Performance of an interseasonal heat transfer facility for collection, storage, and re-use of solar heat from the road surface

by D R Carder, K J Barker, M G Hewitt, D Ritter and A Kiff

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PERFORMANCE OF AN INTERSEASONAL HEAT TRANSFER FACILITY FOR COLLECTION, STORAGE AND RE-USE OF SOLAR HEAT FROM THE ROAD SURFACE

Version: Final

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CONTENTS

Executive summary

The use of ***interseasonal heat transfer*** systems incorporating solar energy collectors in the road and shallow insulated heat stores in the ground is currently innovative and at the forefront of technology. A major instrumented trial of the technique was undertaken on an access road near Toddington which involved constructing two solar heat collectors (pipe arrays each 5m wide by 30m long installed at 120mm depth below the road surface) and two insulated heat stores of similar dimensions but at 875mm depth. One store was beneath the road and the other beneath the verge to simulate new construction and retrofit installations respectively. The solar heat recovered from the road surface was used to investigate the winter maintenance of the road surface and the heating of nearby buildings. The cooling of a building in the summer was also separately simulated.

This report describes the design, construction, operation and performance of the ***instrumented test facility*** to recover heat from the road surface. The performance was monitored over a two year period which gave the opportunity for full seasonal assessments of the recovery of solar heat from the road surface, its re-use for ice-free winter maintenance of the road surface, and protocols simulating the winter heating and summer cooling of a nearby building. Numerical modelling and whole life costing of the recovery of heat for winter maintenance of a highway was included in the study.

Measurements during the good summer of 2006 showed that ***6.5MWh of heat energy was transferred*** from the road collector (at 120mm depth of cover) to the insulated heat store in the ground, i.e. about 43kWh/m^2. During July when the air temperature peaked at 34^{o}C, peaks of 50^{o}C and 38^{o}C were recorded at the road surface and at collector pipe level respectively.

Winter maintenance of the road was carried out in 2006/07 operating from this fully charged heat store. When the road surface temperature fell below 2^{o}C and the heating was activated, this section of road was generally maintained at a temperature about 3^{o}C hotter than that of the unheated control area. Almost without exception the heated area of road remained above freezing until the period of extremely cold weather in early February 2007. On February 7th extreme surface temperatures of -6^{o}C and -3^{o}C were measured for a few hours on the unheated and heated sections respectively. On the following morning snow fell and briefly settled although the road surface was being maintained between 0^{o}C and +0.5^{o}C at the time. Apart from this one incident, no other issues were encountered in keeping the road surface above freezing. Heating was activated automatically on 16 more days than the 28 days on which salting took place on the nearby motorway: further tests would be advantageous to refine the parameters used for triggering surface heating.

The report gives details of ***building heating and cooling simulations*** which demonstrated the potential for seasonal heat storage in the ground, although further full scale trials would be advantageous. There are significant advantages in providing a self-sufficient building system incorporating both heating and cooling capability. In this way heat recovered during the cooling period can be re-used for building heating in the winter. There may be merit in boosting the heat recovery by the recovery of solar energy recovery from asphalt surfaces (road or carpark) particularly during cold summers when building cooling is not required so frequently.

The results from ***computational fluid dynamics*** modelling of solar heat recovery from the road surface and its use for winter maintenance generally showed good agreement with the measurements and demonstrated the validity of the technique in predicting performance. The modelling also indicated that significant improvement in overall performance would be achieved if the depth of cover over the collector pipes below the road surface can be reduced below the 120mm used at Toddington, although this may raise pavement durability issues.

Details of the ***whole life costs*** of a winter maintenance system (incorporating summer heat recovery) suggest that treatment of well-known cold spots on the highway network or treatment of slip roads and interchanges may provide cost effective locations for initial implementation of interseasonal heat transfer systems.

The ***thermal imaging*** successfully detected the presence of the collector pipe array at shallow depth and demonstrated that the technique is an effective “trouble-shooting” tool when operating under-road heating systems in detecting leaks, cold spots and pipe locations to avoid damage during subsequent road and utility maintenance operations.

1 Introduction

In response to the sustainable development agenda there has been an increasing emphasis on the generation of energy from renewable sources. The UK Government's initial target is to exceed 5% from renewable sources by 2003 and 10% by 2010. This target was modified by the Energy White Paper issued on 24th February 2003 which aspired "to double renewables' share of electricity from our 2010 target by 2020". Recognising the importance of developing renewable energy resources, the Highways Agency commissioned a scoping study at TRL to explore available methods and assess the possibility of renewable energy generation being exploited within the highway network.

A previous study (Carder, 2003) recommended a positive response by the Highways Agency in implementing full-scale trials of renewable energy generation. A demonstration trial using photovoltaic panels mounted on the exposed faces of noise barriers to generate electricity from solar power was undertaken on the M27 in Hampshire and this is separately reported by Carder and Barker (2006).

A second trial demonstrating the use of heat exchangers and ground source heat pumps in recovering energy from solar thermal heating of road surfaces was also identified and is the subject of this report. It should be noted that this technique is suited to direct heating applications and cannot be conveniently used for electrical power generation. However, in addition to the possibility of direct heating of nearby buildings, this technique may be of particular advantage to the Highways Agency for the winter maintenance of pavements, i.e. prevention of ice and snow formation on the road surface. Winter maintenance applications may be particularly applicable to areas in England where a micro-climate exists that may impact on the effectiveness of conventional winter maintenance plans.

The use of this technique of interseasonal heat storage is at a critical stage of its evolution. This is linked to the broader capability of building physicists to accurately model complex energy flows at the urban and infrastructure level, using computational techniques (Hewitt, Ford and Ritter, 2000). The increased use of predictive techniques is expected to lead to a rapid expansion in its use in providing a renewable "green energy" source, provided that the findings are validated by full scale trials such as this.

In the past, heat storage has mainly employed very deep stores installed in piled foundations or utilising the aquifer. This particular trial employs the innovative technique of using shallow earth stores which are insulated (Hewitt and Ford, 2002 and 2007).

This report describes the design, construction, operation and performance of the instrumented test facility to recover heat from the road surface. The performance was monitored over a two year period which gave the opportunity for full seasonal assessments of the recovery of solar heat from the road surface, its re-use for winter maintenance of the road surface, and protocols simulating the winter heating and summer cooling of a nearby building. Numerical modelling and whole life costing of the recovery of heat for winter maintenance of a highway was included in the study.

2 Description of the site

2.1 Site location

In view of the prohibitive cost both in terms of construction and disruption to traffic, installation of a heat transfer system on a motorway or trunk road was not considered appropriate until the technique was proven. Initial investigations were therefore carried out to identify suitable locations where the demonstration trial could conveniently take place. The types of location which were considered included access roads to HA Maintenance Depots, access roads to motorway service stations, and quarries.

As the results of a comprehensive evaluation, a site (OS grid reference 50257,22925) was selected on a private access road owned by the Highways Agency which runs northwards from the Toddington Motorway Service Station and is parallel adjacent to the northbound M1. The road carries occasional vehicles accessing the service station and the nearby HA Maintenance Depot and also private vehicles using it as a shortcut to local roads.

The road is 5.6m wide (2 lane, bi-directional traffic) and comprises an approximately 250m length of straight road. To the east of the road there are a number of HA storage compounds and parking areas whilst, on the west, there is a 1-2m wide flat verge after which the ground slopes down to a drainage ditch. There is very little shading of the road surface.

2.2 Ground conditions

Examination of the ground investigation carried out in 1993 as a preliminary to the proposed M1 widening showed stiff grey Gault Clay from about 3m depth to a depth exceeding 25m. In the motorway verge to the east of the trial site, the Gault Clay was overlain by Head Deposits comprising mainly firm silty clay. On the west side of the private access road, a reworked Gault Clay layer of about 0.8m thickness overlayed the undisturbed clay, indicating that some filling had taken place in this area during construction of this section of the M1 before its opening in 1959.

3 Experimental design

3.1 Outline design

At this site an interseasonal heat collection and storage system was installed to evaluate the performance of two different types of storage technique, namely:

- retrofitting the collector pipe arrays to an existing road surface during the normal maintenance regime with the heat store pipe arrays installed in the verge adjacent to the road;
- a new build situation with the heat store and collector pipe arrays both incorporated into the road structure during the construction process.

The schematic layout to model these situations at Toddington is shown in plan and three-dimensional views in Figures 3.1 and 3.2 respectively. Each store and collector pipe array was of identical dimension (5m × 30m) and comprised 25mm diameter cross-linked polyethylene pipes with a spacing of 250mm between adjacent longitudinal pipe runs, more details on these are given later.

An insulation layer comprising 200mm thick expanded polystyrene was placed over each heat store to prevent heat loss. This insulation layer generally extended 6m to each side of the four sides of the rectangular stores to prevent heat loss from the surrounding ground. On one side of store 2, the insulation was placed beneath the surface of a slope to a drainage ditch.

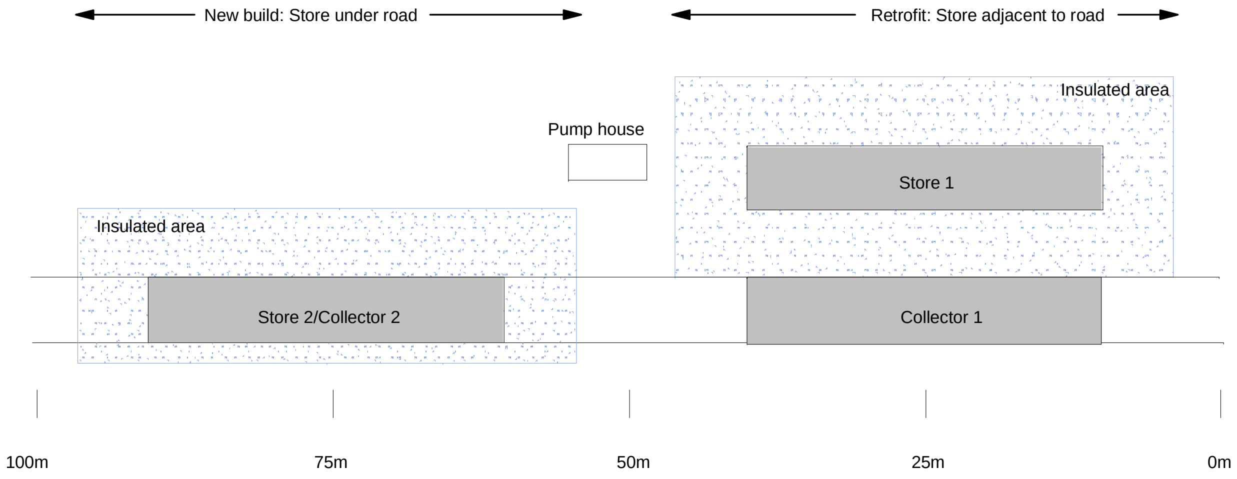

Figure 3.1. Plan showing the layout of the trial

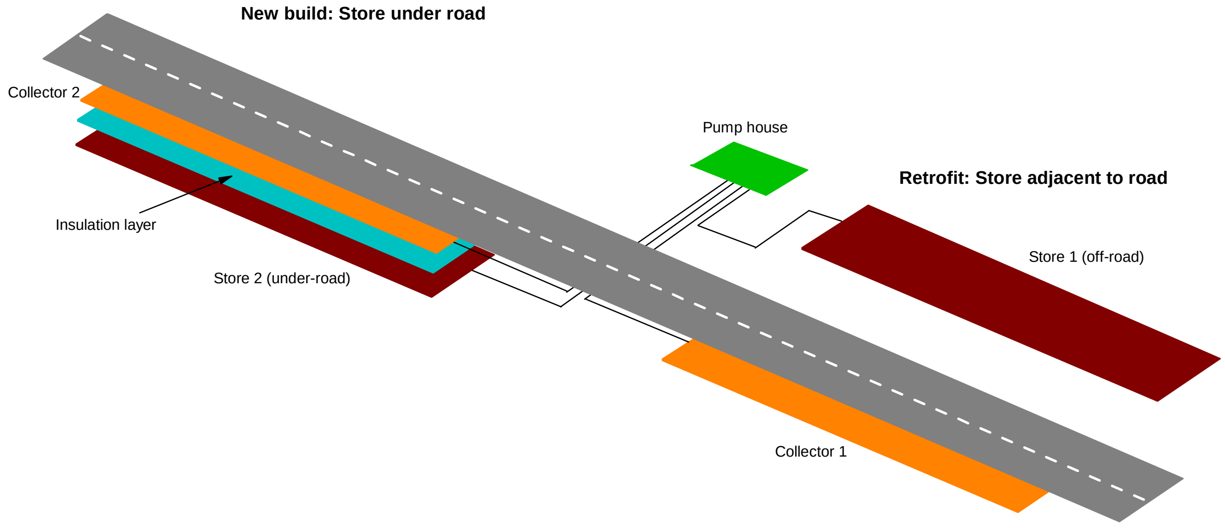

Figure 3.2. Three-dimensional schematic showing the layout of the trial

3.2 More detailed design layout

Some modifications were necessary to the outline design to accommodate various constraints at this site, notably:

- The presence of buried utilities (gas, water, telephone, motorway communication cables) in the verge areas meant that mechanical excavation could not be used in their proximity. For this reason continuity in the insulation layer was achieved, where necessary, by installing layers at slightly different levels and overlapping the layers.
- On the west side, and adjacent to the under-road store, the ground slopes down to a drainage ditch. For this reason the polystyrene insulation could not be placed horizontally, but instead was placed just below the slope surface.

A cross-section through collector 1 and the off-road store is shown in Figure 3.3. It must be noted that for clarity in Figure 3.3, the scale in the horizontal and vertical directions differ by a factor of 100. As previously mentioned the different levels of the insulation were necessary to avoid the buried utilities and would not be a normal construction feature. The pipes forming the heat store were fixed to the underlying clay surface using metal pins, whilst the collector pipes were fixed using wire ties to a 6mm steel square mesh. The concepts used for the design of the road structure are described in more detail in Section 3.3.

Figure 3.4 shows a cross-section through the under-road store and collector system. The pipes were fixed using pins and wire ties in the same way as before. However it should be noted that a stiffer grade of polystyrene insulation (Fillmaster 200) was used in the load-bearing situation below the road rather than the Fillmaster 100 used elsewhere. On the west side of the road, the insulation extended about 3.7m down the slope following its profile, although minor amendments to the polystyrene detail were made to avoid the telephone cable where necessary. The design of the road structure is dealt with below.

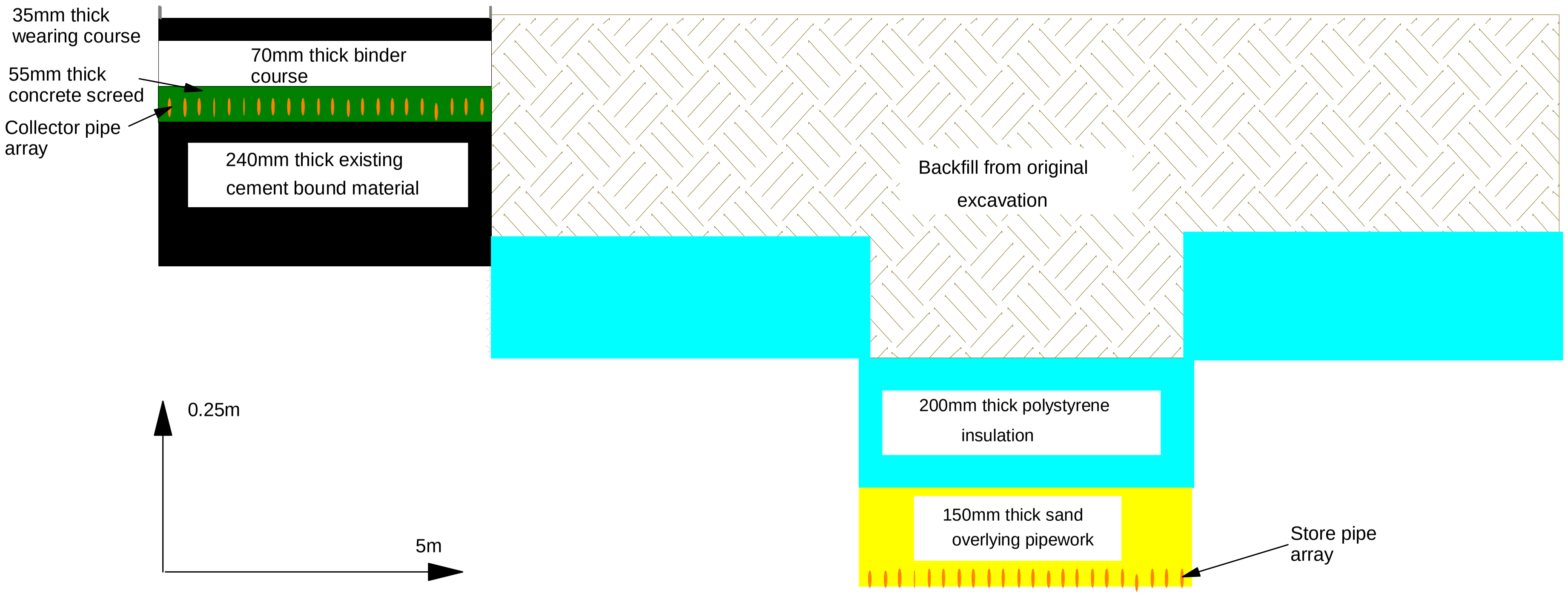

Figure 3.3. Cross-section through collector 1 and the off-road store 1

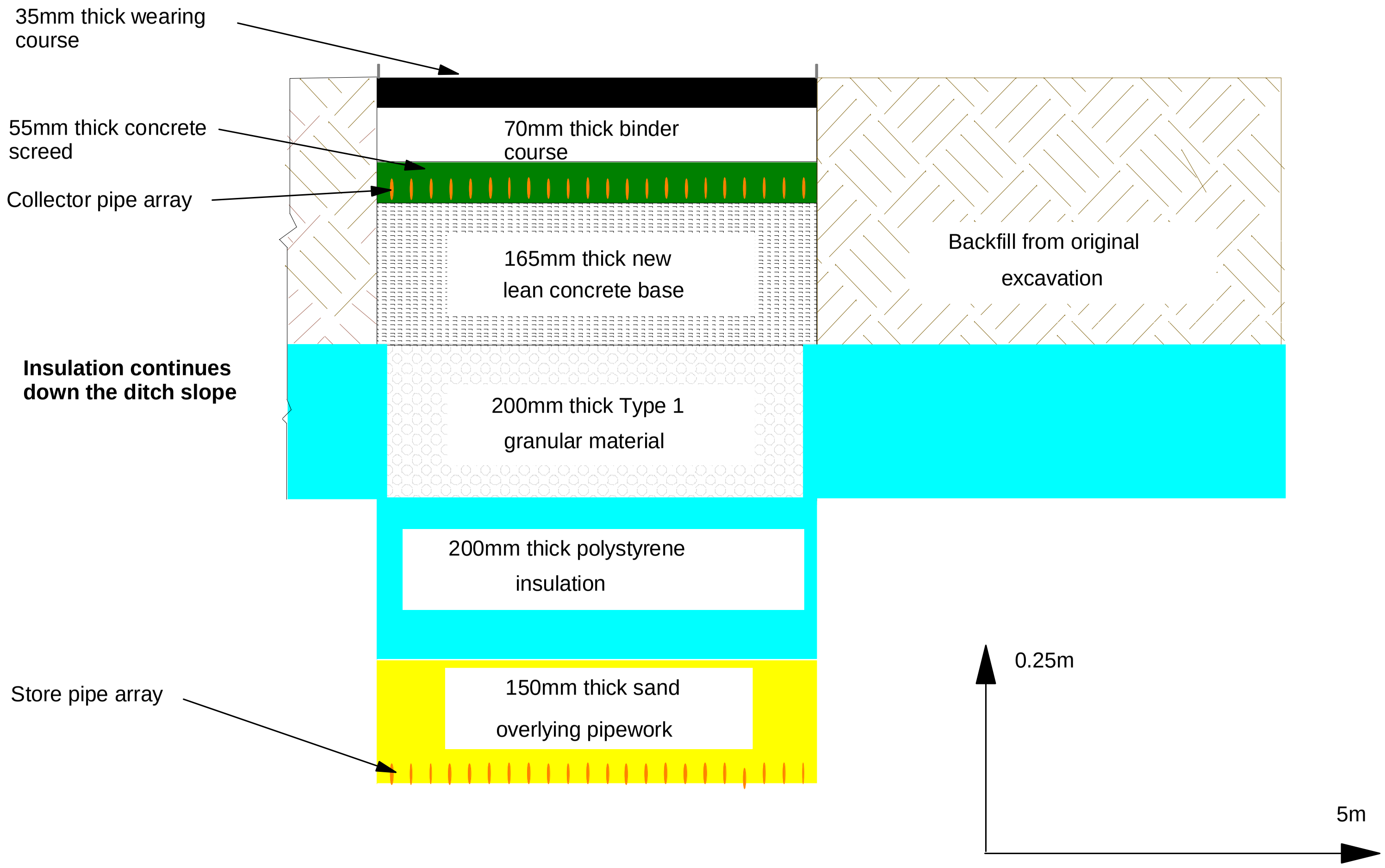

Figure 3.4. Cross-section through collector 2 and the under-road store 2

3.3 Design of the road structure

The existing road structure was cored prior to the commencement of works. The coring established that the structure comprised 160mm of asphalt overlying 240mm of cement bound material. Dynamic cone penetrometer tests below this depth established 200mm of type 2 granular material overlying the Gault Clay. Empirical correlations on the findings indicated that the California Bearing Ratio (CBR) of the clay exceeded 9% as is shown in Figure 3.5. Based on these parameters the original road structure would be adequate for a design life of 20 million standard axles (msa).

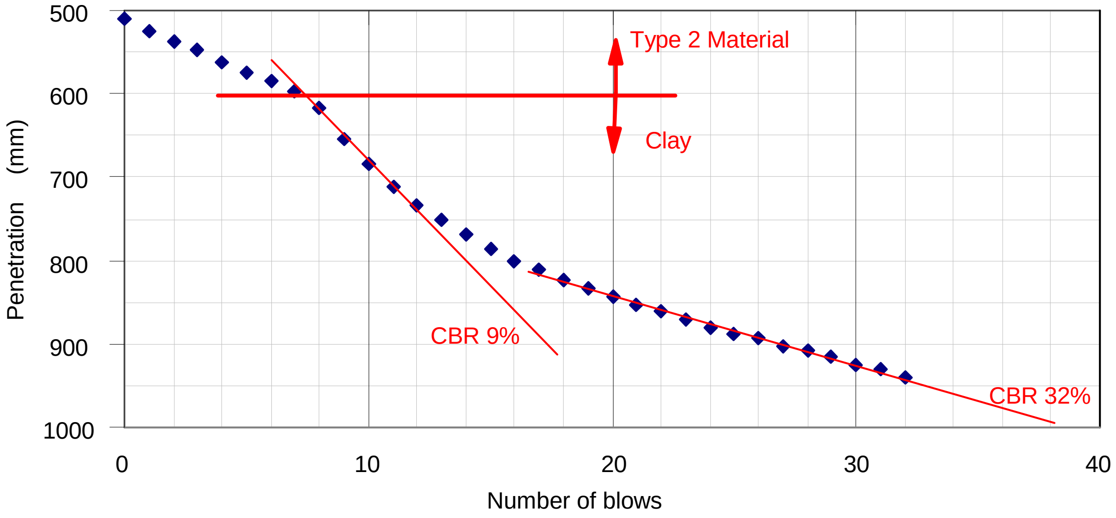

Figure 3.5. Dynamic cone penetrometer tests on the existing formation

In terms of the design of the new road structure, the intention was to ensure that the structure was at least as strong as the existing road. Because of the need to accommodate the pipe arrays and insulation layer within the structure, the design was non-standard.

