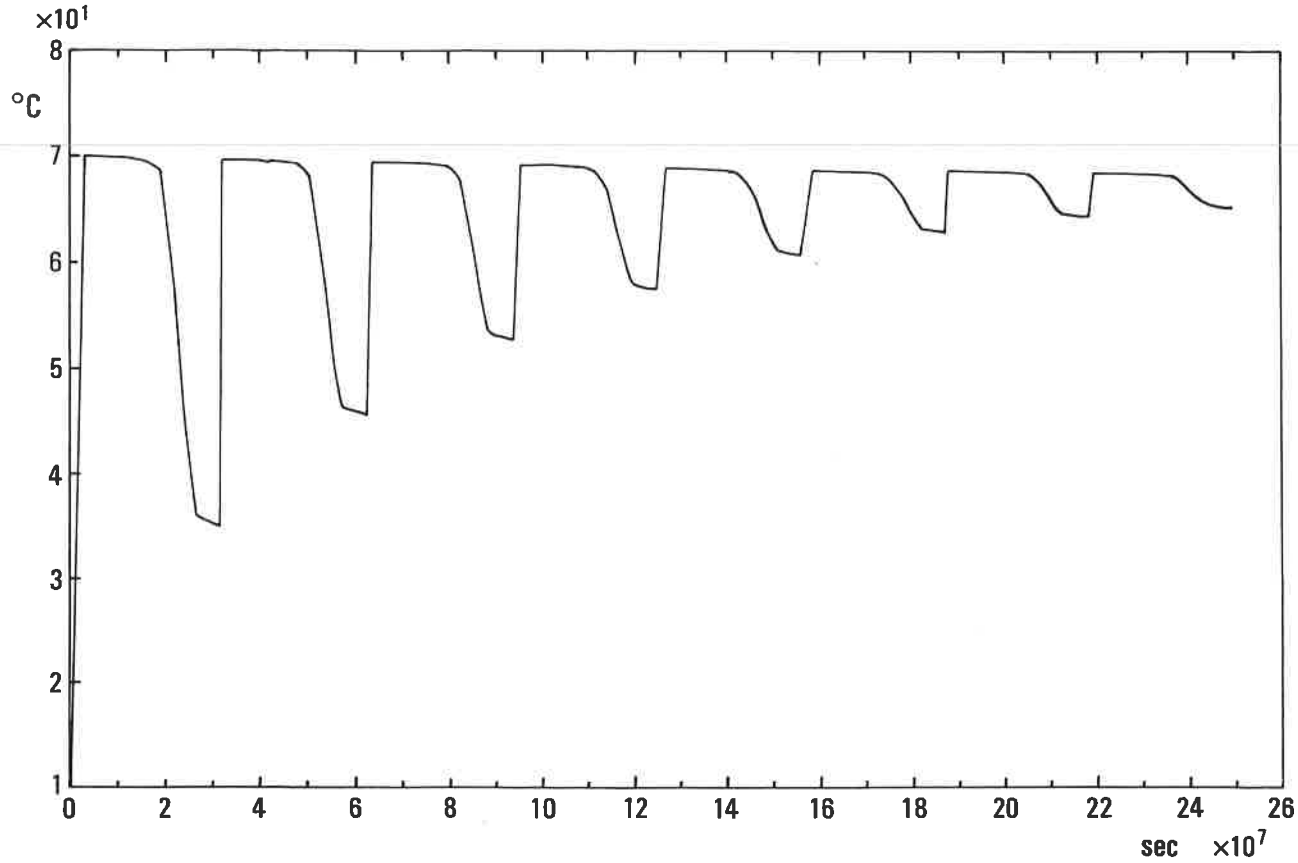


Figure 25 Abstraction temperature for proposed 7.4 MW inter-seasonal storage scheme.

REFERENCES

Adams, B, Kitching, R, Barker, J A, and Miles, D L. 1981. Investigation of the potential of aquifer thermal storage in the UK. Proceedings of the International Conference on Energy Storage-Brighton, 285–300.

Day J B W, and Kitching R. 1981. Prospects for groundwater heat pumps in the UK. Water, 29–31.

Kazmann, R G. 1971. Exotic uses of aquifers. J. Irrigation and Drainage Division, Proc. Amer. Soc. Civ. Eng., 97, IR3, 515–522.

Kitchen, R, and Lambert B. 1983. Report on the installation and operation of a groundwater heat pump in a house at Irvine New Town, Scotland. Internal Report WD/ST/83/3, Institute of Geological Sciences, London.

— 1984. The applicability of groundwater heat pumps to space heating. Agricultural Engineer, Vol.39, 28–32.

— 1985. Groundwater: An economical source of heat. Span, Vol.28, 39–40.

— and Adams B. 1985. Thermal Energy Storage studies in the Lower Greensand Aquifer in Cambridgeshire. Q. J. Eng. Geol., Vol.19, 143–154.

Mangold, D C, Lippman, M J, and Bodvarsson, G S. 1980. Computer Program CCC. Lawrence Berkeley Laboratory Pub. No. LBL-10909.

Meyer, C F, and Hausz, W. 1980. Guidelines for conceptual design and evaluation of aquifer thermal energy storage. Report for Pacific Northwest Laboratory STES Program. PNL 3581 94e GE 80T MP-44.

— and Todd, D K. 1973. Conserving energy with heat storage wells. Environmental Sciences and Technology, 7, 512–516.

Molz, F J, Melville, J G, Guven, O, and Parr, A. 1983. Aquifer thermal energy storage: an attempt to counter free thermal convection. Wat. Res. Res. 19, No. 4, 922–930.

— Parr, A D, and Andersen, P F. 1981. Thermal energy storage in a confined aquifer: second cycle. Water Res. Res. 17, No. 3, 641–645.

— — — Lucido, V D, and Warman, J C. 1979. Thermal energy storage in a confined aquifer: Experimental results. Water Res. Res. 15, No. 6, 1509–1514.

Tsang, C F (Ed.). 1978. Thermal energy storage in aquifers workshop—proceedings. Lawrence Berkeley Laboratory, Univ. California LBL-8431. NTIS (CONF-7805140).

Van Beek, C G E M. 1980. A model for the induced removal of iron and manganese from groundwater in the aquifer, Int. Assoc. Geochem. and Cosmochem. and Alberta Research Council. 3rd Int. Symp. on Water-Rock Interaction— Edmonton.

Yan, Q S. 1981. The development and applications of aquifer storage in China. Proceedings of the International Conference on Energy Storage—Brighton. 275–283.

BGS Research
Report SD/90/1

Groundwater heat pumps and aquifer heat storage

ISBN 0 85272 195 1

£6.50

Natural
Environment
Research
Council