With regards to the foundation design, the dynamic cone penetration tests showed that the California Bearing Ratio (CBR) of the Gault Clay immediately beneath the existing road structure exceeded 9%. Reference to Figure 3.1 of HD25/95 Foundations (DMRB 7.2.2) indicates that for this subgrade CBR, the alternative designs of (i) 150mm sub-base on 200mm capping, or (ii) 180mm sub-base would be acceptable. On the basis of (ii) the 200mm thick layer of type 1 granular material was adequate in its own right, and both criteria to produce a “standard foundation” are more than met if the Fillmaster 200 (which has a compressive strength of 90kPa at 1% strain) is considered as structural.

The design thicknesses of the asphalt layers and the lower base of the road structure were evaluated following the approach of HD26/01 Pavement Design (DMRB 7.2.3). The lower base materials comprised 165mm of lean mix (CBM3 containing gravel aggregate and with a minimum compressive strength of 10N/mm^2) and the 55mm thick concrete screed. Figure 2.3 of HD26/01 indicates that this total thickness would be appropriate for design traffic of 20 million standards axles.

Figure 2.3 of HD26/01 also shows that for the total thickness of the asphalt layers of 105mm, the design traffic would be 4.5msa which is considered more than adequate for this private access road. It should be noted that a thickness of 150mm would normally be required for a 20msa life of a trunk road. Whilst the thickness of asphalt employed might be susceptible to reflective cracking in later life, it can be argued that the heat collectors would act to keep the road surface at a more even temperature throughout the year. This would reduce movement at natural cracks in the lean mix and hence the risk of reflective cracking occurring.

4 Construction process

The sequencing of the construction operations is given in Appendix A. The major activities are now described.

4.1 Enabling works

Trial holes were excavated to expose the buried utilities and confirm their locations within the construction zone. The following services were identified:

- gas main (polyethylene lined cast-iron) at a depth of 0.75m and at 0.8m from the east kerb of the road,
- NTL cable at a depth of 0.4m and at 1.9m from the east kerb,
- water main (asbestos-cement) at 1m depth and at 3.2m from the east kerb,
- telephone cables (in 100mm diameter PVC duct) at 0.7m depth and at 5m from the east kerb,
- telephone cable at 0.55m depth and at about 1m from the west kerb,
- motorway communication cables running about 2m outside of the motorway perimeter fence and inside of the construction zone.

The locations of these services had already been taken into account in the design process and only minor changes were subsequently necessary. These were in the polystyrene detail near the west kerb which was locally adjusted because the telephone cable was found to meander rather than running in a straight line.

Preliminary activities included stripping off the topsoil and removing vegetation in localised areas where it interfered with the proposed construction. After these activities, the site was marked out ready for the excavation for the various pipe arrays comprising the heat collectors and stores.

4.2 Excavation

Excavation in all areas was carried out to the required depths using laser levelling to control the process. Figure 4.1 shows a photograph of the site when excavation was near completion.

Throughout the excavation process, the excavated material was stockpiled to the north and south of the site for re-use at a later stage. Generally the excavated depth did not exceed 1m and for this reason no special drainage or ground support measures were required.

Figure 4.1. General excavation

4.3 Manhole, pipe array and header installation

Following excavation in each area the 25mm diameter cross-linked polyethylene pipes were installed to form each pipe array according to the construction schedule given in Appendix A. Both of the heat stores and collector 1 used pipe manufactured by Wirsbo, whilst collector 2 used pipe manufactured by Rehau. Both pipes incorporated an oxygen diffusion barrier and the main difference between them was the stiffer flexural rigidity of the Rehau pipe. Initially there were concerns that forming the required bends might therefore prove more difficult with the latter pipe, however this proved not to be the case.

As mentioned in Section 3.2 the heat store pipes were pinned to the underlying clay surface. Figure 4.2 shows the pipe array for store 1 being installed. The pipe array for heat store 2 was near identical apart from the fact that the pipe exits were to one side of the array rather than to its end. In all cases the pipe runs between the array and the manifolds within the manhole were insulated using 32mm thick Armaflex insulation.

Figure 4.3 shows the pipe array for collector 2 after its installation and prior to road surfacing. As previously mentioned these pipes were retained in their position using wire clips attached to 6mm steel square mesh.

Figure 4.2. Pipework for off-road heat store being installed

Figure 4.3. Completion of pipework for heat collector 2

Pipes from each heat collector and store were connected to a manifold installed in a nearby inspection chamber (Figure 4.4). Taps on each flow and return line enable individual loops to be activated as required. The flow and return header pipes from each manifold to the pump house were polyethylene and 76mm in outside diameter.

Figure 4.4. Manifold system within inspection chamber

4.4 Placement of insulation

Following installation of the heat stores in each area and the placement of a 10mm thick layer of sand over the pipe arrays (Figure 4.5), a 200mm thick layer of polystyrene was placed over the two heat stores (Figure 4.6). The polystyrene boards (2.44m × 1.22m) forming this layer were carefully positioned to butt against each other so that no gap was left through which heat loss could occur. As shown in Figure 3.3 for the off-road store, this layer was extended to a distance of 6m beyond each edge of the rectangular store area. Because of the presence of buried services, this surrounding insulation was at a different level from that immediately over the store although a minimum overlap of 200mm was ensured at all times. As laser levelling was used to control the excavated level of the clay, it was only necessary to use sand to make good the level in a few isolated areas prior to placing the polystyrene.

Continuity of insulation at the edges of the heat store below the road was maintained by removal of the kerbs during construction and re-building the kerb line on top of the polystyrene layer. As with the off-road store, horizontal insulation extended a distance of 6m beyond the edges of the store where possible. However on the west side of the road this was not feasible and insulation was therefore installed to follow the profile of the slope as is shown in Figure 4.7. In this area the polystyrene boards needed cutting to achieve a good fit and a hot wire cutter was used for this purpose.

Figure 4.5. Placing sand over the off-road heat store

Figure 4.6. Placement of polystyrene over the off-road heat store

Figure 4.7. Polystyrene insulation being installed on the slope

4.5 Ground reinstatement

After installation of the insulation in all of the off-road areas, the excavated clay was placed and compacted over the insulation prior to replacing the topsoil. The surplus material from the excavation was formed into an earth bund of about 1m height around the site to prevent off-road parking on top of the experimental area.

Stability of the ditch side-slope was ensured by placing a layer of hessian over its face and then grass seeding.

4.6 Road construction

Following placement of the polystyrene insulation layer over the sand layer containing the under-road store pipes, the following road construction activities took place:

- Compaction of Type 1 granular material (Clause 803, SHW) to a thickness of 200mm;
- Placement and compaction of 165mm thick layer of new lean concrete road-base material;
- Installation of collector pipework onto 6mm steel square mesh;
- Placement of 55mm thick layer concrete screed around the pipework using a vibrating metal beam screed to compact. The concrete was ST4 (P300) specified for a 50mm slump except using a 10mm aggregate instead of the usual 20mm. This has the effect of increasing actual slump to 200+ (ie a slurry);

- Compaction of 70mm thick binder course layer of heavy duty macadam (HDM 50, ie. 50 pen bitumen) with a 20mm aggregate size (clause 933, SHW);
- Compaction of 35mm thick wearing course comprising stone mastic asphalt (SMA, proprietary product name "Smatex") with a 10mm aggregate size (clause 942, SHW)

When the road was complete, its centre line was remarked and the extent of the collector areas indicated by broken yellow lines on the final surface.

4.7 Installation of pump house

During the works, six reinforced concrete pads were constructed to provide a foundation for the pump house. The pump house was purpose-built and fully equipped off-site and lifted into place using a Hiab (Figure 4.8). This meant that the pumps, valves, control system, etc. were all in place and on-site commissioning could be undertaken fairly rapidly.

Figure 4.8. Pump house delivery

The main activities of the on-site commissioning were electrical connection, connection of the flow and return pipes from the collectors and stores to the pump house, filling the system, balancing the pumps and checking operation of the motorised valves, testing the heat pump, and commissioning the control system. The complete system, comprising the pipe arrays and pump house unit, was filled with water containing 10% by volume of an anti-freeze mix to provide frost protection. The mix comprised mono-ethylene glycol with corrosion, scale and biological inhibitors.

4.8 Contractor feed-back on construction process

Following completion of construction a meeting was held with the Principal Contractor for the civil works to discuss any improvements which could be incorporated into future construction of a similar type. The following main points emerged:

(i) General comment: No problems were encountered with the excavation, backfilling and road surfacing. The buried utilities in the area were successfully avoided without damage although careful supervision was necessary. The different designs of the off-road and under-road stores meant that construction could proceed continuously rather than there being delays to the construction whilst the pipe arrays were installed. Sectionalising in this way is recommended for future constructions to avoid extra costs through delays to the contractor.

(ii) Installation of store pipe arrays: These pipe arrays were pinned to the excavated clay surface prior to placing and compacting a 100mm thick layer of sand over them. No difficulties were encountered with this procedure.

(iii) Installation of collector pipe arrays: Although the installations were completed without modification to the original design, a number of possible improvements connected with asphalt planing, concrete screeding and pipe placement were discussed as follows.

- Using a 2m wide tracked planer, rather than a wheeled version, would have provided better level control in retrofittting the collector array to the existing road.
- The plastic collector pipes were wired to a steel mesh laid on the planed surface. A slightly heavier gauge mesh than the A142 (6mm wire size at 200mm pitch) may have helped to minimise movement of the pipework.
- Placement of some concrete at mesh corners and at various points along the mesh may also have helped to prevent movement of the mesh.
- The collector pipes need to be tied to the steel mesh at intervals of no more than 500mm. This procedure was adopted for the second collector and helped to minimise distortion of the plastic pipes in hot weather.
- The use of steel mesh on top of the collector pipes may possibly help to both hold the pipes in place and minimise shrinkage cracking of the concrete screed placed over them in critical cases. It should be noted that only very fine shrinkage cracks of no consequence were encountered at this site.
- The collector pipes were pressurised with water during placement of the concrete screed. Circulation of water may be advantageous if the weather is hot.
- Use of a vibrating metal beam screed proved advantageous.

(iv) Placement of polystyrene: Laser levelling was used to control the excavated level at this site and this approach is generally recommended. The quality of finish is then good and sand in-fill is only necessary for a few uneven areas to prepare for placement of the polystyrene sheets. Pins were successfully used to retain the polystyrene sheets on the sloping surface.

(iv) Asphalting: Cooling water was circulated to avoid damage to the collector pipes during asphalting. This essential operation would have been easier if the pump house had been in place.

Further advice on construction and operational issues is given in Appendix B.

5 Monitoring instrumentation

The performance of the complete interseasonal heat recovery system was monitored in detail. For this purpose instruments were installed to monitor temperatures in the ground, heat transfer and energy usage by the system, and climatic conditions.

5.1 Ground instrumentation

Instrumentation was installed to measure the following:

- temperatures at depth in the ground below the store arrays and at control locations;
- temperatures in the two collector arrays;
- the distribution of temperature with depth within the asphalt surfacing;
- the thermal strains measured in the concrete screed below the asphalt layers at collector and control locations.

The outputs from these instruments were computer logged with the data being downloaded by mobile phone link for real time plotting on a dedicated website.

5.1.1 Temperatures at depth in the ground

A Comacchio rotary drilling rig (Figure 5.1) was used to sink nine boreholes of 100mm diameter to about 13m depth so that eleven thermistors (temperature sensors) could be installed at selected depths in each borehole. The locations of these boreholes are shown in Figure 5.2. After the thermistors were installed, all boreholes were backfilled using bentonite pellets with appropriate addition of water. Access for the rig was provided by the Principal Contractor when excavation in each area was at maximum depth.

Figure 5.1. Rotary drilling for thermistor installations

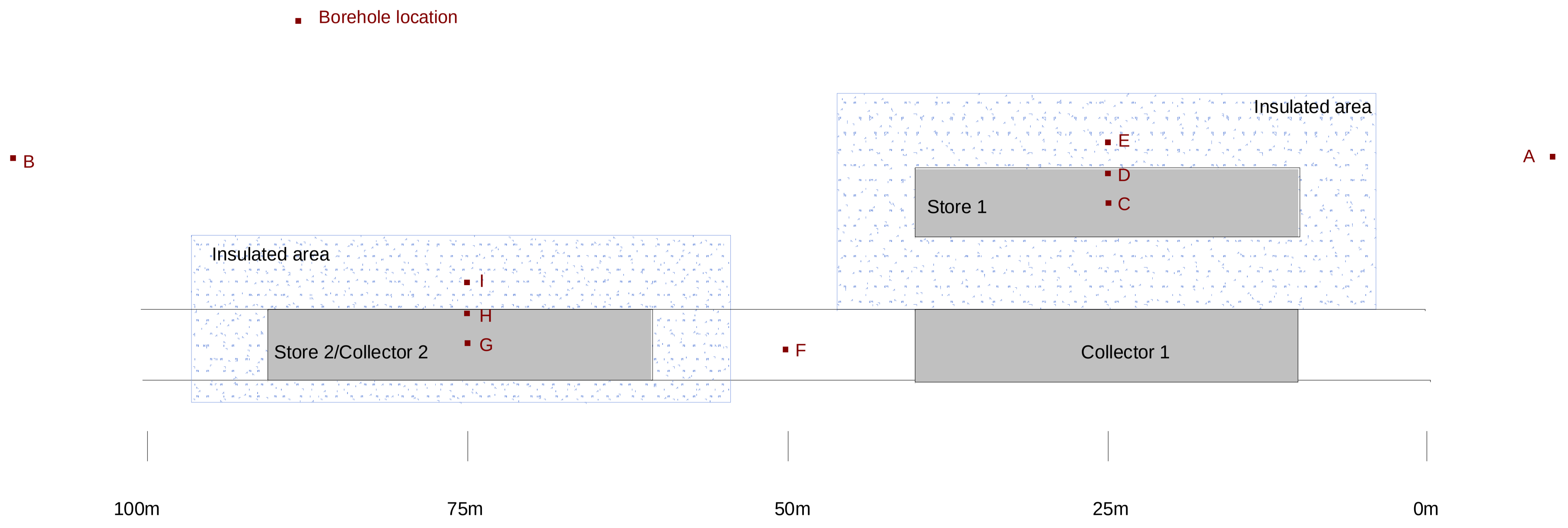

Figure 5.2. Plan view showing the locations of instrument boreholes

Thermistors were installed in boreholes C to I (Figure 5.2) at depths of 0.875, 0.925, 0.975, 1.025, 1.175, 1.375, 1.875, 2.875, 3.875, 7.875 and 12.875m. In heat store areas this meant that the uppermost thermistor was at a level corresponding to that of the pipe inverts. In borehole F, a control borehole in the road between the two collectors, the lowest two thermistors were omitted because of a drilling rig failure. Delay to construction in waiting for rig spares to arrive was deemed unacceptable on this occasion.

Control boreholes A and B were located to the south and north respectively of the construction zone to monitor normal temperatures in the undisturbed ground. Thermistors in these boreholes were installed at depths of 0.025, 0.125, 0.825, 0.875, 1.025, 1.175, 1.375, 1.875, 3.875, 7.875 and 12.875m.

In addition to the thermistor profiles, a thermocouple was installed at a depth of 0.875m (ie. at pipe invert level) in the centre of each of the two heat stores. This thermocouple was used for controlling the pumping system.

5.1.2 *Temperatures in the collector arrays*

An array of twelve thermistors was installed in each collector array to ascertain the distribution of temperature. The layout of these instruments in collector 1 is shown in Figure 5.3, the layout for collector 2 was a mirror image. Each thermistor was positioned midway between the pipe runs. In addition to the thermistor arrays, a thermocouple was installed at the centre of each collector which was dedicated to the control of the pumping system.

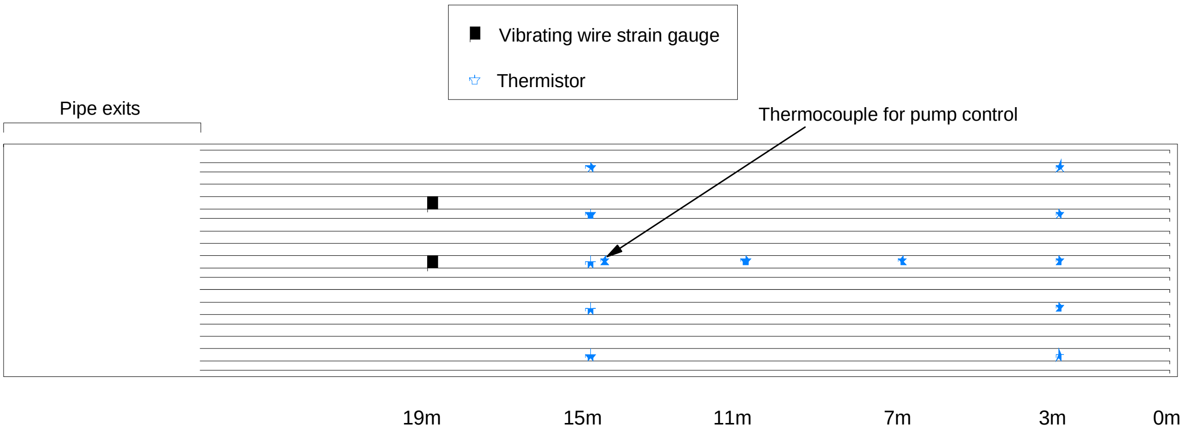

Figure 5.3. Plan view showing instrument layout in collector 1

5.1.3 *Temperatures of the asphalt surfacing*

Two profiles of thermistors were installed in the road surface at the centre of each collector area and one in the control zone between the two collectors. These thermistors were installed by drilling holes from the surface after carriageway construction: the holes were then backfilled with bitumen.

Each profile consisted of thermistors at depths of 10, 25, 50, 75 and 100mm below the carriageway surface which comprised 35mm of wearing course and 70mm of binder course.

5.1.4 Thermal strains in the concrete screed

Embedded vibrating wire strain gauges were placed in between pipe runs in each collector at the locations indicated in Figure 5.3 prior to pouring the concrete screed. A similar arrangement was also employed in the control area between the collector arrays. At each location, one gauge was oriented to measure strains along the road direction whilst a second measured strains perpendicular to this direction. Comparisons between the strain data were expected to provide an evaluation of whether thermal strains were reduced as the road temperature is kept more constant throughout the year by the heat transfer system.

5.2 Heat transfer and energy usage

In addition to the instrumentation installed in the ground to measure temperatures (Section 5), the system performance was monitored to enable an assessment of the heat transfer between collectors and stores, the heat used for winter maintenance and building simulation, and the electrical energy used by the pumping system. The components of this system included:

- four in-line induction flow meters (Flomags 3000) and associated thermistors (two with each flow meter) to monitor the flow of heat from collector to store, and vice-versa[1];
- a flow meter (Flomag 3000) and two thermistors to monitor the heat re-distributed by the heat pump[1];
- electrical current meters on the main pumps and the heat pump to monitor the power consumption.

As with the ground instruments, the outputs from these instruments were computer logged with the data being downloaded by mobile phone link for real time plotting on a dedicated website.

5.3 Weather station

Because of the dependence of solar heating of the road surface upon weather conditions, a weather station was installed at the site to measure solar irradiation, rainfall, humidity, temperature, wind speed and direction. These data were transmitted back to the office by mobile phone link.

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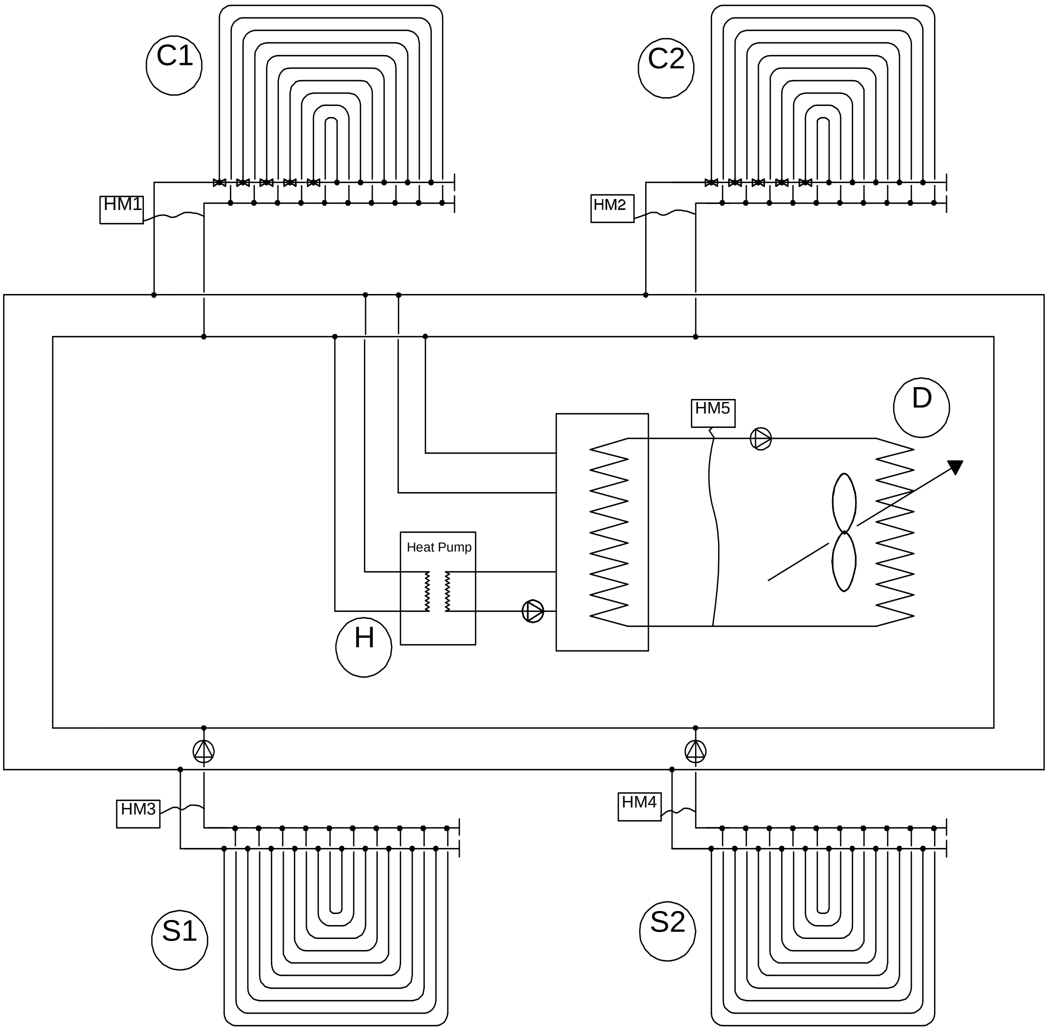
[1] These instruments were also used by the control system to control the pumps.

6 Pump house

6.1 Principle of operation

Photographs of the inside of the pump house are shown in Figure 6.1. The system comprised four variable speed pumps and sixteen motorised valves, a water to water heat pump, three dry coolers (for the building heating simulation), two pumps for frost protection and the plant control system. A simplified schematic of the layout of the pump system is shown in Figure 6.2. Appropriate use of motorised valves enables flexibility in running the system as a single or two experiments as required.



Key:

Stores, S1 and S2

Collectors, C1 and C2

Heat pump, H

Heat dump, D

Heat meters, HM1 to HM5

Figure 6.2. Schematic of the layout of the pump system

Figure 6.1. Photographs of the inside of the pump house

6.2 Control protocols

Protocols were developed to control the system and to meet the experimental requirements. These requirements are given in Table 6.1 together with the assigned mode identifier.

Table 6.1. Modes of operation

Mode identifier	Description	Season of operation
A	Heating from store to dump buffer store	Winter
B	Heating from store to dump buffer store via heat pump	Winter
C	Collect cold from collector 2 and put in store 2 (reject heat)	Winter
D	Collect cold from collectors 1 and 2 and put in store 2 (reject heat)	Winter
E	Collect heat from collector 1 and put in store 1 (reject cold)	Summer
F	Collect heat from collectors 1 and 2 and put in store 2 (reject cold)	Summer
G	Collect heat from collector 1 and put in store 1 (reject cold)	Summer
	Collect heat from collector 2 and put in store 2 (reject cold)	Summer
H	Cooling from store to dump buffer store	Summer
I	Cooling from store to dump buffer store via heat pump	Summer
J	De-icing	Winter

Note: In addition to these main modes, a frost protection mode is also incorporated in the system.

It must be noted that only certain of the modes can operate together, when driving the twin collector/store systems separately or in a combined fashion.

6.3 Experimental schedule

The experimental schedule from September 2005 for the 2 year period of performance monitoring is shown in Figure 6.3.

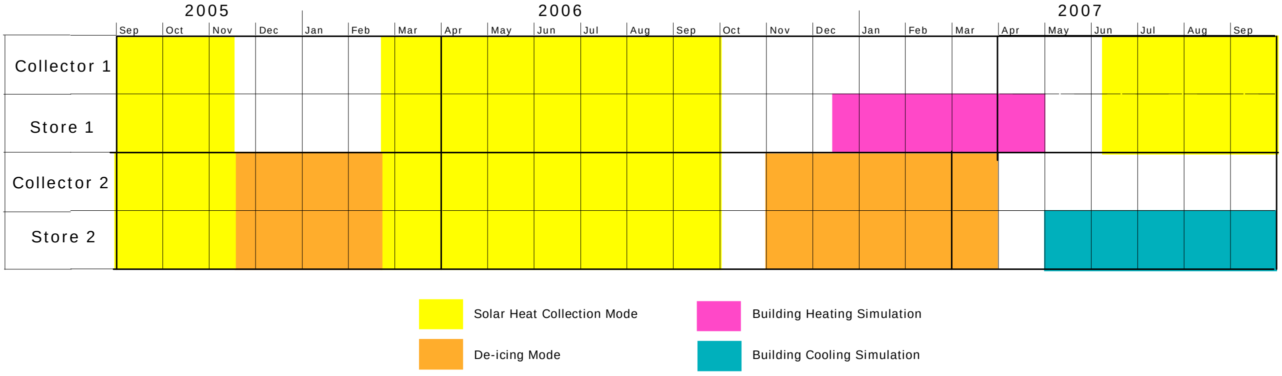


Figure 6.3. Experimental schedule over the 2 year period

7 Monitoring of the collection and storage of solar heat (23rd August to 14th November 2005)

Monitoring of performance under different operational protocols was carried out over a two year period commencing from the start of heat collection in late August 2005. The findings during each stage are now reported in sequence.

Collection and storage of heat was automatically controlled under mode G (see Table 6.1). When the temperature of the collector arrays exceeded that of the store arrays by more than 2°C, fluid was separately pumped from collector 1 to store 1 and from collector 2 to store 2 so elevating the temperatures of both stores.

7.1 Collector and road temperature

The variations of road surface, collector and air temperatures over late summer 2005 are shown in Figure 7.1. Temperatures towards the end of August were quite high with peak air and collector temperatures of about 30°C being recorded, whilst road surface temperatures of 40°C were reached. The daytime values of road surface and collector temperature were of course recorded whilst the heat collection mode was operative.

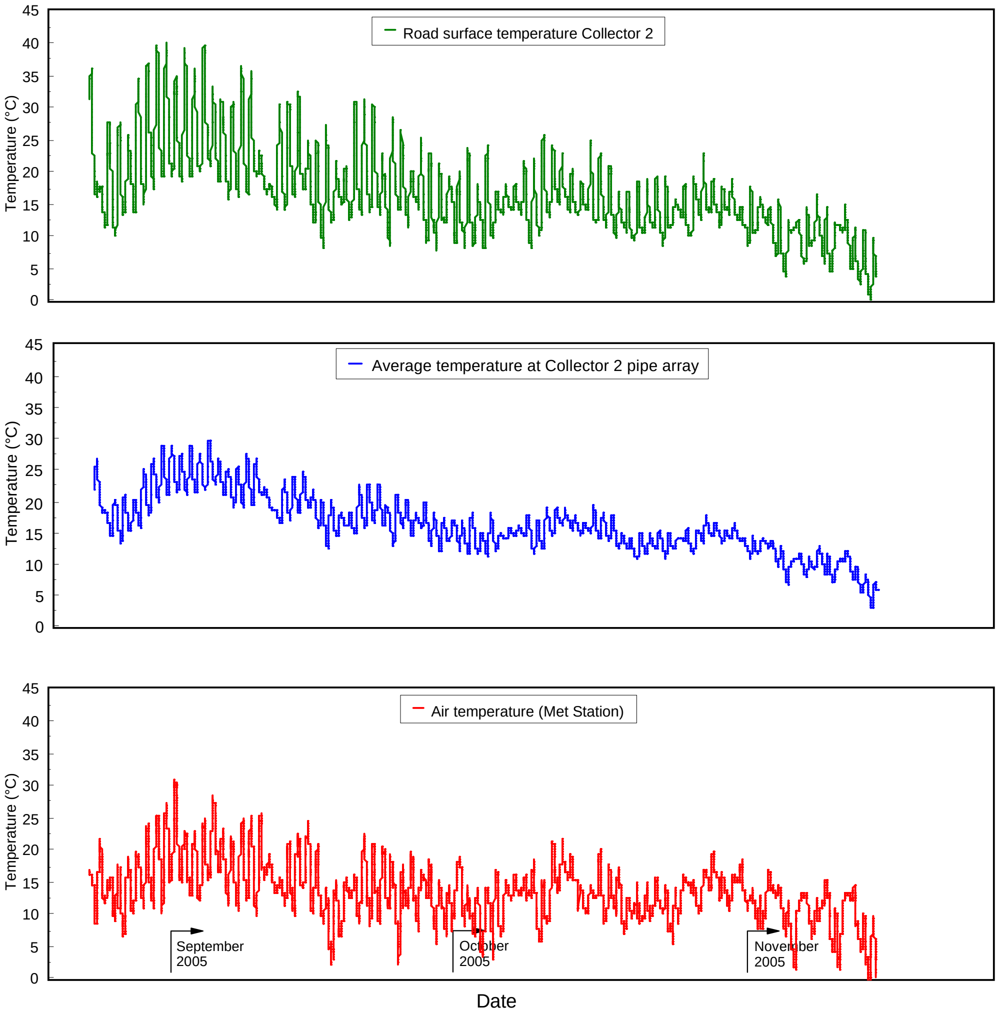


Figure 7.1. Variation of road surface, collector and air temperatures (late summer 2005)

The temperature profiles measured using the thermistors in the asphalt of the road at 1.15pm on three dates selected to illustrate a range of temperatures are shown in Figure 7.2. On all three occasions, the transfer of heat from the collectors to the stores was active. The measurements obtained in the surfacing above both collectors and in the control area were compared. The results for the hottest day during the period (31st August) showed a peak temperature of 40°C was reached near the asphalt surface in the control area. The extraction of solar heat from the asphalt by the two collectors lowered this surface temperature by about 2°C and the temperature at 100mm depth by a similar amount. Interestingly, slightly elevated temperatures occurred at 50mm depth in response to the flow of heat from the surface to the immediate area where heat was being extracted by the pipe arrays (at 120mm depth of cover) forming the collectors.

A similar mechanism was observed on the other two dates, but to a lesser extent as road temperatures were lower. On 5th October, there was little difference between collector and store temperatures so the effect, although there, was scarcely noticeable.

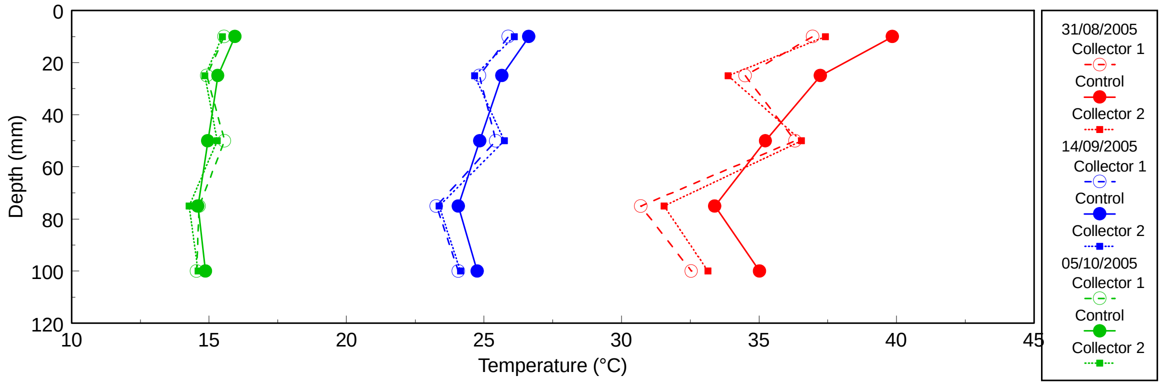


Figure 7.2. Comparison of asphalt temperatures at selected dates

7.2 Ground temperatures below the heat stores

Figure 7.3 shows the variation of temperatures with time recorded from 23rd August to 14th November 2005 using the thermistors in boreholes C (directly below the centre of store 1), D (on its edge) and E (2.5m from its edge). These temperatures are also compared in Figure 7.4 with the measured global irradiance and air temperature. The results shows discrete peaks in temperature measured by the shallow thermistors in boreholes C and D which coincide with sunny days (identifiable from the irradiance and temperature plots) and relate to periods when heat was being passed to the store. At depth in these boreholes and in borehole E, a more gradual rise in temperature was measured.

Heat recovery and storage continued throughout most of September with small boosts in store temperature still occurring on occasional warm days during October. Whilst the overall trend clearly indicated maximum temperatures at shallow depths below the store pipe arrays during early September, it is apparent that temperatures at more than 2m depth still increased and did not appear to stabilise until near the end of October. The concept of interseasonal storage relies on this storage at depth and, if heat recovery could have been initiated earlier in the year, higher temperatures would have been expected.

Results from boreholes G, H and I below and adjacent to store 2 were near identical and these are shown in Figure 7.5.

Distributions of temperature with depth in the boreholes at stores 1 and 2 are shown in Figures 7.6 and 7.7 respectively at selected dates. In all cases the readings were those taken at midnight, i.e. when no pumps were in operation. The results for the boreholes below the store pipe arrays illustrated the effect described above with temperatures building up, especially at shallow depths, during September in response to heat circulation from the road collectors. Even though the temperatures immediately below the store arrays started to fall in October, temperatures of the clay at depths of more than 2.5m (below ground level) continued to show a slight rise until about the end of the month.

7.3 Ground temperatures in control areas

Distributions of temperature with depth in borehole A (off-road and 60m to the south of the trial area) and in borehole F (in an un-insulated area of road between collectors 1 and 2) are shown in Figure 7.8. As would be anticipated, temperatures were higher at shallow depths in borehole F rather than borehole A during September because of the effect of road heating by the sun. Readings were also available from thermistors installed in borehole B to the north of the trial area, these instruments were manually read rather than computer logged. Similar results were recorded to those from borehole A.

It must be noted that temperatures in the control boreholes at the same dates were actually higher than those reported below the heat stores in Section 7.1.1. This apparent anomaly occurred because the insulation was placed over the heat stores in early May 2005 and this prevented normal heating up of the ground during the summer. It was not until 23rd August that heat recovery commenced and this situation started to be redressed.

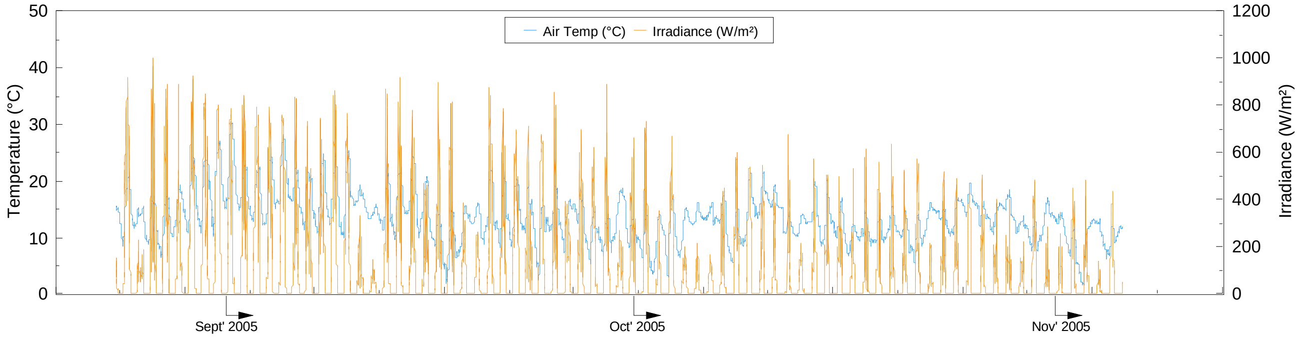
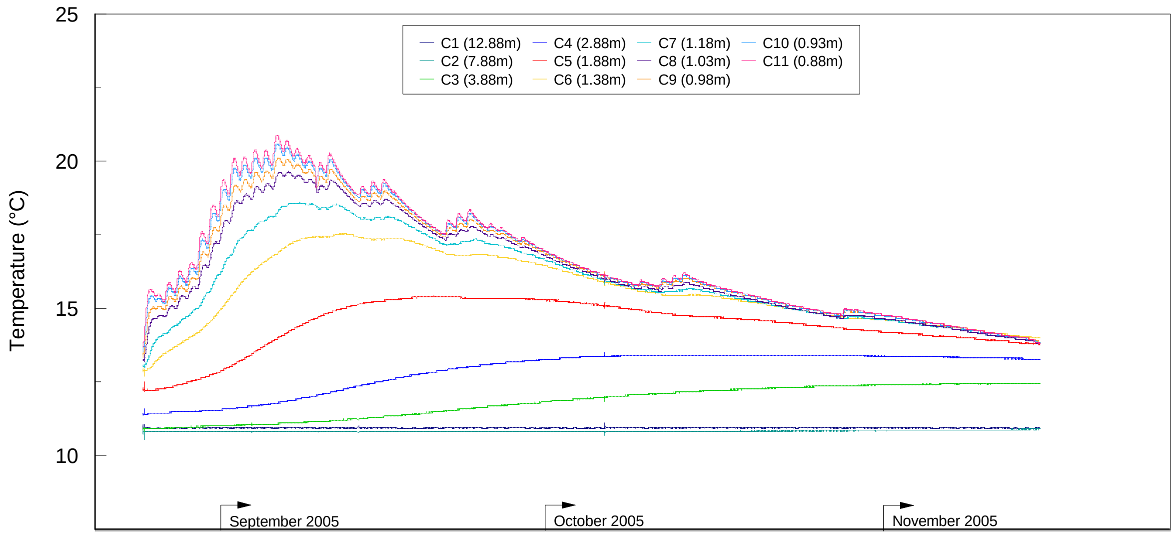
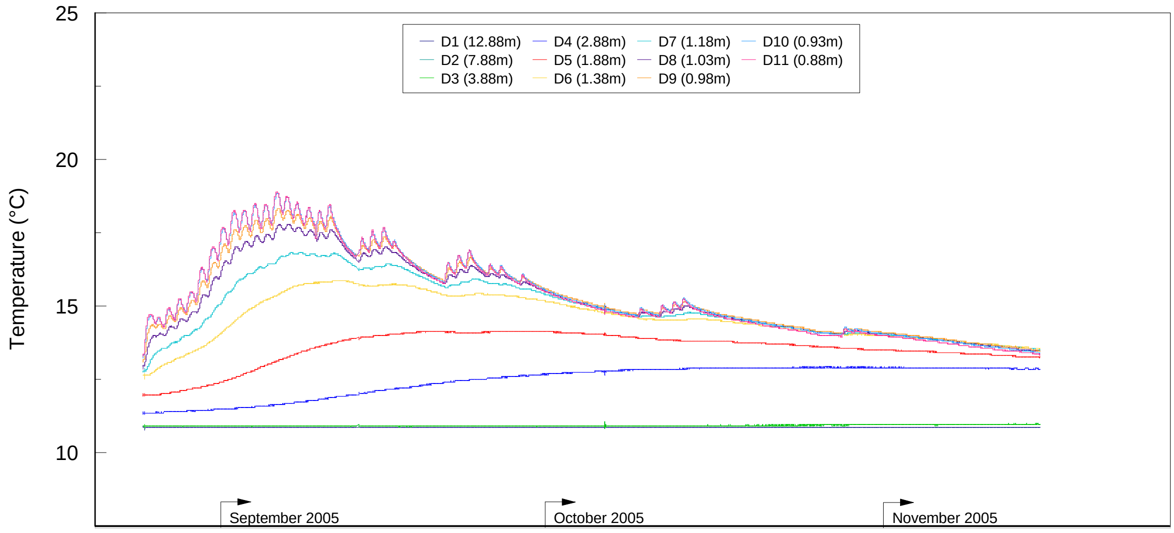


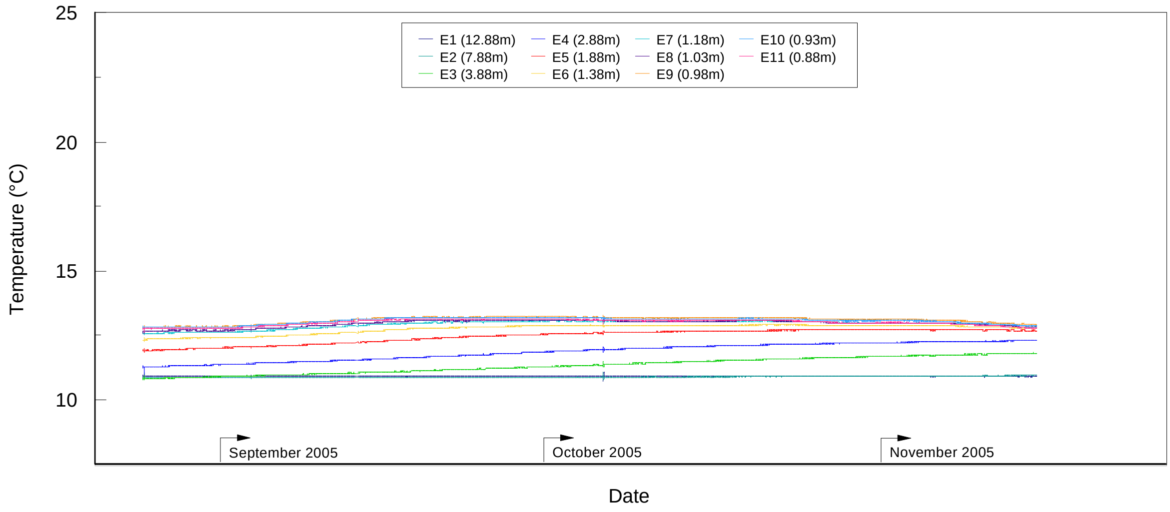
Figure 7.4. Variation of air temperature and irradiance with time (late summer 2005)



(a) Borehole C (below centre of store 1)

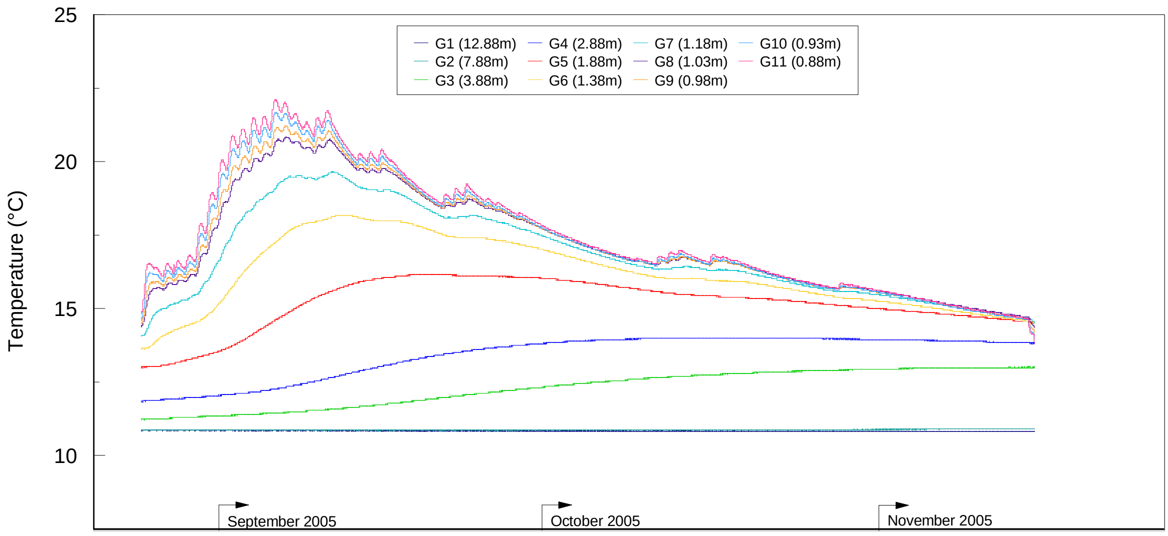


(b) Borehole D (edge of store 1)

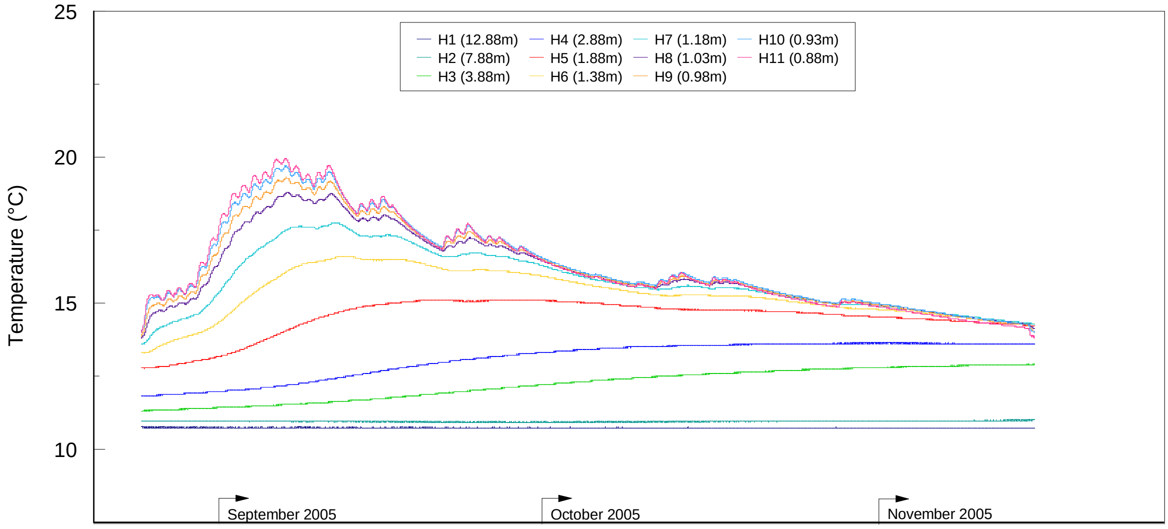


(c) Borehole E (2m from edge of store 1)

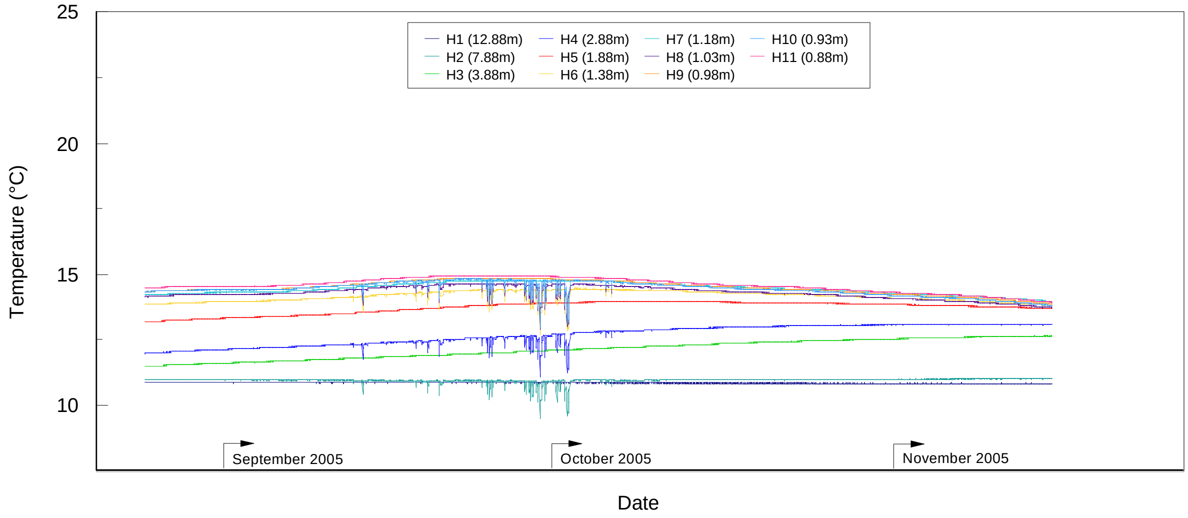
Figure 7.3. Variation of ground temperatures with time below store 1 (late summer 2005)



(a) Borehole G (below centre of store 2)

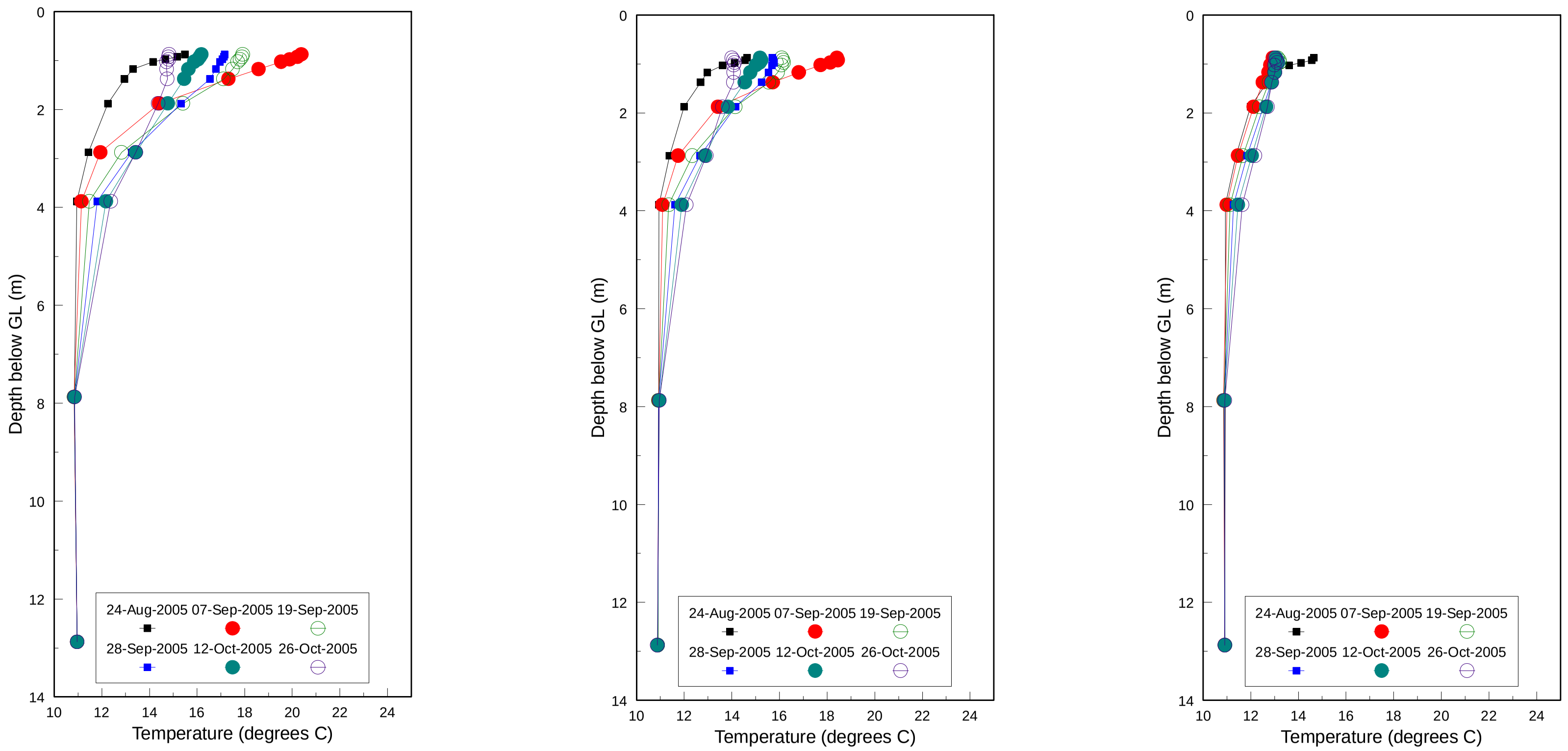


(b) Borehole H (edge of store 2)



(c) Borehole I (2m from edge of store 2)

Figure 7.5. Variation of ground temperatures with time below store 2 (late summer 2005)

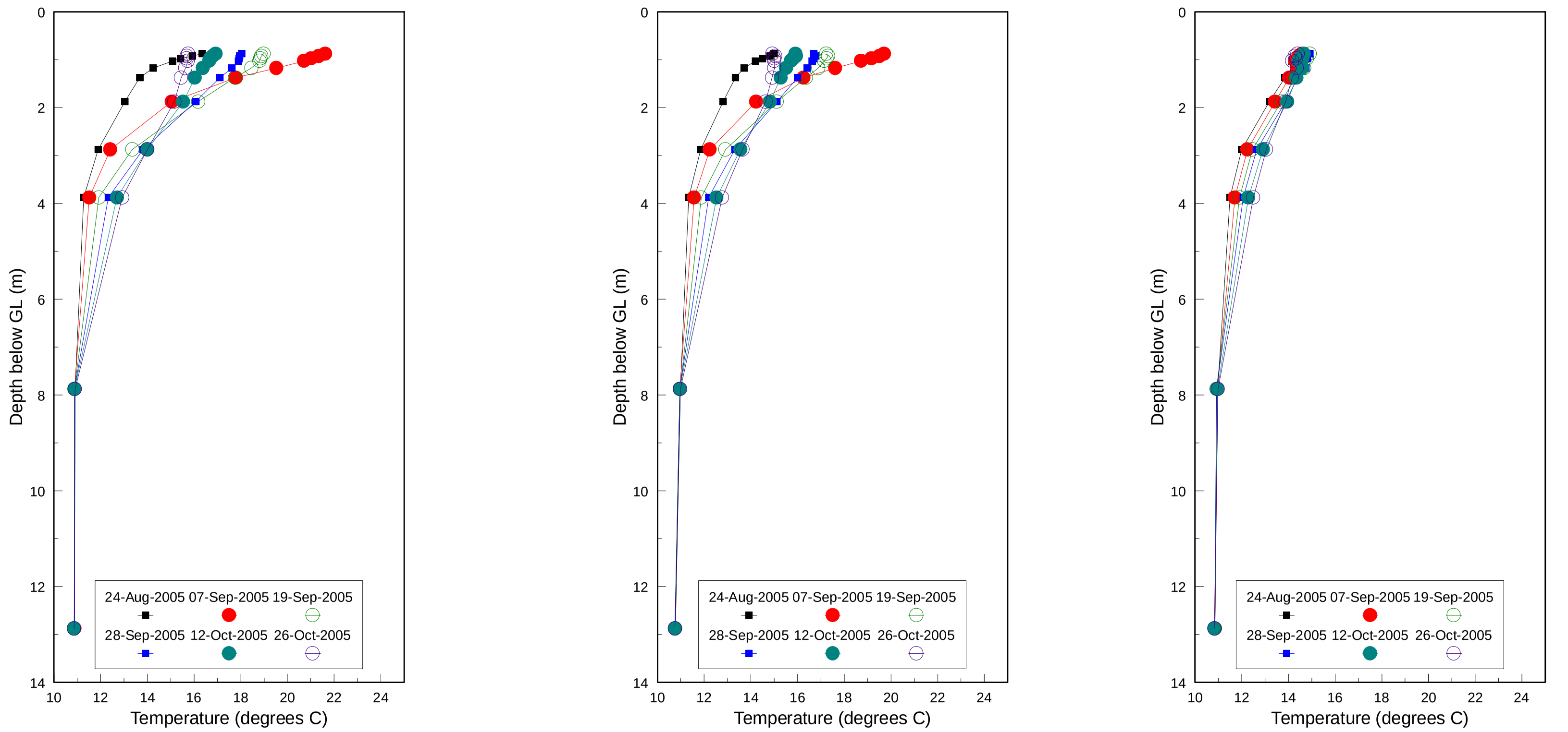


(i) Borehole C: Centre of Store 1 (Off-Road)

(ii) Borehole D: Edge of Store 1 (Off-Road)

(iii) Borehole E: Offset from Store 2 (Off-Road)

Figure 7.6. Profiles of ground temperature with depth below store 1 (late summer 2005)

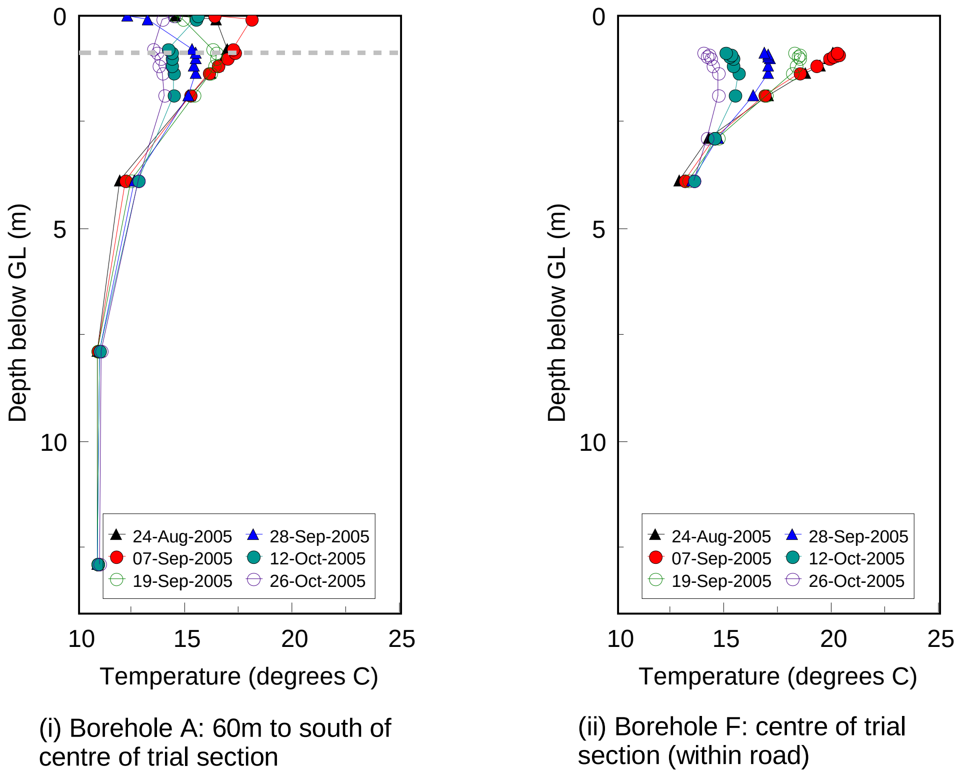


(i) Borehole G: Centre of Store 2 (Road)

(ii) Borehole H: Edge of Store 2 (Road)

(iii) Borehole I: Offset from Store 2 (Road)

Figure 7.7. Profiles of ground temperature with depth below store 2 (late summer 2005)



(i) Borehole A: 60m to south of centre of trial section

(ii) Borehole F: centre of trial section (within road)

Figure 7.8. Profiles of ground temperature with depth at control locations (late summer 2005)

7.4 Energy recovered and used

The heat flow (Q) being recovered by each collector was determined by measuring the volumetric flow rate (V) to the pump house and the fluid temperatures in the centre of the flow and return lines from each collector to the pump house. The temperature difference (ΔT) between the flow and return was then used to calculate the heat recovered using the following formula:

$$Q = c.\ V.\ \Delta T$$

The specific heat capacity (c), if more rigorously determined, will depend on both temperature and pressure of the fluid, but in this case has been assumed to have a constant value of 4.046 joule/gm/^{o}C for the water/glycol mix (10% concentration by volume). On this basis, after conversion of units to those being measured, the formula applied was:

$$Q\ (kW) = 4.046.\ V\ (l/s).\ \Delta T(^{o}C)$$

The heat transferred to each store was also measured in the same way. In an ideal situation, the heat collected would equal the heat stored although in reality losses occur during the circulation of the fluid through the intermediate pipework and pumping system.

Figure 7.9 compares the cumulative heat energy calculated for each collector and store during the period up to 14th November. In each case the heat recovered from the collector exceeded the heat transferred to the store. Although the pipework beneath the ground and in the pump house was insulated, this difference was accounted for by system losses.

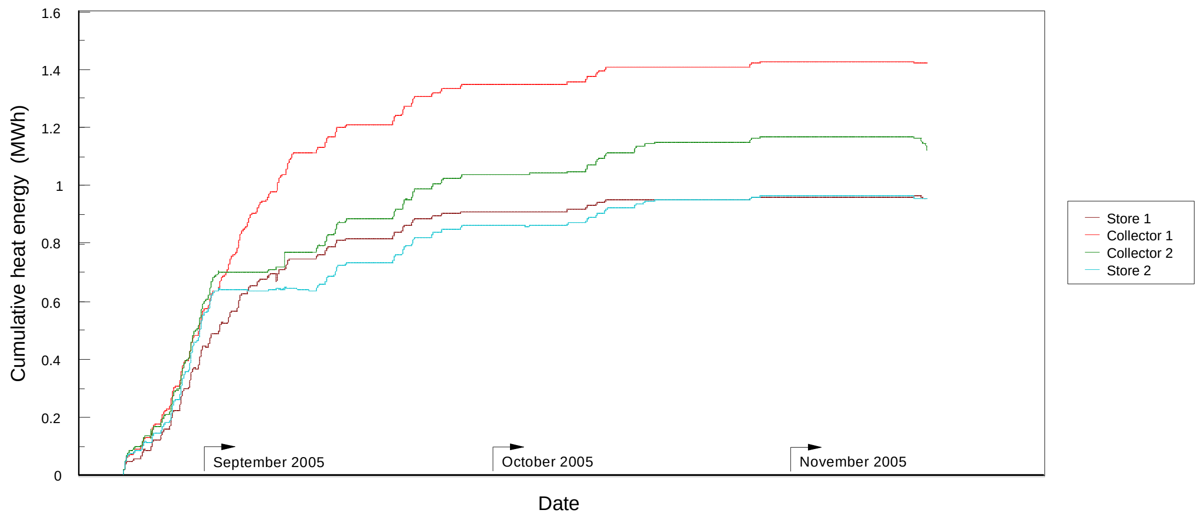


Figure 7.9. Cumulative heat energy recovered and stored (late summer 2005)

During the period, the cumulative energy recovered from collector 1 was 1.42MWh of which 0.96MWh was transferred to store 1. Less energy, 1.16MWh was recovered from collector 2, although the energy transferred to store 2 was about the same as store 1. The reason for this discrepancy between energies from the collectors is not apparent, but may due to a combination of a number of factors. These factors include the location of collector 2 (which has store 2 under the road beneath it), slightly different pipe types were used for collectors 1 and 2, and pipe runs between collector 1 and store 1 were slightly longer.

In order to assess the overall energy efficiency during this period, the electrical power consumption of the pumps was monitored using current meters. The cumulative electrical energy used is shown in Figure 7.10. Compared with the energy recovered from solar heating of the road surface, the electrical power proved small.

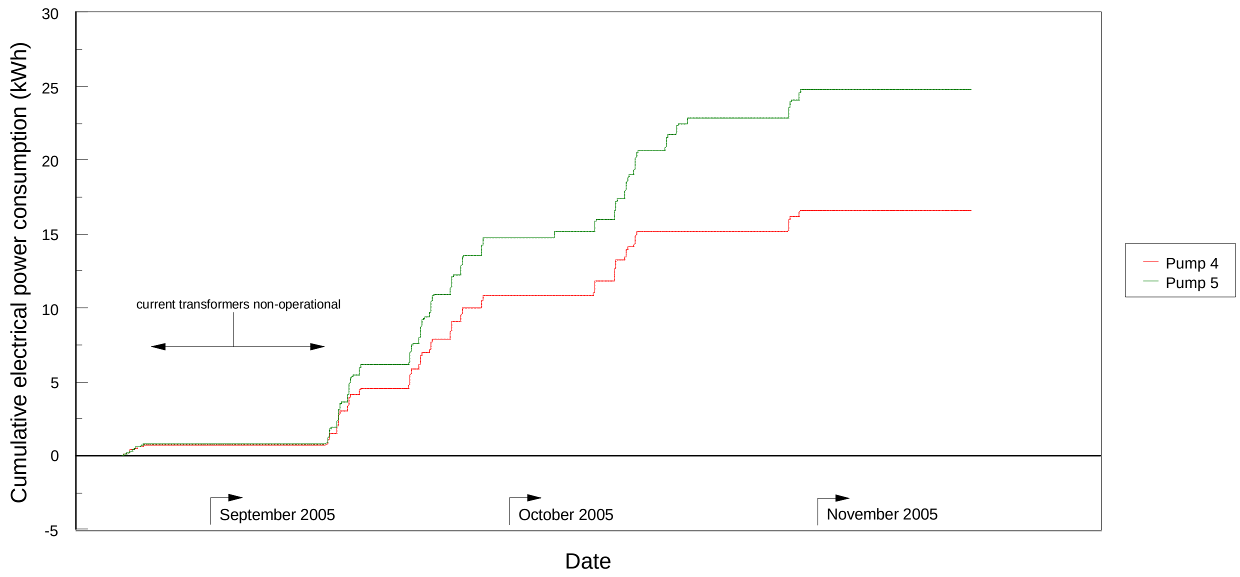


Figure 7.10. Cumulative electrical power used by the pumps (late summer 2005)

8 Monitoring of the re-use of stored heat for winter maintenance of the road (15th November 2005 to 20th February 2006)

Following the limited collection and storage of solar heat carried out during the late summer 2005, the available heat stored in store 2 was used for a preliminary investigation of ice and snow prevention on the road surface above collector 2 during the period from 15th November 2005 to 20th February 2006. For this purpose operational mode J (see Table 6.1) was employed using the protocol that when the road surface temperature fell below 2°C for more than 15 minutes, fluid was pumped from store 2 to collector 2 to heat the road surface. Conversely when the road surface temperature rose above 2°C for more than 15 minutes the pump was automatically switched of.

8.1 Temperatures of the road surface in the heated and unheated areas

Figure 8.1 shows the variations of air temperature, road surface temperature in the unheated control area, and road surface temperature above the operational collector. The results show that air temperatures fell below -5°C for short periods on a few occasions. At these times the measured temperatures of the road surface in the control area (untreated) were generally slightly higher than the air temperature and in the range -3°C to -5°C, although generally within this period there were many occasions when the surface temperature was sub-zero. Close examination of the road surface temperatures over collector 2 confirmed that generally the surface remained at least 2°C hotter than

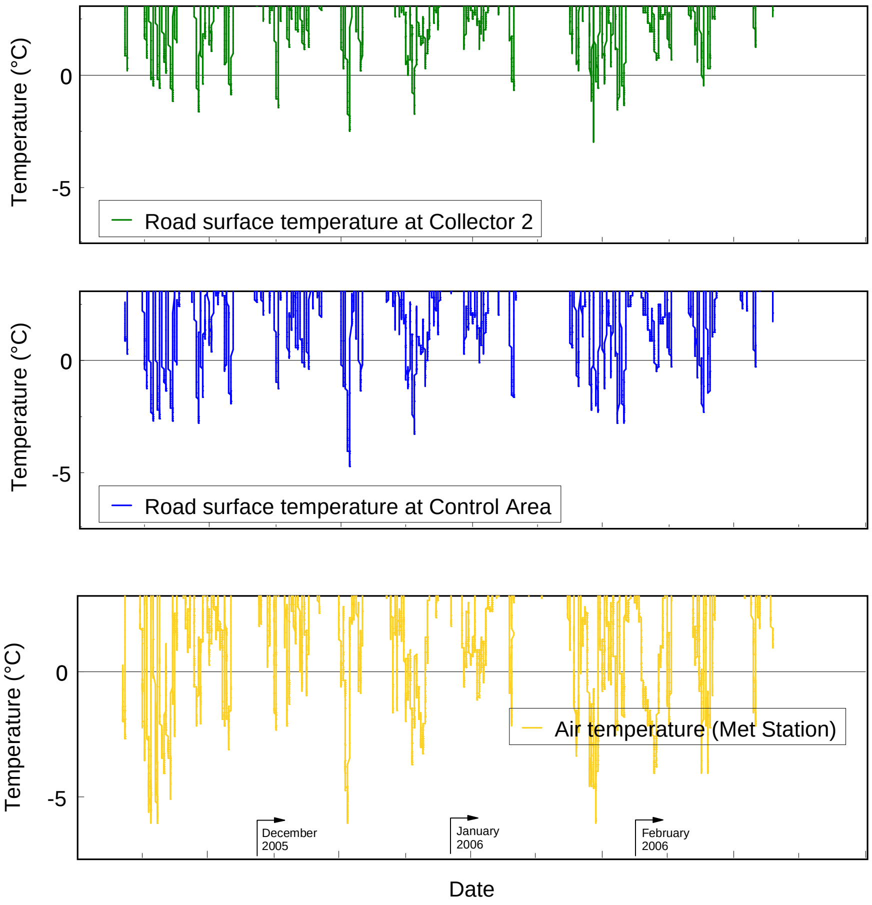


Figure 8.1. Variations of air temperature and road surface temperatures (winter 2005/06)

that in the control area. Although the road temperatures over collector 2 did fall below zero on a few occasions, with only two exceptions the temperatures remained above -1.5°C. In actual practice of course this temperature does not necessarily mean that icing occurs as it will depend upon the relative humidity and the dew point.

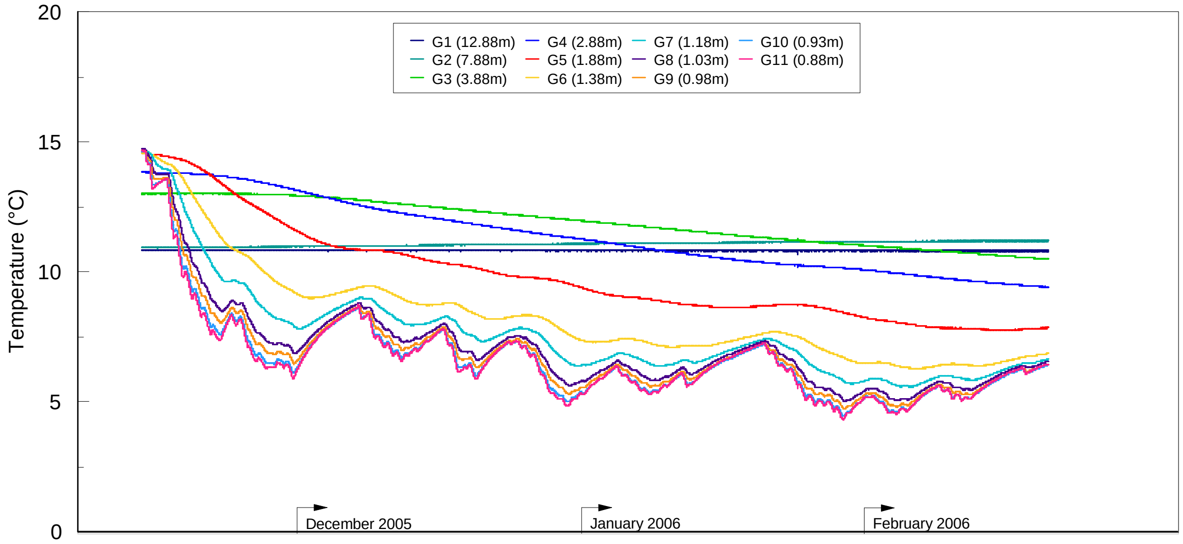
Clearly in terms of safety of the road user, the formation of any ice cannot be tolerated and the effectiveness of the winter maintenance protocol was further investigated when a fully charged heat store was available for use in the winter of 2006/07 (Section 10).

8.2 Ground temperatures below heat store 2

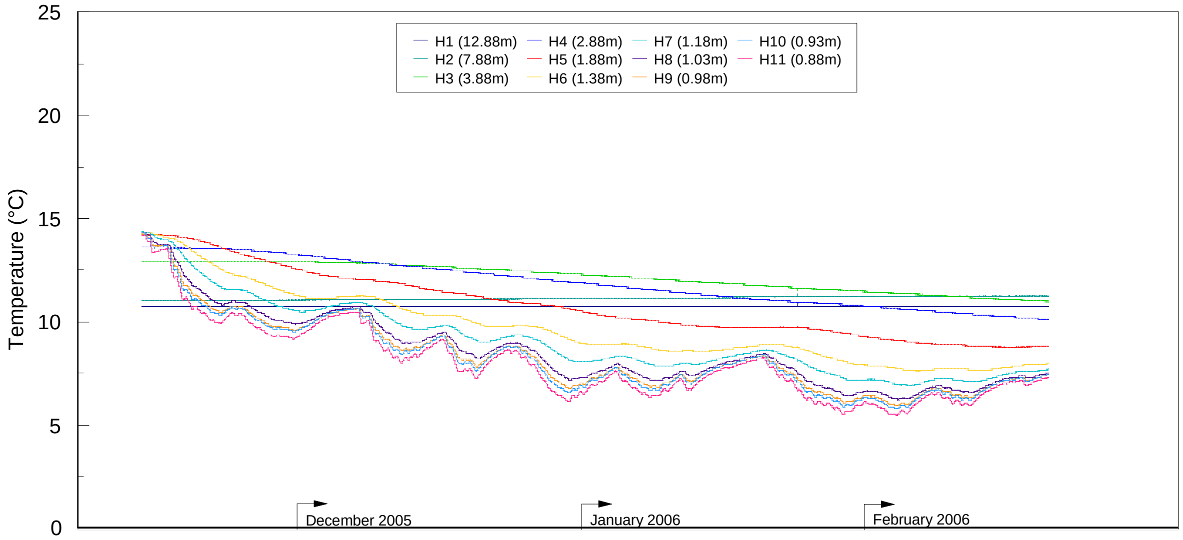
The ground temperatures measured at various depths below the pipe array comprising store 2 are shown in Figure 8.2. In Figure 8.2c it should be noted that the output noise recorded on some of the thermistors in borehole I during January are not real, but due to a poor electrical contact which was subsequently repaired.

Discrete troughs in the graphs of temperature against time (for boreholes G and H) are recorded when heat is being circulated from the store to heat the road collector: obviously minimum temperatures tend to occur at night when it is colder. The temperature reductions in the ground are clearly more noticeable at shallow depths below the store array, thermistors at depths of 7.88m and 12.88m show very little change in temperature. During intervening warmer periods there is some recovery in temperature values due to heat transfer from warmer and deeper horizons.

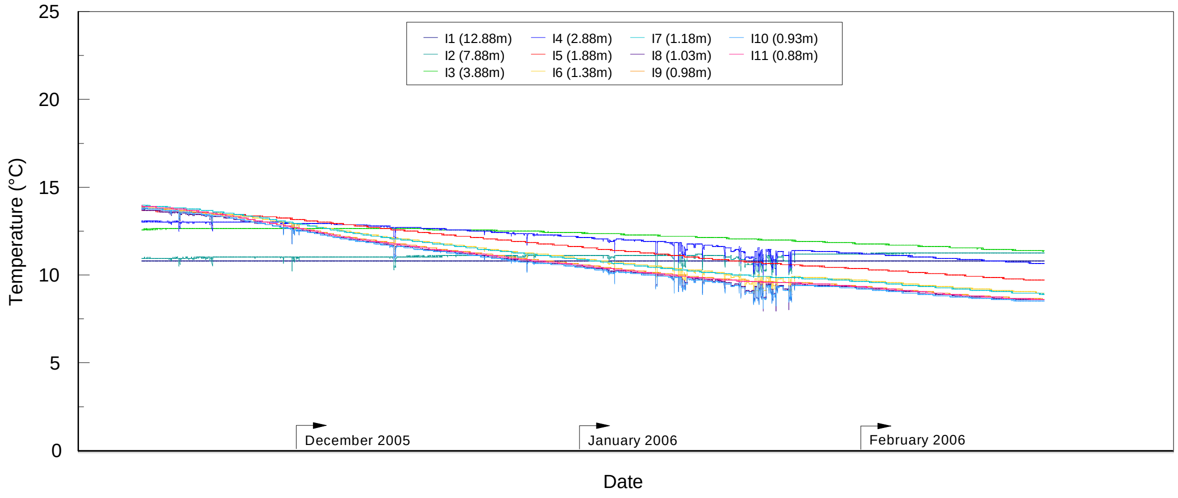
In Figure 8.2 it is evident that the largest fall in temperature occurred in the first month of operating the winter maintenance protocol. When operating from a fully charged store in which the ground at depth was hotter, the recovery in temperature at shallow depths below the store pipe arrays was more rapid (see Section 10).



(a) Borehole G (centre of store 2)



(b) Borehole H (edge of store 2)



(c) Borehole I (2m from edge of store 2)

Figure 8.2. Variation of ground temperatures with time below store 2 (winter 2005/06)

8.3 Energy used to heat the road

The cumulative heat energies extracted from store 2 and passed to collector 2 are shown in Figure 8.3. Over the period from 15th November to 20th February, these separate measurements (derived from the flow meters and differential fluid temperatures) both indicated that the heat energy used for road heating during this period was about 3MWh. As only about 1MWh was transferred to store 2 during the limited heat recovery period (Section 7.4), it was therefore concluded that most of the heat was extracted from the natural ground. The electrical power consumption of the pump was 173kWh during this period.

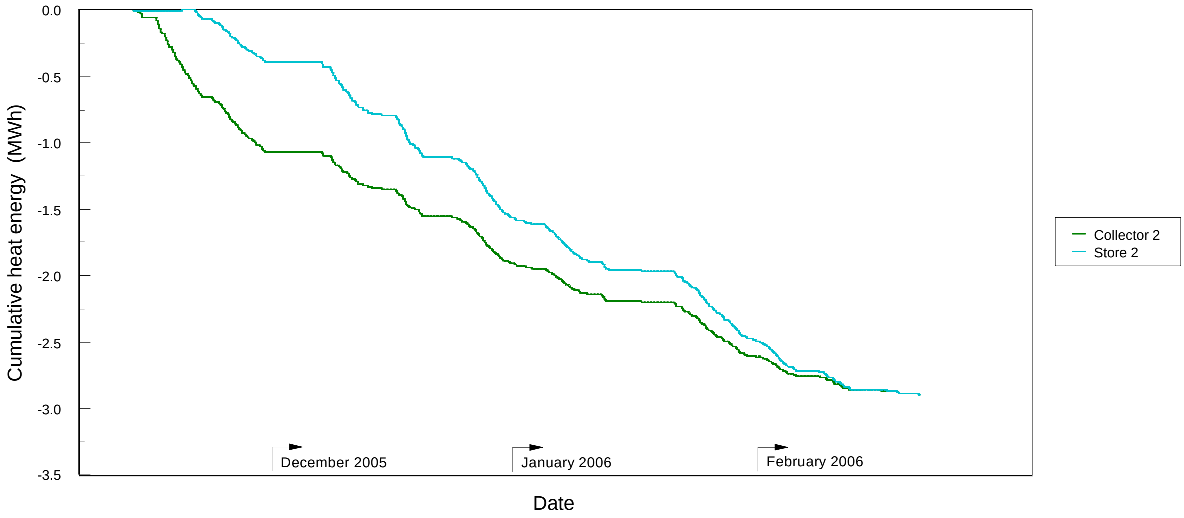


Figure 8.3. Cumulative heat energy used to heat the road (winter 2005/06)

8.4 Thermal imaging

A preliminary investigation of the road surface temperature using thermal imaging was carried out during the evening of 25 February 2006 when air temperatures were predicted to be sub-zero. Details of this investigation are given in Appendix C.

The thermal imaging successfully detected the presence of the collector pipe array at shallow depth below the surface. Temperature differences will be greater when circulating fluid from a heat store which had been fully warmed by a complete summer of heat recovery and thermal imaging effects will then be even more pronounced.

The findings demonstrate that thermal imaging is an effective “trouble-shooting” tool when operating under-road heating systems and in particular can assist with:

(i) detecting fluid leaks if they should arise,

(ii) detecting cold spots which might present a safety hazard to road users,

(iii) detecting heating pipe locations to avoid subsequent damage during road maintenance operations or installation/repair of buried services.

9 Monitoring of the collection and storage of solar heat (27th April to 31st October 2006)

The second period of collection and storage of solar heat from the road surface was commenced on 27th April 2006. Heat recovered from collector 1 was transferred to store 1, and likewise from collector 2 to store 2. The process continued satisfactorily until 18th May when significant airlocks prevented operation. Fortunately this down time coincided with the wet May so loss of solar heat which would have otherwise been recovered was minimal. Some limited operation recommenced on 1st June, although full operation was again in progress from 7th June after repair of a water leak at a manifold connection from one of the road loops from heat store 2.

A heat wave was experienced from 30th June for about 1 week with further very hot spells during July. Peaks in road, collector and store temperatures were apparent at these times.

9.1 Collector and road temperature

Figure 9.1 shows the variation of the road surface temperature, the average collector temperature and the air temperature with time over the summer 2006 heat collection period. The hot spells of late

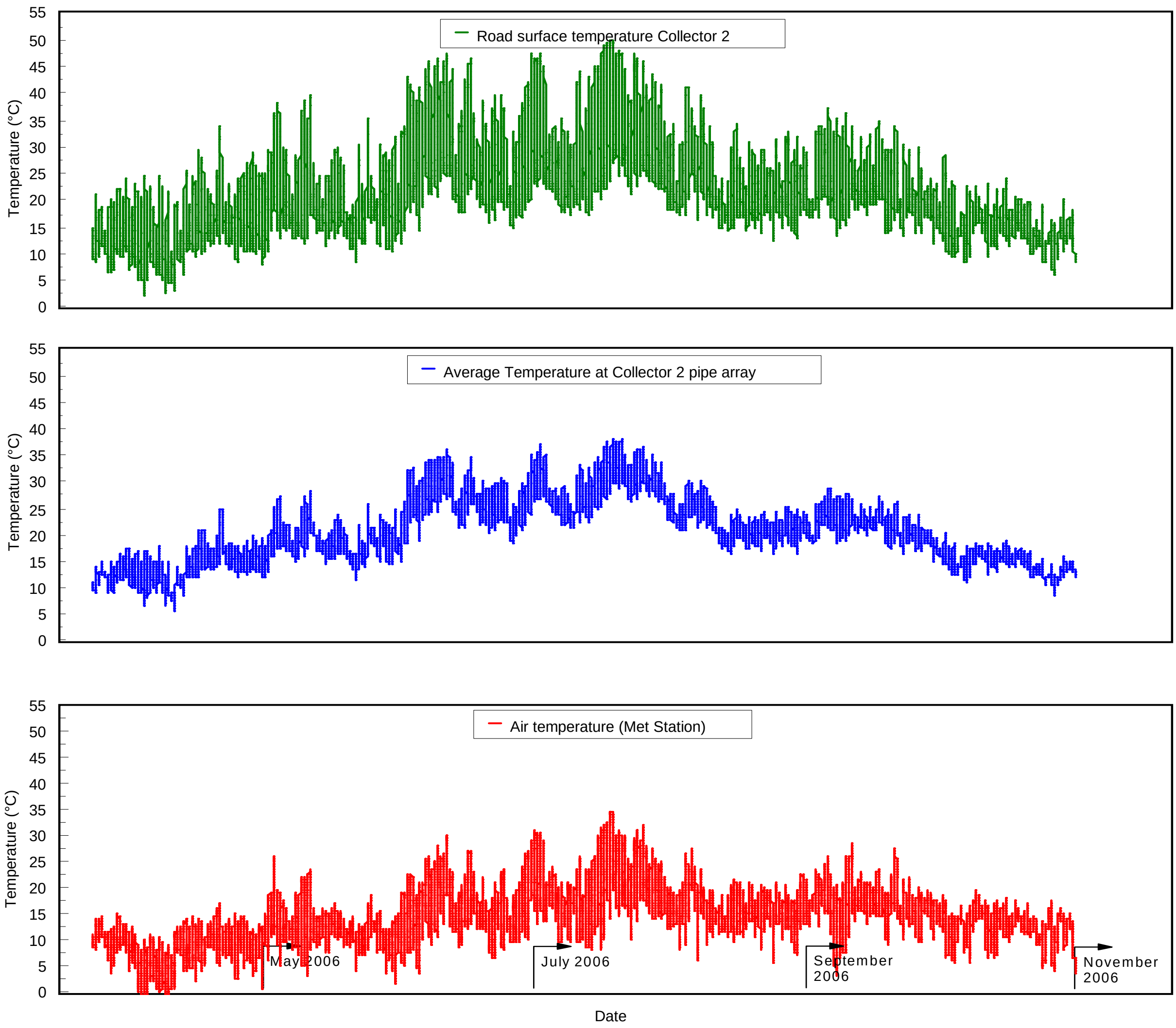


Figure 9.1. Variation of air, road surface and collector temperatures (summer 2006)

June and July produced maxima in the temperatures as expected. During July when the air temperature peaked at 34°C, a peak road surface temperature of 50°C was recorded. At this time, the temperature of the operating heat collector array reached 38°C. Significant heat was transferred to the ground heat store at this time as is reported in Section 9.4. The results in Figure 9.1 are for collector 2; those for collector 1 are very similar.

The temperature distributions recorded in the asphalt at 1.15pm on two selected dates when the transfer of heat was active are shown in Figure 9.2. Measurements obtained in the asphalt surfacing above both collectors and in the control area are compared. The extraction of heat lowered the surface temperatures by a few degrees compared with that in the control area. The readings on 12th May also indicate that the temperatures at 100mm depth near to the collector pipe arrays were reduced due to the heat recovery than in the control area. It is likely that the same effect occurred on 27th July although the comparison was limited because of failure of the deepest thermistor in the control area.

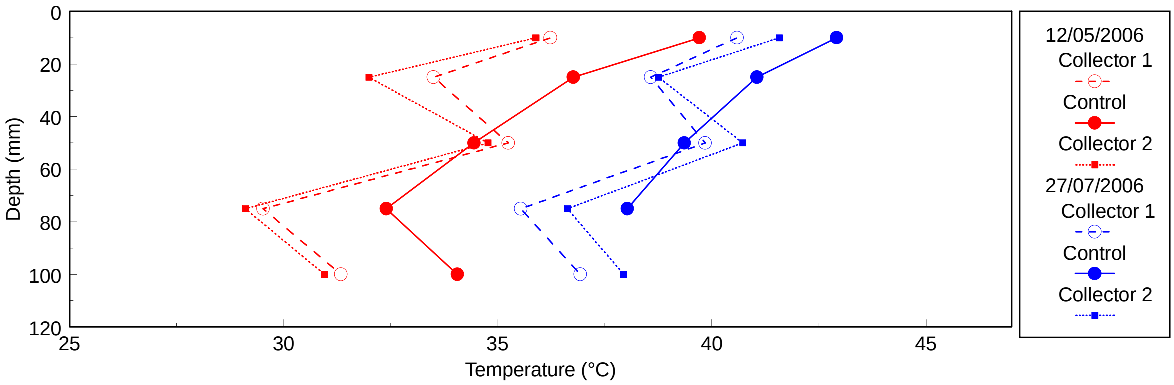


Figure 9.2. Comparison of asphalt temperatures at selected dates

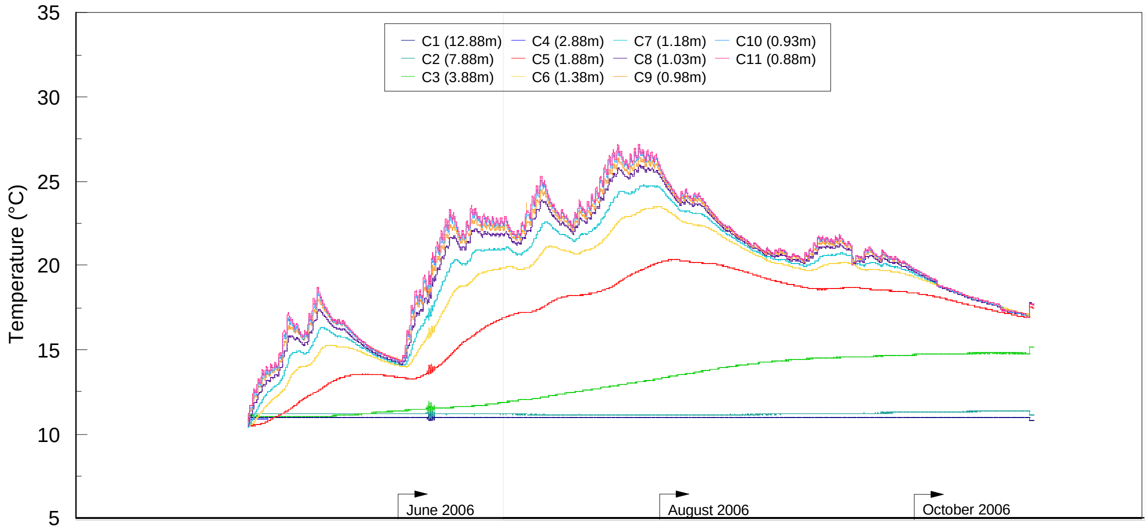
9.2 Ground temperatures below the heat stores

Figures 9.3 and 9.4 show the variations with time of the subsurface temperatures measured in the ground below stores 1 and 2 respectively. In both cases, the thermistor measurements from boreholes directly below the centre of the store, on its edge, and at 2.5m from its edge are shown.

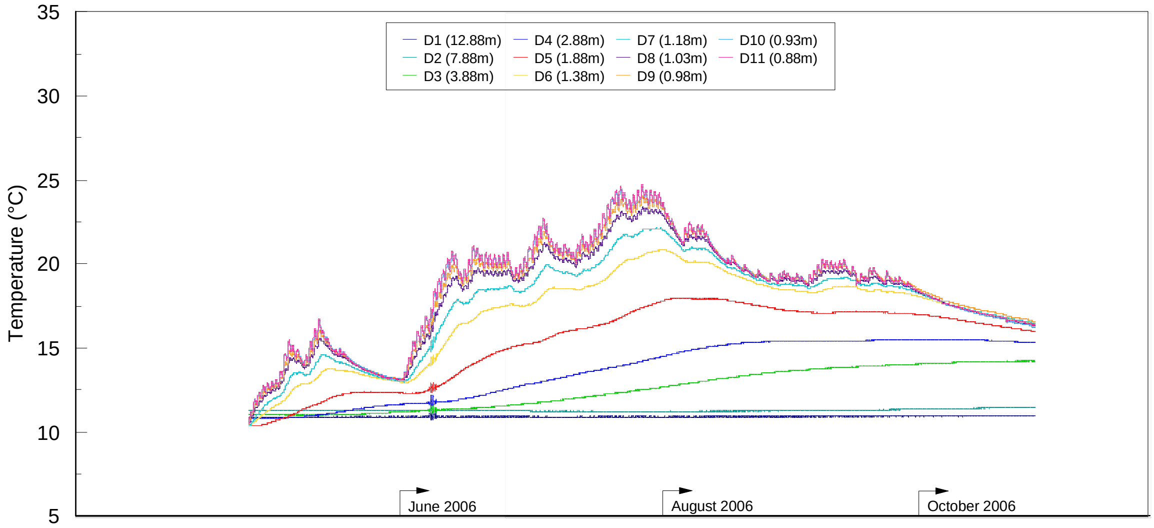
Generally the rate of increase in the ground temperatures below each of the store pipe arrays was related to the solar irradiance and the air temperature. These parameters are plotted against time in Figure 9.5.

In Figures 9.3 and 9.4, the mechanism of heat transfer from the pipe array to the underlying clay is clearly illustrated as the temperature peaks at different depths are out of phase in terms of time. For example, the peak in temperature on thermistor C1 at pipe invert level in Figure 9.3a occurs towards the end of July whilst on thermistor C5, at 1m below pipe invert, the peak occurs a little later in early August. This behaviour is consistent with the heat building up slowly at depth and it is achieving a good depth of penetration of the heat which is essential to the success of the technique.

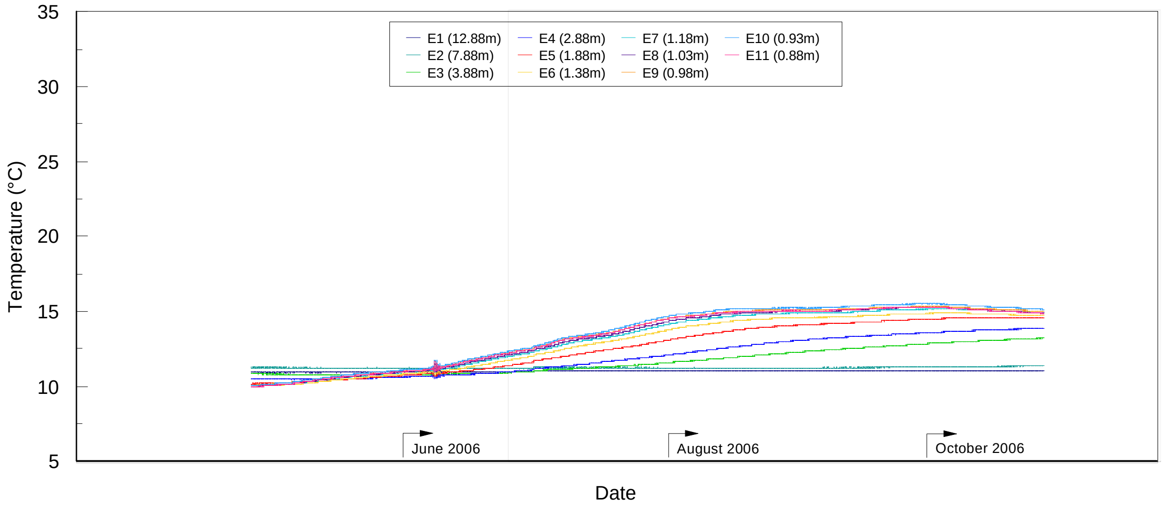
The distributions of temperatures with depth in each borehole are shown in Figure 9.6 and 9.7 for stores 1 and 2 respectively. In both cases a marked increase in temperature at depths of up to about 4m was recorded in all boreholes directly beneath the pipe array comprising each store by 3rd July (during the heat wave). Although some increase in temperatures of a few degrees was recorded at similar depths in boreholes E and I (offset from the stores by 2.5m), compared with the other boreholes the limited nature of this increase indicated that the insulation to the side of each store was fulfilling its purpose.



(a) Borehole C (below centre of store 1)

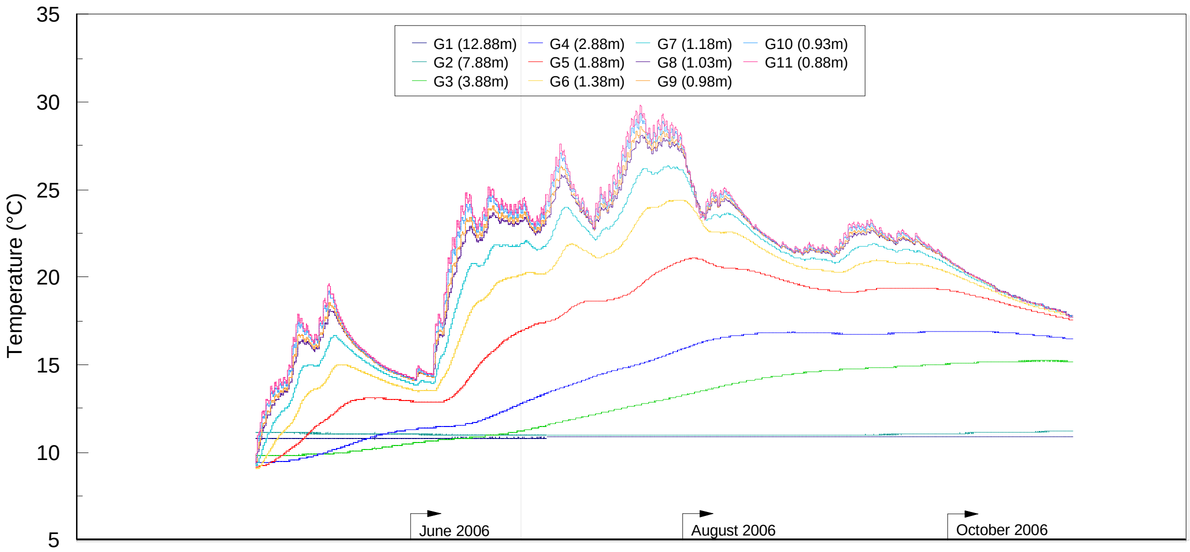


(b) Borehole D (edge of store 1)

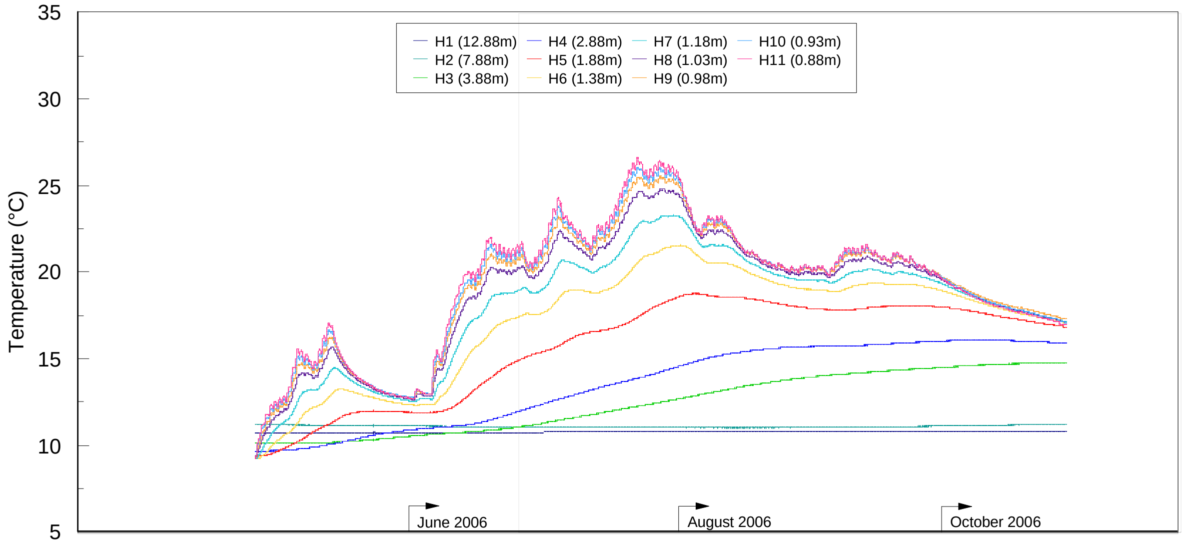


(c) Borehole E (2m from edge of store 1)

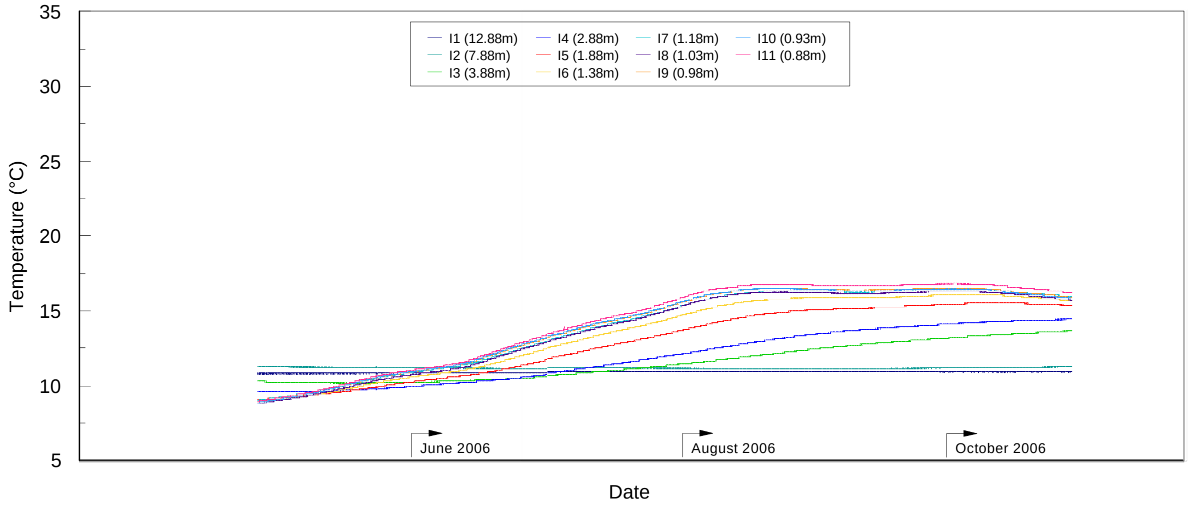
Figure 9.3. Variation of ground temperatures with time below store 1 (summer 2006)



(a) Borehole G (centre of store 2)



(b) Borehole H (edge of store 2)



(c) Borehole I (2m from edge of store 2)

Figure 9.4. Variation of ground temperatures with time below store 2 (summer 2006)

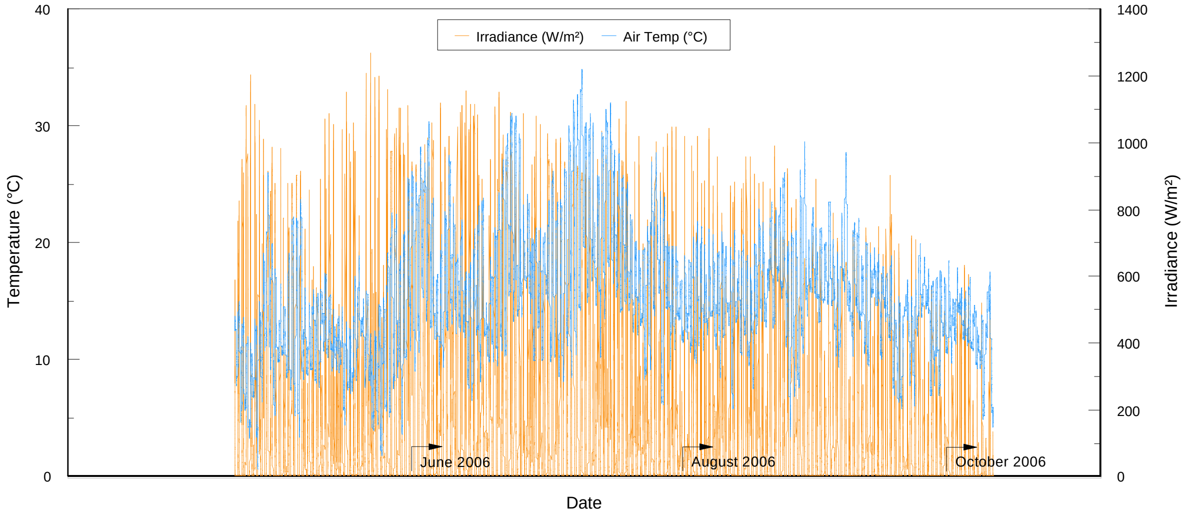


Figure 9.5. Variation of air temperature and irradiance with time (summer 2006)

The ground temperatures peaked on 27th July 2006 (Figures 9.6 and 9.7) and a contour plot of the temperatures below store 2 is shown in Figure 9.8. This contour plot illustrates that ground temperatures reached 26°C below the under-road store and were generally slightly higher under the centre rather than the edge of the road as would be expected. Temperatures at 2.5m away from the edge of the heat store and beneath the insulated verge area fell off to about 15°C at store pipe level.

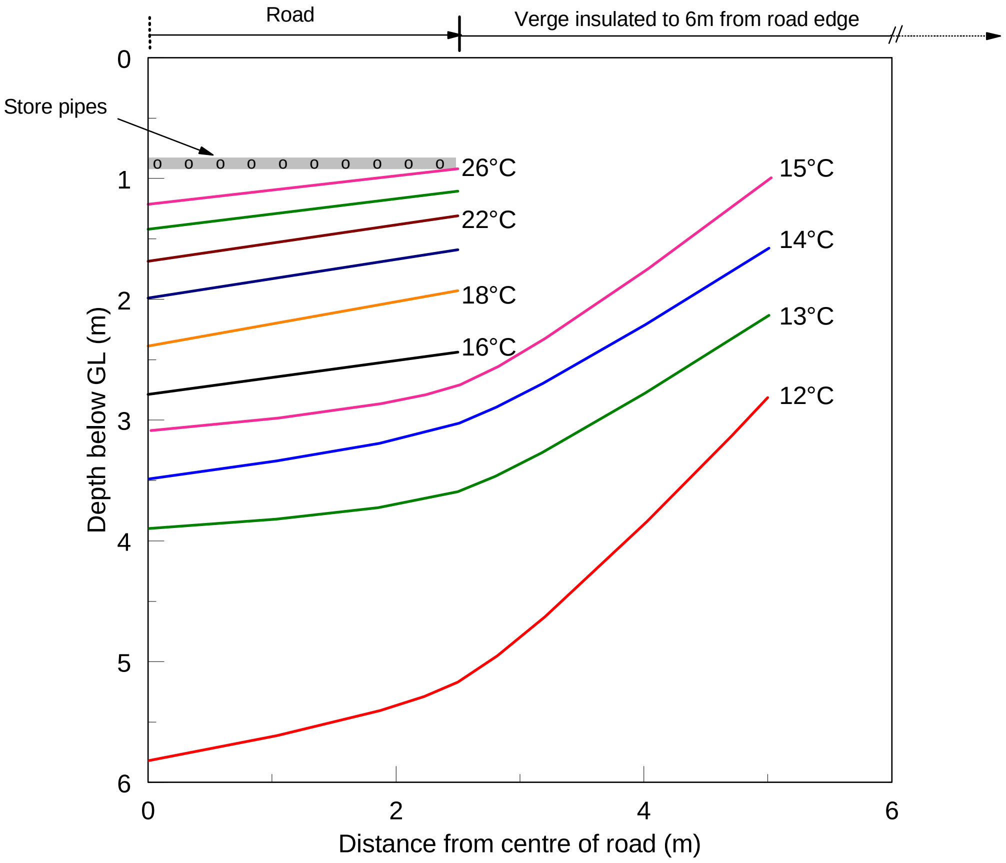
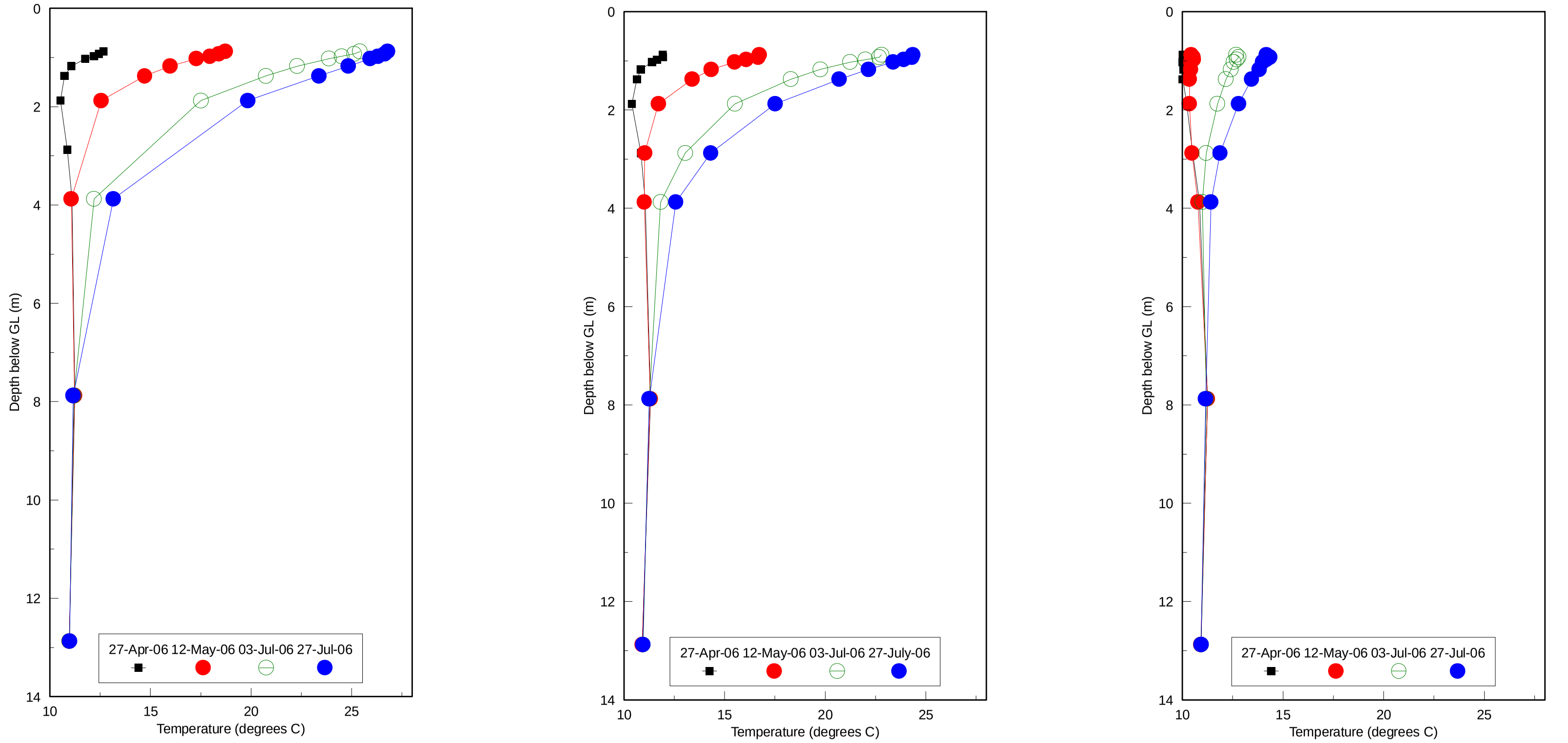


Figure 9.8. Contour plot of ground temperatures below store 2 on 27 July 2006

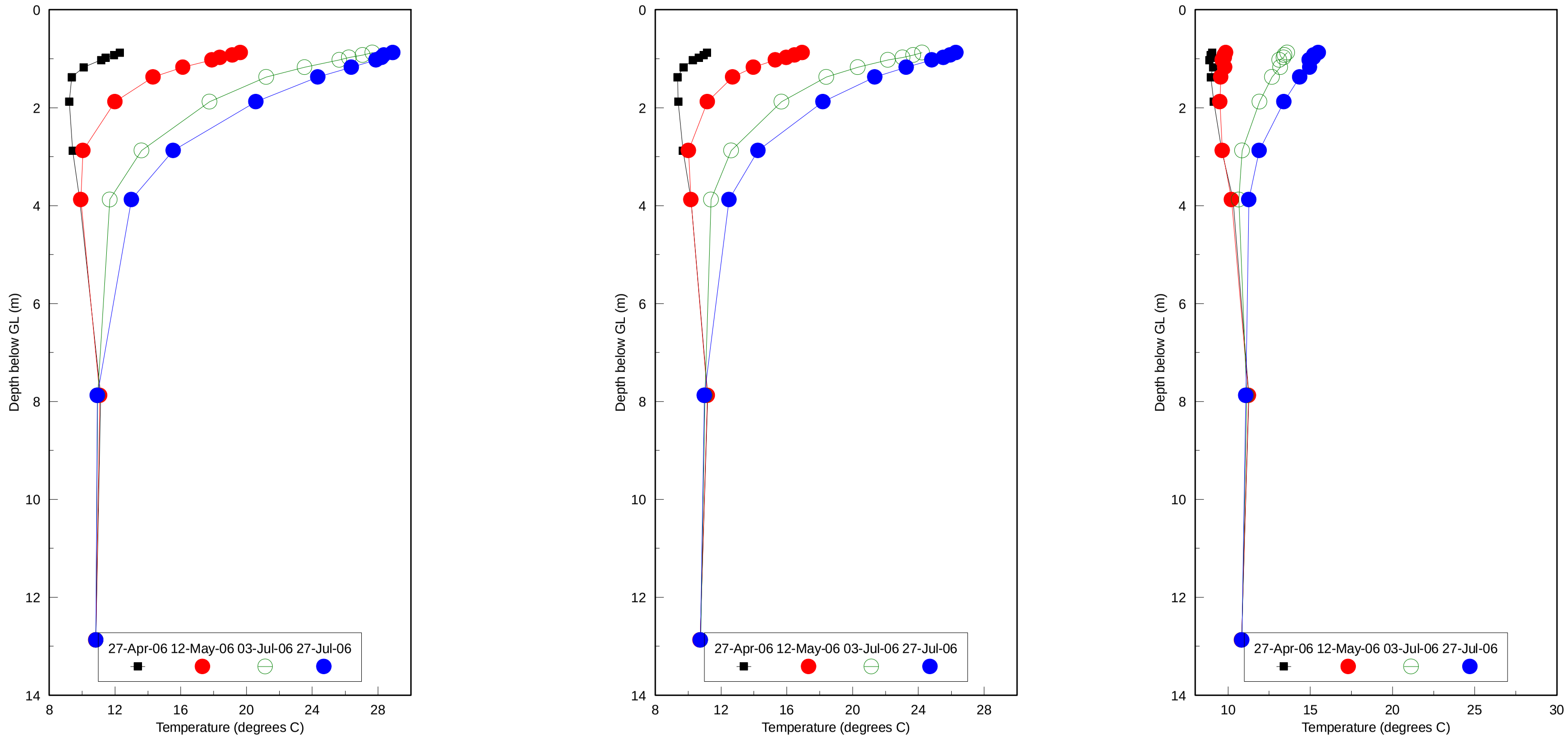


(i) Borehole C: Centre of Store 1 (Off-Road)

(ii) Borehole D: Edge of Store 1 (Off-Road)

(iii) Borehole E: Offset from Store 2 (Off-Road)

Figure 9.6. Profiles of ground temperature with depth below store 1 (summer 2006)



(i) Borehole G: Centre of Store 2 (Road)

(ii) Borehole H: Edge of Store 2 (Road)

(iii) Borehole I: Offset from Store 2 (Road)

Figure 9.7. Profiles of ground temperature with depth below store 2 (summer 2006)

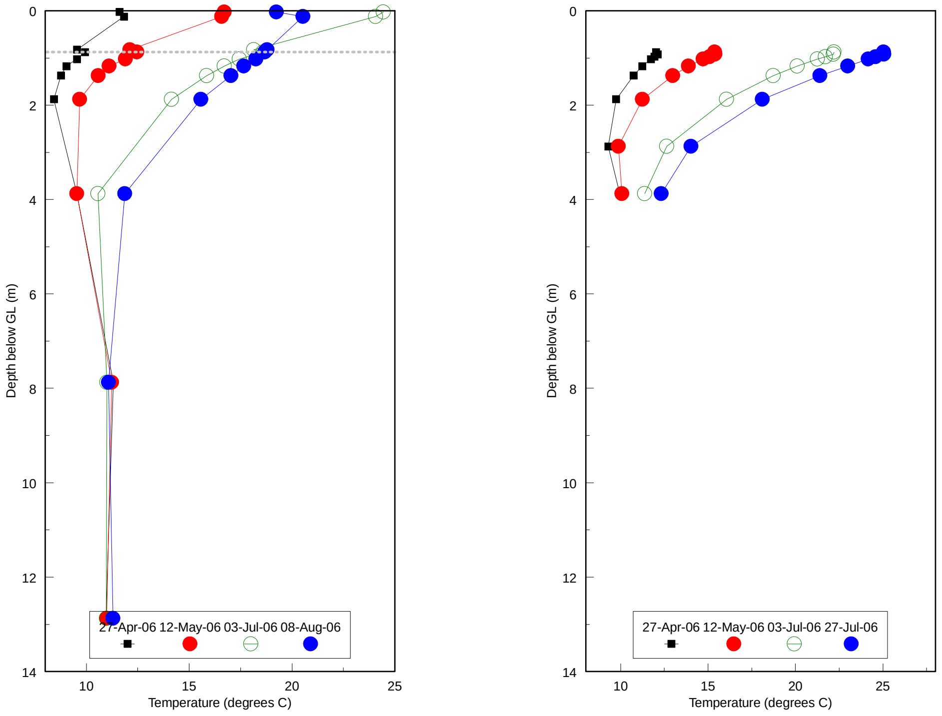
9.3 Ground temperatures in control areas

Figure 9.9 shows the temperature profiles in the control boreholes in the ground and untreated section of road. If the temperatures at 0.875m depth (ie. store pipe level) on 3rd July are compared, the results are as follows:

- 27.7°C temperature below the centre of under-road store 2 (Figure 9.7);
- 25.4°C temperature below the centre of off-road store 1 (Figure 9.6);
- 22.2°C temperature below the centre of the untreated road (Figure 9.8);
- 18.6°C temperature in the ground remote from the instrumented area (Figure 9.8).

On this basis, under-road store 2 was about 2°C hotter than the off-road store 2. As first sight this was surprising as store 2 was initially more depleted because of the winter maintenance protocol which was previously operated from it. However the results in Section 9.1 indicated that collector 2 was always slightly hotter than collector 1 because of the insulating effect of the polystyrene placed below it. For this reason more heat was transferred from collector 2 to store 2 as discussed in Section 9.4.

As would be anticipated, temperatures below the untreated road were lower than those in the treated road, although higher (because of absorption of the solar irradiation by the asphaltic surface) than in the ground adjacent to the road.



(i) Borehole A: 60m to south of centre of trial section

(ii) Borehole F: centre of trial section (within road)

Figure 9.9. Profiles of ground temperature with depth at control locations (summer 2006)

9.4 Energy recovered and used

The cumulative heat energies transferred between the collectors and stores are shown in Figure 9.10. These energies are calculated in the normal way using the flowmeter and associated thermistor measurements from the start of heat recovery on 27th April 2006. As noted in Section 7.4, the heat recovered from the collectors again exceeded the heat transferred to the stores because of heat losses in the connecting pipework and pumphouse.

More heat was generally transferred to store 2 than store 1, i.e. about 6.5MWh as opposed to 4MWh respectively. This was considered to be for two main reasons (a) initial temperatures in store 2 were lower than those in store 1 because heat store 2 was depleted by the winter maintenance schedule (b) collector 2 was completed unshaded whereas collector 1 was partially shaded by trees in the late afternoon. Losses of about 1MWh and 1.6MWh occurred in transferring heat from collectors 2 and 1 respectively, this may because slightly longer header pipes were used in the latter case or because store 2 was beneath the road rather than adjacent to it.

Figure 9.11 shows the cumulative electrical power used in operating pump 4 (collector 1/store 1) and pump 5 (collector 2/store 2). Slightly more electricity was used by the latter, which was consistent in that more solar heat was recovered. However in both cases the electrical power used was small and the average of the power used by pumps 4 and 5 was 370kWh over the summer period.

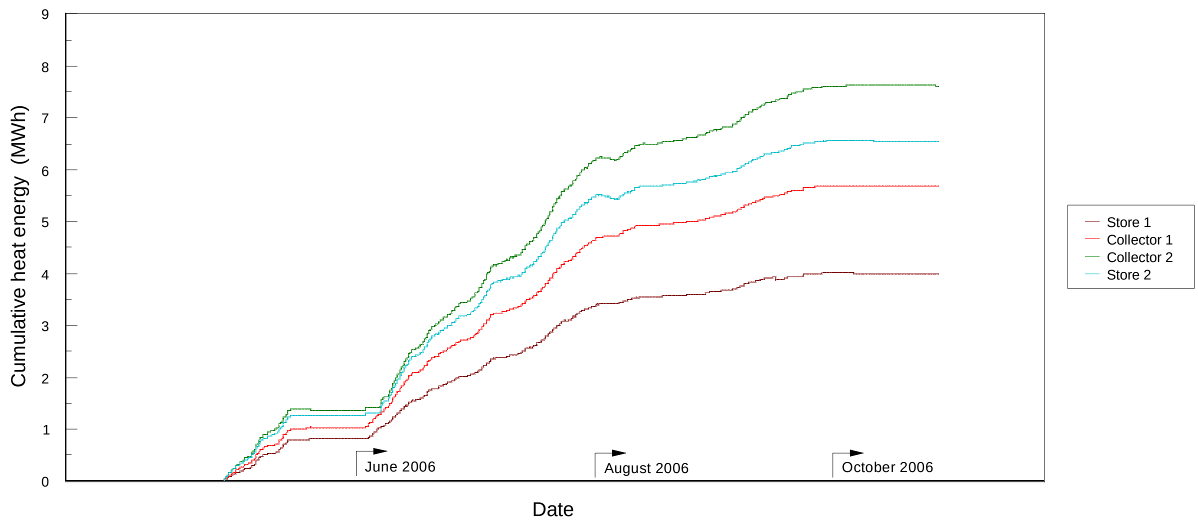


Figure 9.10. Cumulative heat energy recovered and stored (summer 2006)

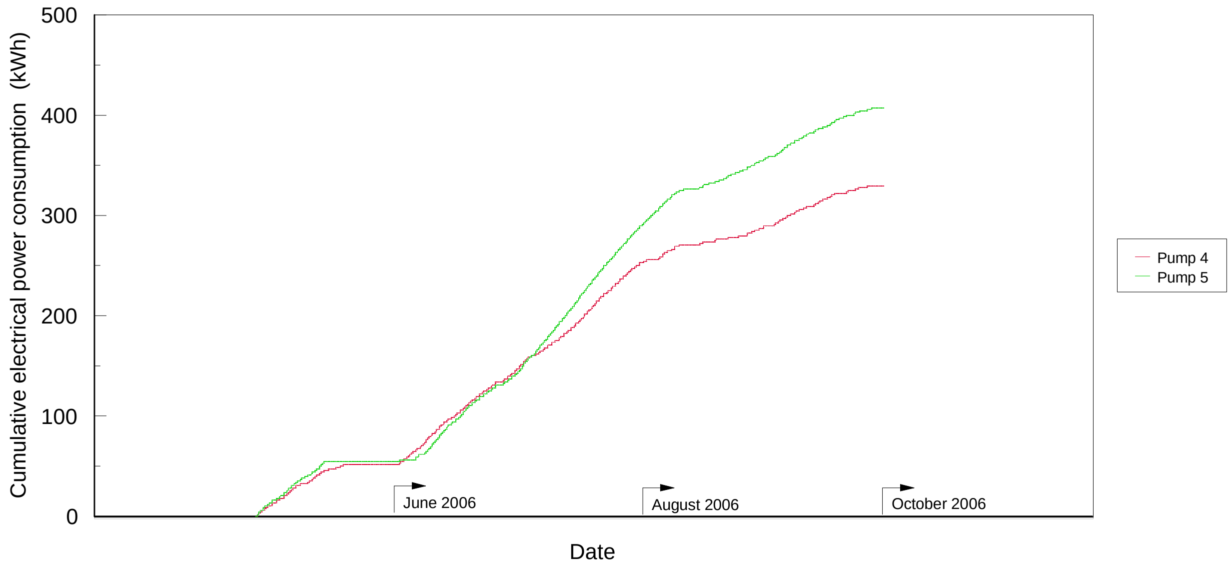


Figure 9.11. Cumulative electrical power used by the pumps (summer 2006)

9.5 Numerical modelling

Analyses were carried out using computational fluid dynamics (CFD) to predict the heat energy recovered during the course of the trial and the usage of this energy for the winter maintenance of a road surface. A full description of the model used, the mesh design, the soil parameters, and the findings is given in Appendix D.

Following validation of the model after comparing the predicted and measured heat recovery over the August and September 2005, an analysis was undertaken to estimate the annual heat collection capacity for a system implementing a road winter maintenance protocol only.

On the basis of this stabilised model, the total annual solar heat transfer calculated was then approximately 4.9MWh/annum. This prediction can be compared with the measured values of heat energy recovered in summer 2006 and shown in Figure 9.10. The measurements showed that more heat was generally transferred to store 2 than store 1, i.e. about 6.5MWh as opposed to 4MWh respectively. The predicted value of 4.9MWh therefore showed good agreement with the measurements.

10 Monitoring of the re-use of stored heat for winter maintenance of the road (1st November 2006 to 1st March 2007)

The 6.5MWh of solar heat transferred to store 2 (under-road) during the summer of 2006 was re-used to provide winter maintenance of the road surface above collector 2. As reported in Section 8, the operational protocol was that when the road surface temperature fell below 2°C for more than 15 minutes, pump 5 was activated to circulate fluid to heat the road surface.

It should be noted that the heat contained in store 1 was used for a separate experiment carried out simultaneously to simulate the heating of nearby buildings; these findings are discussed in Section 11.

10.1 Temperatures of the road surface in the heated and unheated areas

A comparison of the road surface temperatures in the heated and unheated sections of road is shown in Figure 10.1. Also shown are the associated air temperatures obtained from the weather station at the site. For convenience of scaling, only temperatures below 3°C are shown in these plots.

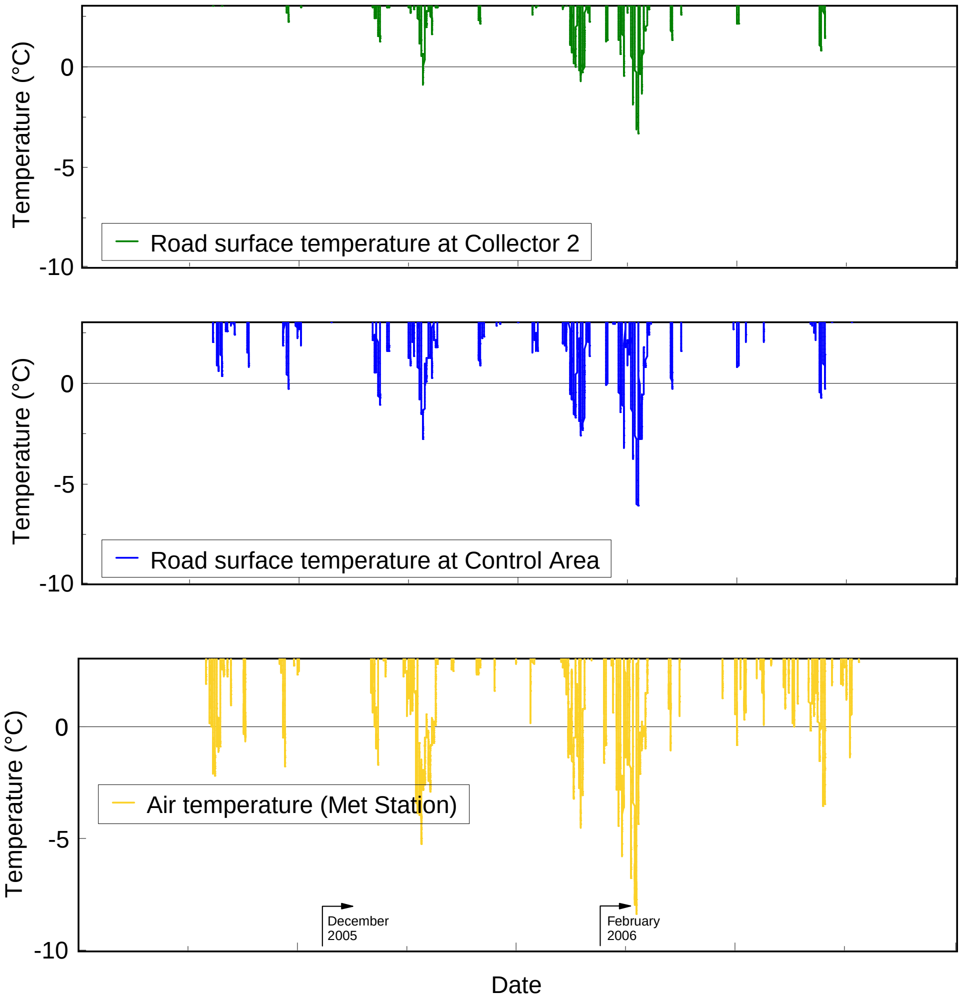


Figure 10.1. Variation of air temperature and road surface temperatures (winter 2006/07)

Examination of the findings shows that, when the road surface temperature fell below 2°C and the heating was activated, this section of road was generally about 3°C hotter than the unheated area.

Almost without exception the heated area of road remained above freezing until the period of extremely cold weather in early February, whereas there were quite a few occasions when sub-zero temperatures were recorded in the unheated area.

On February 7th extreme surface temperatures of -6°C and -3°C were measured for a few hours on the unheated and heated sections respectively, as a result the system briefly struggled to maintain the road above freezing.

The events during the snowfall on the following day are shown in Figure 10.2. The system did not prevent the snow settling[2] although the road surface temperature was being maintained between 0°C and +0.5°C at the time of the fall. However the snow in the Toddington area thawed fairly rapidly during the morning of the day of the fall, and it was therefore not possible to assess the influence of the under-road heating on the thawing process.

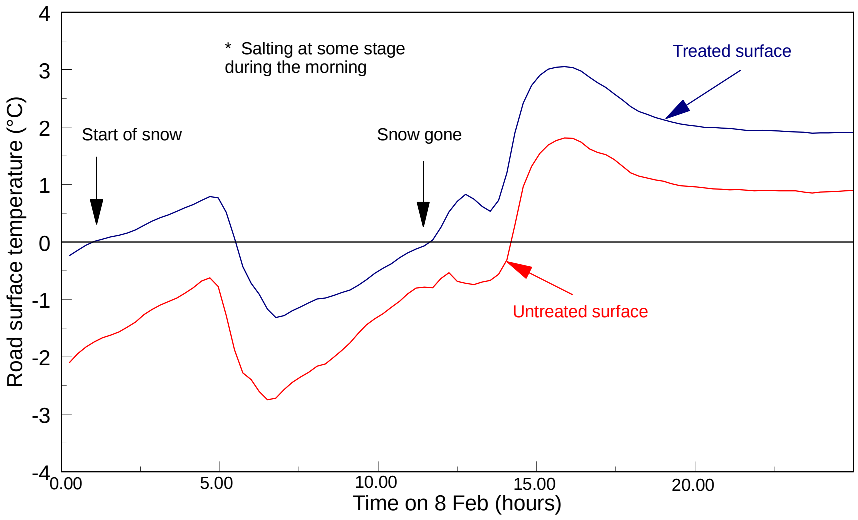


Fig 10.2. Sequence of events during the snow fall on 8th February 2007

It is believed that fine tuning of the system in one or a combination of the following ways would prevent the snow settling on future occasions:

i. having the heat pipe array at a shallower depth in the asphalt is predicted by numerical analysis to be more efficient than the current 120mm depth. However in heavily trafficked roads, durability and maintenance issues may preclude this.

ii. using smarter sensing of atmospheric conditions and better control protocols would prevent unnecessary triggering of road heating on occasions when sub-zero temperatures do not result in ice formation. Avoiding heat wastage should improve efficiency later in the winter season. For example, the under-road heating was activated on 16 more days than the 28 days in which salting took place on the nearby motorway (see Table 10.1). It is also worth noting that two salting runs were carried out on four of these days and six runs on 8th February.

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[2] Although it is by no means certain, it can be postulated that if there had been any significant traffic on this access road, the combined effect of heating and trafficking might possibly have preventing the snow from settling.

iii. by using techniques of temporarily boosting the heat output in extreme weather conditions, such as employing a heat pump.

Table 10.1 gives a full comparison of the times at which the under-road heating was switched on (i.e. when the road surface temperature fell below 2^{o}C) with the occasions when salt spreading took place on the nearby M1.

Table 10.1 Comparison of times when road heating and salting took place

DATE	ON TIME	OFF TIME	DURATION	SALTING
03/11	00:15	09:15	9	√
04/11	01:00	09:45	8.75	
06/11	06:15	06:30	0.25	
09/11	24:00	08:30	8.5	√
18/11	02:45	09:45	7	√
18/11	23:15	10:15	11	√
21/11	06:00	09:45	3.75	
22/11	06:15	09:15	3	
08/12	20:45	11:00	14.25	√
09/12	20:15	11:15	15	√
11/12	23:15	10:15	11	√
16/12	20:45	11:30	14.75	√
18/12	01:00	06:15	5.25	√
19/12	17:45	11:45 (21/12)	42	√ (2 Runs)
21/12	17:45	13:00	19.25	
22/12	17:15	12:30	19.25	√
27/12	17:15	19:45	2.5	
29/12	06:45	08:15	1.5	
01/01	10:00	10:45	0.75	
01/01	22:30	11:30	13	
02/01	21:30	02:30	5	
06/01	01:45	05:15	3.5	
06/01	23:00	02:45	3.75	
14/01	05:15	10:30	5.25	√
14/01	21:45	10:00	12.25	
21/01	07:00	10:45	3.75	
21/01	21:15	01:00	3.75	√
22/01	18:45	12:45	18	√
23/01	18:15	12:15	18	√ (2 runs)
24/01	18:45	12:15	17.5	√ (2 runs)
25/01	18:30	11:30	17	√
27/01	03:15	10:45	7.5	√
31/01	01:30	10:45	9.25	
03/02	00:15	11:00	10.75	√
03/02	22:00	11:15	13.25	√
05/02	00:30	10:15	9.75	√
05/02	19:45	12:00	16.25	√
06/02	19:00	12:30	17.5	√
07/02	18:45	15:15	20.5	√ (2 runs)
08/02	18:00	12:00	18	√ (6 runs)
09/02	19:30	02:45	7.25	√
10/02	06:45	08:00	1.25	
14/02	22:45	09:30	10.75	√
17/02	06:30	10:00	3.5	√

* Shaded dates indicate road heating of duration of 3 hours or less.

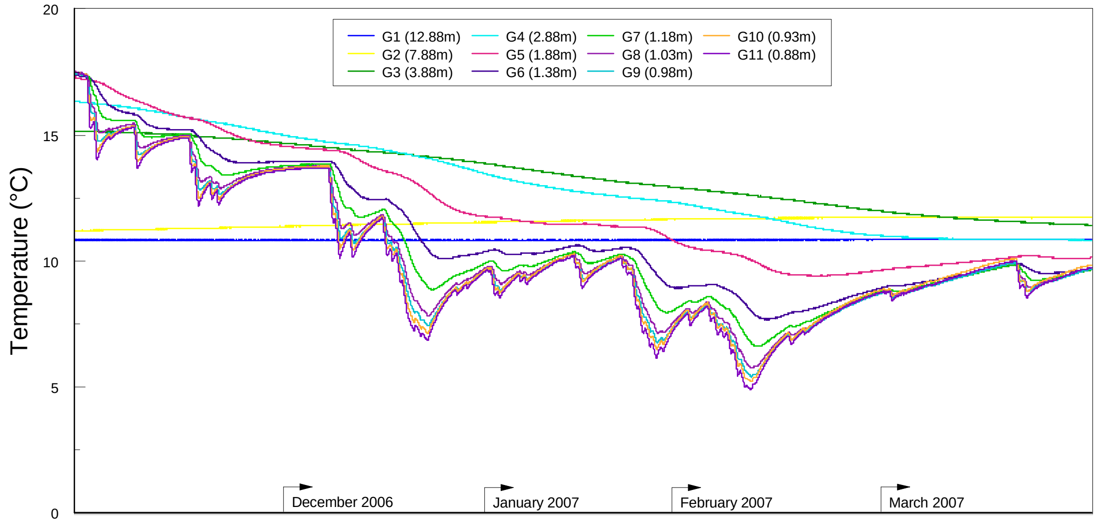
As might have been expected the results in Table 10.1 demonstrate over-usage of the under-road heating in certain situations. For example the road heating was operating near continuously in the foggy spell between 19th and 23rd December when the relative humidity was greater than 97% and the road and air temperatures were both less than 2°C throughout each day. Salt spreading activities were far more limited during this period. Also indicated in Table 10.2 are dates when the road heating was switched on for a period of 3 hours or less. No salt spreading took place on these dates and a small amount of heat was therefore wasted from the heat store on these occasions.

10.2 Ground temperatures below the heat stores

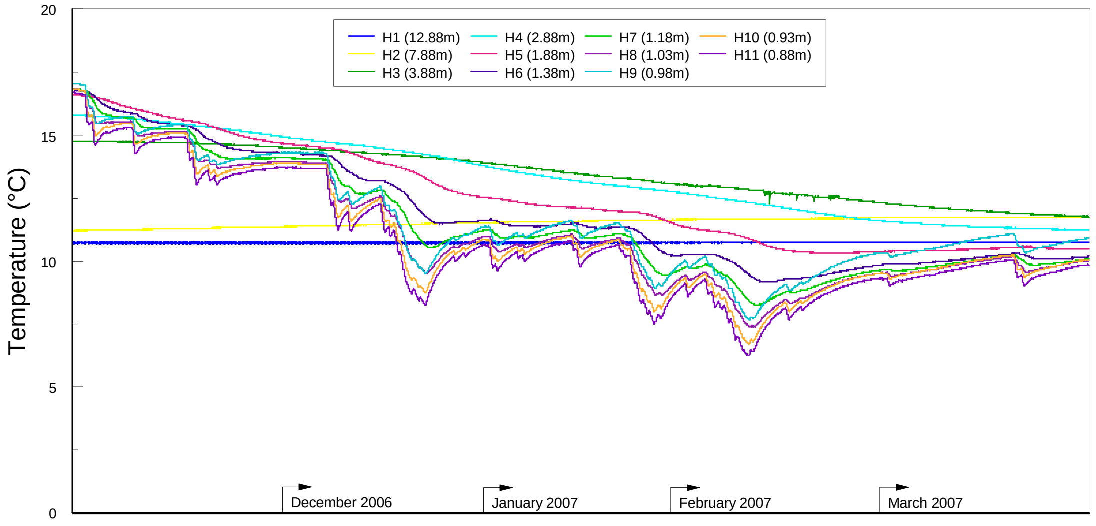
The ground temperatures measured at various depths below the pipe array comprising store 2 are shown in Figure 10.3. Falls in temperature are recorded when heat is being extracted from the store to heat the road surface at the times indicated in Table 10.1 and these temperature reductions are particularly noticeable in the few metres of ground immediately below the store pipe array.

During intervening warmer periods there is some recovery in temperature values due to heat transfer from warmer and deeper horizons. It is the magnitude of this recovery which is particularly important. Comparison with similar plots shown in Figure 8.2 for winter 2005/06, when the heat store was only partially charged, show much better recovery in winter 2006/07. For example Figure 10.3a shows that after major dips in the temperature of thermistor G9 (shallowly placed in borehole G near the centre of the heat store), measured temperatures still recovered to about 10°C throughout the winter 2006/07. This is in contrast to the results shown in Figure 8.2 where recovery was only to a temperature of about 7°C. As the system operates on narrow margins of temperature the better performance in 2006/07 can be directly attributed to having a fully charged heat store.

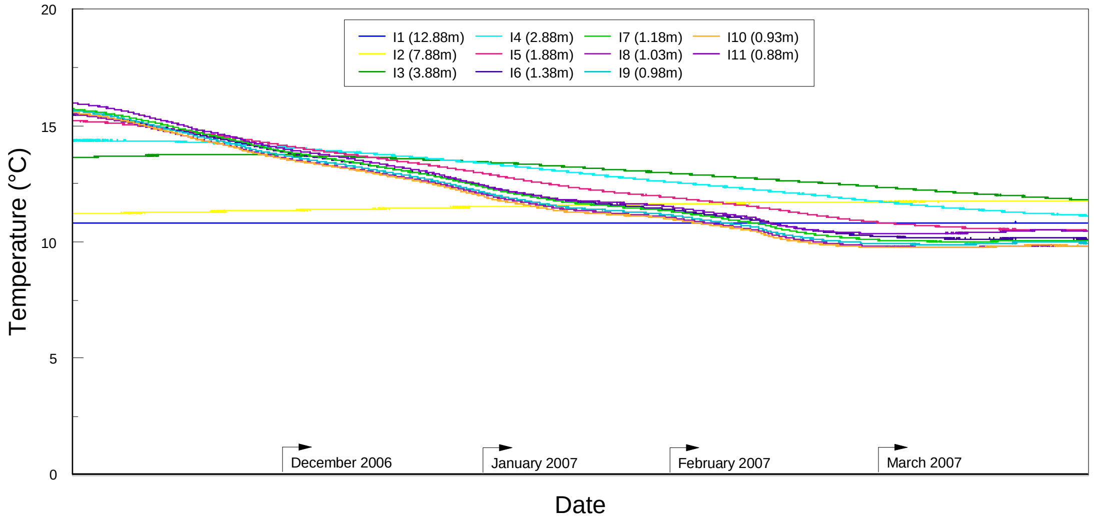
Further details of the distribution of temperature with depth below and adjacent to store 2 are shown in Figure 10.4. The starting profiles are shown for 1st November 2006, at which time the road heating protocol was activated, and these clearly indicate high temperatures beneath the pipe array after a full summer of heat collection. Some depletion of the store heat had occurred by 1st January after two months of winter maintenance, but nevertheless the results in Figures 10.4a and 10.4b indicate that a bulb of higher temperatures still remained, peaking at about 4m depth below ground level. However, activation of road heating during the colder weather during late January and early February 2007 caused a noticeable drop in this reservoir of heat. Although some recovery in temperature subsequently occurred in the ground immediately below the store pipes, by the end of the winter season temperatures were fairly constant with depth and in the range 10-11°C.



(a) Borehole G (centre of store 2)

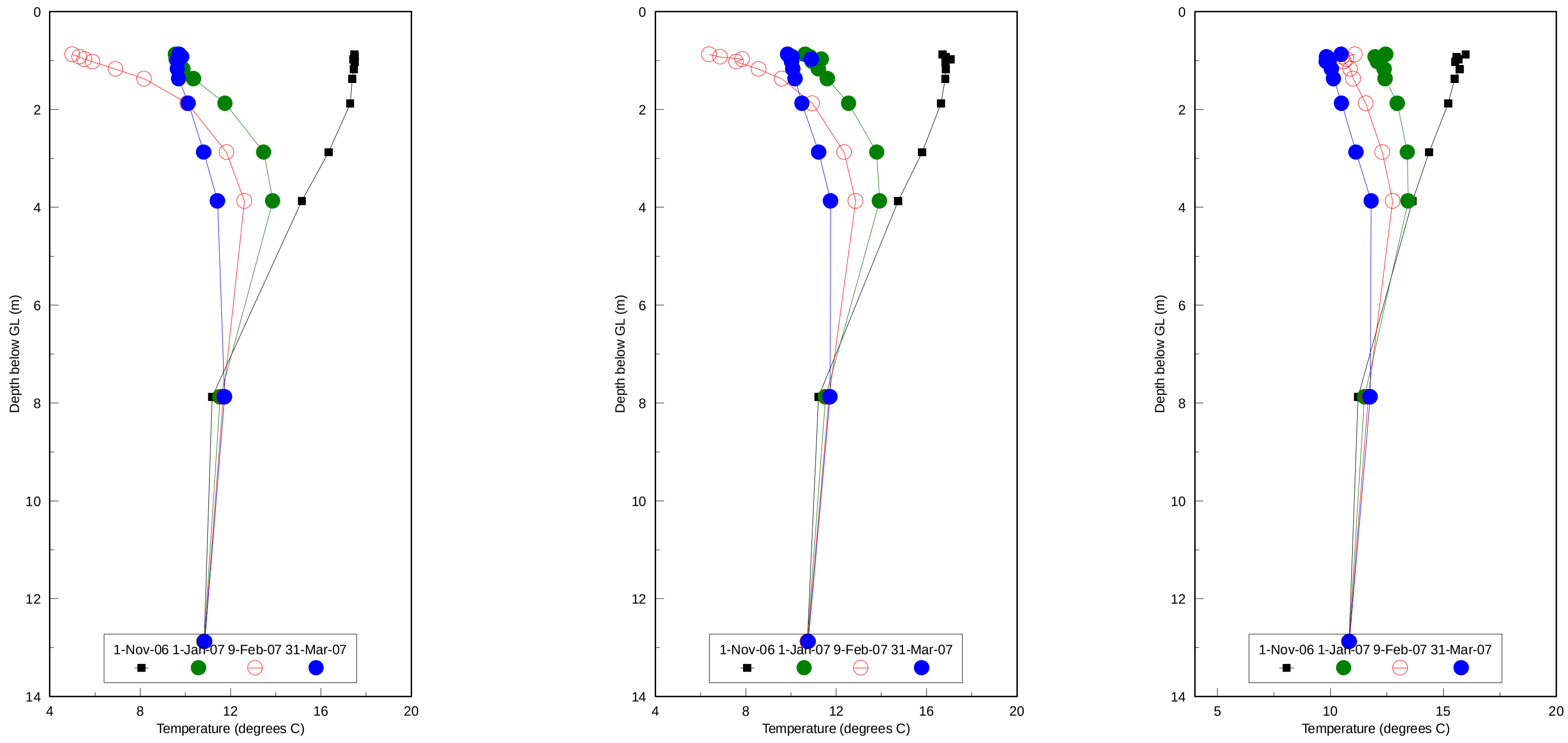


(b) Borehole H (edge of store 2)



(c) Borehole I (2m from edge of store 2)

Figure 10.3. Variation of ground temperatures with time below store 2 (winter 2006/07)



(i) Borehole G: Centre of Store 2 (Road)

(ii) Borehole H: Edge of Store 2 (Road)

(iii) Borehole I: Offset from Store 2 (Road)

Figure 10.4. Profiles of ground temperature with depth below store 2 (winter 2006/07)

10.3 Energy used to heat road

The cumulative heat energy used to heat the road is shown in Figure 10.5. These data were obtained from the flow meters and differential fluid temperatures measurements in the header pipes to collector 2 and from store 2. Good agreement was obtained between the measured heat flows as would be anticipated.

Of the 6.5MWh of solar heat transferred to the store during the summer of 2006, about 2.5MWh was required to heat the 150m^2 area of road during winter 2006/07. This latter value can be compared with the heat energy of about 3MWh required during winter 2005/06. These findings were reasonably consistent bearing in mind that winter 2006/07 was generally fairly mild with the exception of two cold spells towards the end of January and in early February. These two cold spells alone accounted for about 1MWh of the 2.5MWh used.

An overall electrical power consumption of approximately 95kWh was used for winter maintenance during 2006/07.

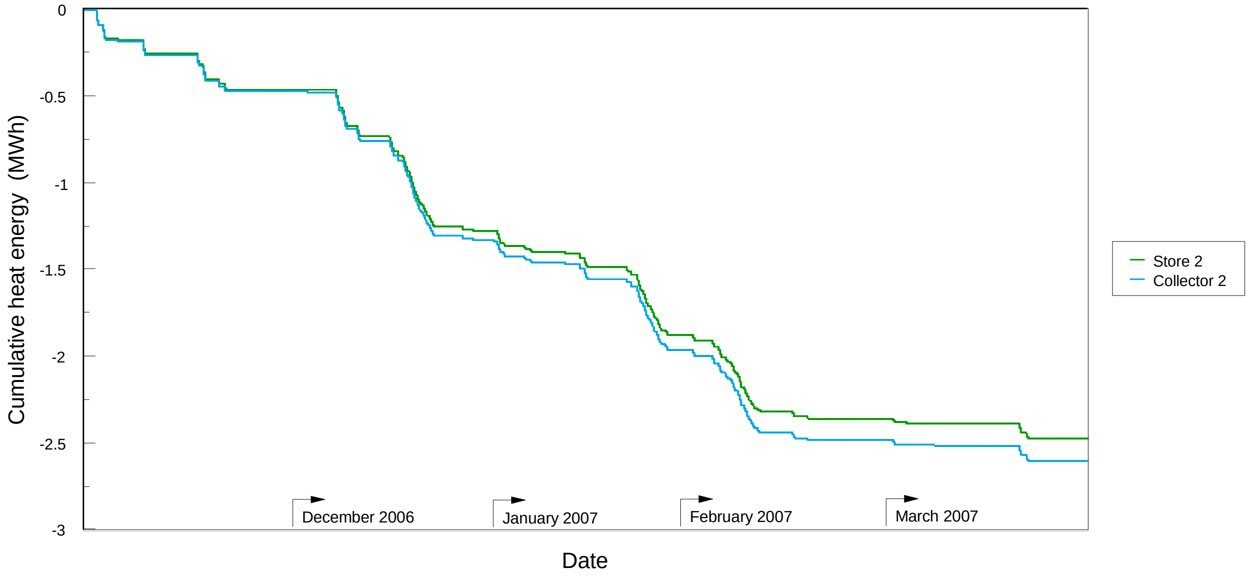


Figure 10.5. Cumulative heat energy used to heat the road (winter 2006/07)

10.4 Numerical modelling

Following the successful CFD modelling of the annual solar hear recovery, the analysis was extended to investigate the performance during the associated period of winter maintenance. Full details of the analysis and its findings are given in Appendix D.

The simulation of the winter maintenance protocol revealed that the performance, (i.e. the heat output and the ability of the system to raise the temperature of the collector surface relative to the control surface) increases with the starting temperature of the store and decreases with the depth of the collector pipe beneath the road surface.

In summary, the simulation clearly demonstrated that a pipe invert depth of 90mm gives an improved heat output relative to a system with a pipe invert depth of 140mm. The heat output increased by up to 20% for cool initial store temperatures of 5°C, and by about 8% when the initial store temperatures were elevated to 19°C.

Whereas the measurements (described in Section 10.1) indicated that generally the heated road surface remained at least 2^{o}C hotter than that in the control area at a time when the store temperature was at the low end of the modelled range, the calculated performance from the CFD modelling slightly under-predicted this measured performance.

10.5 Whole life costing of winter maintenance system

A detailed whole life costing of interseasonal heat storage was reported by Carder (2005) in an initial feasibility study prior to this trial and this analysis was subsequently refined in the light of the experience and cost data obtained during the trial. Full details of this new study are presented in Appendix E.

The whole life cost evaluated using the above factors over a 30 year accounting period was found to be £164,293 for 100m length and two lanes. Taking account of the annual discount rate of 3.5% this means that a saving of £8,631 per annum needs to be made for break even over the 30 year period for this section of road.

It must be noted that a *very significant* increase in the overall effectiveness of the interseasonal heat transfer system is expected to occur if the collector pipe array is at a shallower depth in the road than that used at Toddington. However apart from the effect this would have on the pavement maintenance schedule and the associated cost implications in replacing the collector pipe array if planing occurred to pipe depth, there are concerns about the increased risk of reflection cracking of the pavement surface. Currently, for this latter reason alone, it is not envisaged that the depth of cover to the pipes can be reduced below 100mm on UK motorways and trunk roads subjected to heavy trafficking. The situation is clearly different for local roads, car-parks, etc. where trafficking is lighter.

Appendix E also compares the costs of operating a renewable energy system, electrical under-road heating, and salt spreading. At first sight, the operating costs of salt spreading are lower than those of an interseasonal heat transfer system, and both are an order of magnitude lower than those of a totally electrical system as might be expected. However allowance needs to be made for the fact that operating costs derived for salt spreading take no account of the time of supervisory staff and weather forecasting for which no figures are readily available. In summary, treatment of well-known cold spots on the highway network or treatment of slip roads and interchanges may provide cost effective locations for initial implementation of interseasonal heat transfer systems.

11 Building heating simulation (14th December 2006 to 31st April 2007)

The design of the pump house and its principles of operation (Figure 6.2) were such that the effects of heating a building using interseasonal heat transfer could be investigated. Solar energy was collected from the road surface during summer 2006 and retained in the off-road heat store (store 1). In response to the demand for building heat, fluid was pumped from the ground heat store to the heat pump (H in Figure 6.2) where its temperature was elevated to maintain the temperature in the buffer vessel at a maximum temperature of 36°C. Heat was then rejected from the buffer vessel at a pre-programmed rate using the dry air coolers which comprised the heat dump D. The control protocols also allowed for some direct pre-heating of the buffer vessel from the ground store bypassing the heat pump when necessary. The magnitude of the heat dumped was measured using heat meter HM5.

The sequence of buffer heating and heat rejection employed during the simulation is given in Table 11.1.

Table 11.1. Sequence of buffer heating and heat rejection

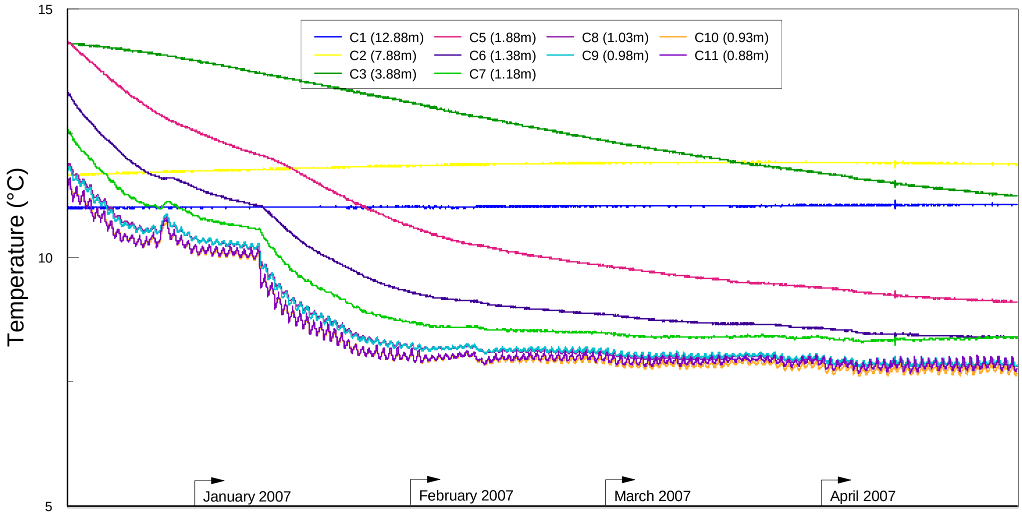
Start date	Finish date	Buffer heating	Planned heat rejection	
		Time period	Time period	kW load set point
14/12/2006	31/12/2006	08:00 - 18:00	16:00-18:00	5
10/01/2007	10/01/2007	08:00 - 18:00	14:00-16:00	20
11/01/2007	24/01/2007	08:00 - 18:00	14:00-16:00	10
25/01/2007	07/02/2007	08:00 - 18:00	12:00-16:00	10
08/02/2007	28/02/2007	08:00 - 18:00	10:00-18:00	10
01/03/2007	07/03/2007	08:00 - 18:00	12:00-16:00	10
08/03/2007	31/03/2007	08:00 - 18:00	10:00-18:00	10
01/04/2007	07/04/2007	08:00 - 18:00	12:00-16:00	10
08/04/2007	30/04/2007	08:00 - 18:00	10:00- 18:00	5

The relevant measurements taken during the building heating simulation are now described.

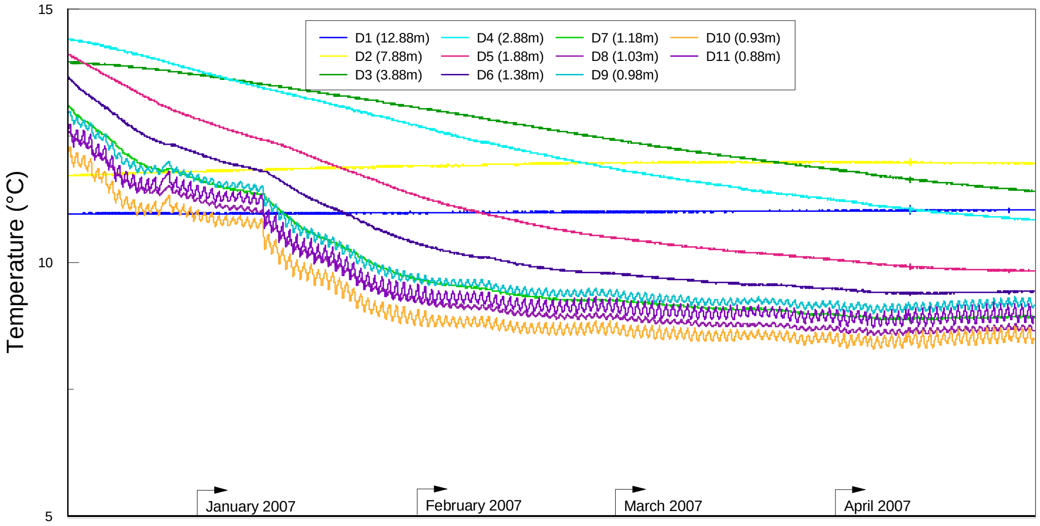
11.1 Ground temperature below the heat store

The ground temperatures measured at various depths below the pipe array comprising store 1 are shown in Figure 11.1. Reductions in temperature are recorded when heat is being extracted from the store and rejected to simulate the heating of a nearby building. These temperature reductions are particularly noticeable on the thermistors in the first metre of ground immediately below the store pipe array, i.e. on thermistors 9, 10 and 11 in boreholes C and D. At these depths, heat extraction in the first few months caused a rapid fall in temperatures although from February these temperatures stabilised as heat replenishment from depth approximately balanced the heat being extracted from the ground store.

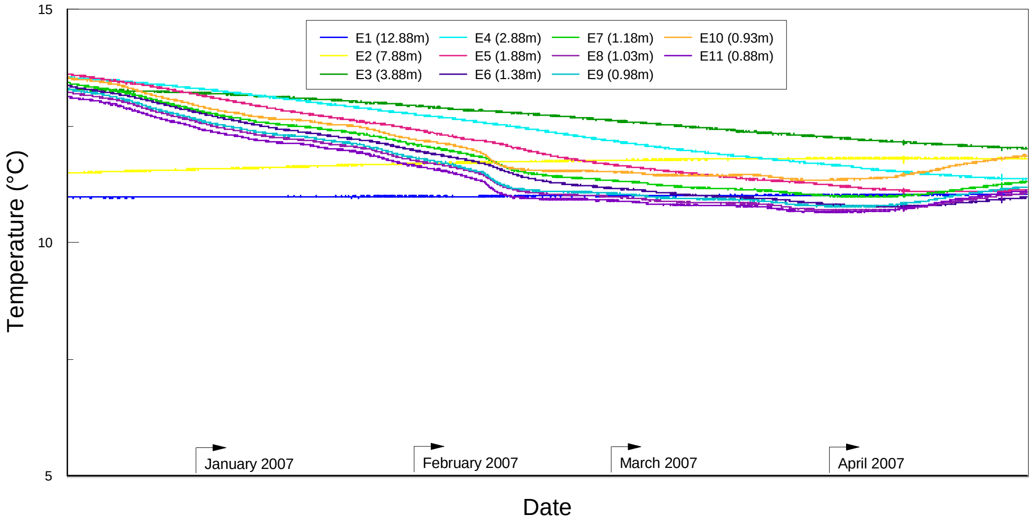
The ability to replenish the heat in the store pipe array is further indicated in the plots of temperature against depth shown in Figure 11.2. Prior to commencement of heat extraction (13th December 2006), a bulb of higher temperatures existed below the store pipes in boreholes C and D down to a depth of about 5m. Towards the end of January the heat extraction caused some reduction in temperatures at



(a) Borehole C (centre of store 1)

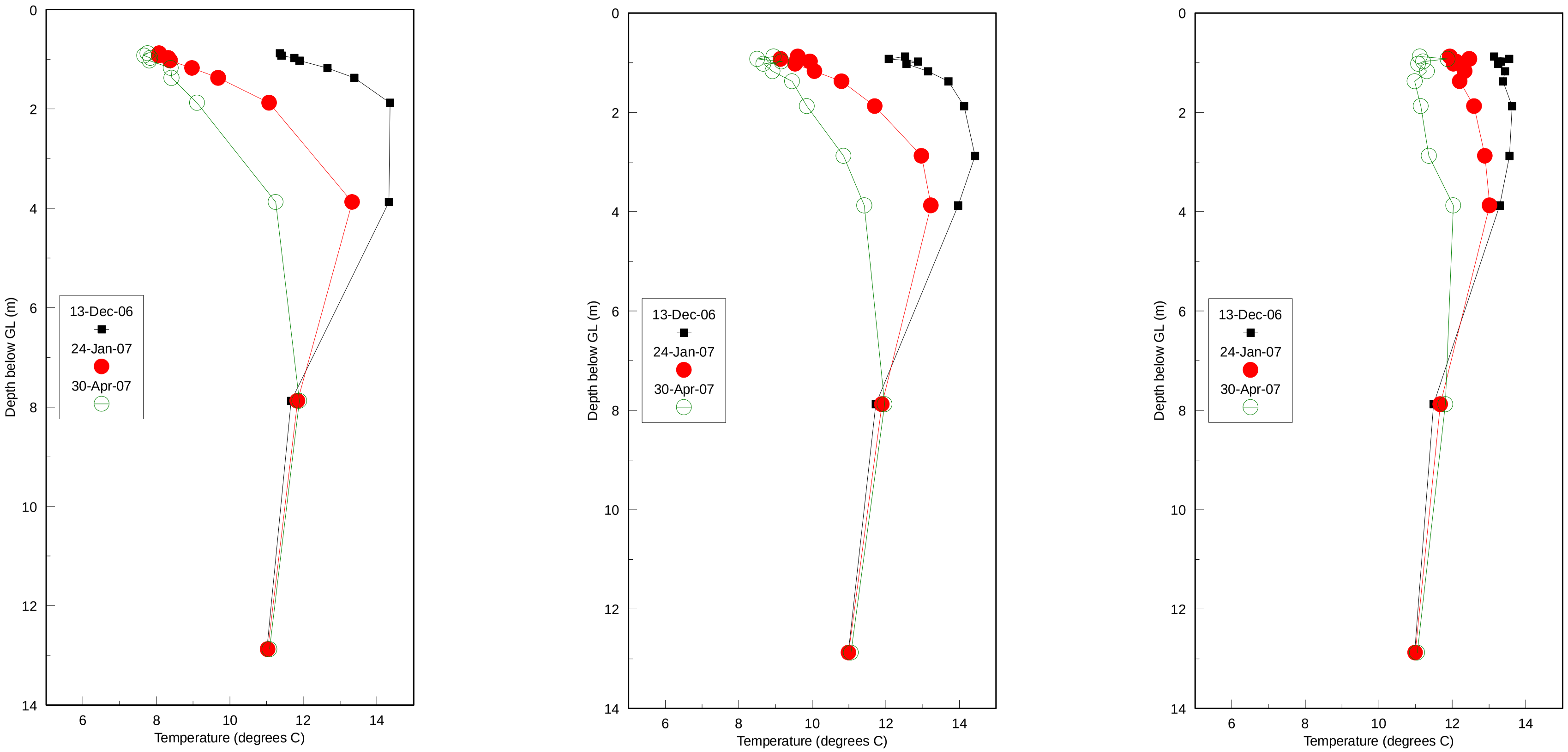


(b) Borehole D (edge of store 1)



(b) Borehole E (2m from edge of store 1)

Figure 11.1. Variation of ground temperatures with time below store 1



(i) Borehole C: Centre of Store 1 (Off-road)

(ii) Borehole D: Edge of Store 1 (Off-road)

(iii) Borehole E: Offset from Store 1 (Off-road)

Figure 11.2. Profiles of ground temperature with depth below store 1 during building heating simulation

these depths, however it is evident from Figure 11.2(i) and (ii) that a reserve of heat still remains at depth below the store array. This enabled further heat extraction to proceed in the following three months. By the end of April this bulb of temperature had diminished further and continued operation, although feasible, was probably extracting naturally occurring geothermal heat from the ground rather than the solar heat recovered from the road surface in the previous summer.

The replenishment of the heat (extracted by the store pipe array) from the ground below is fundamental in the operation of an interseasonal heat transfer system. It should be noted that the rate of replenishment will depend on the thermal conductivity and specific heat of the soil strata, and the temperature difference between the soil below the store and the fluid in the pipe array transferring the heat.

11.2 Measured heat rejection

The measured heat rejection is compared with the heat recovered from the ground heat store in Figure 11.3. During this investigation 4.05MWh of heat was rejected in the building heating simulation and of this 3.66MWh was extracted from the heat store prior to boosting the fluid temperature using the heat pump.

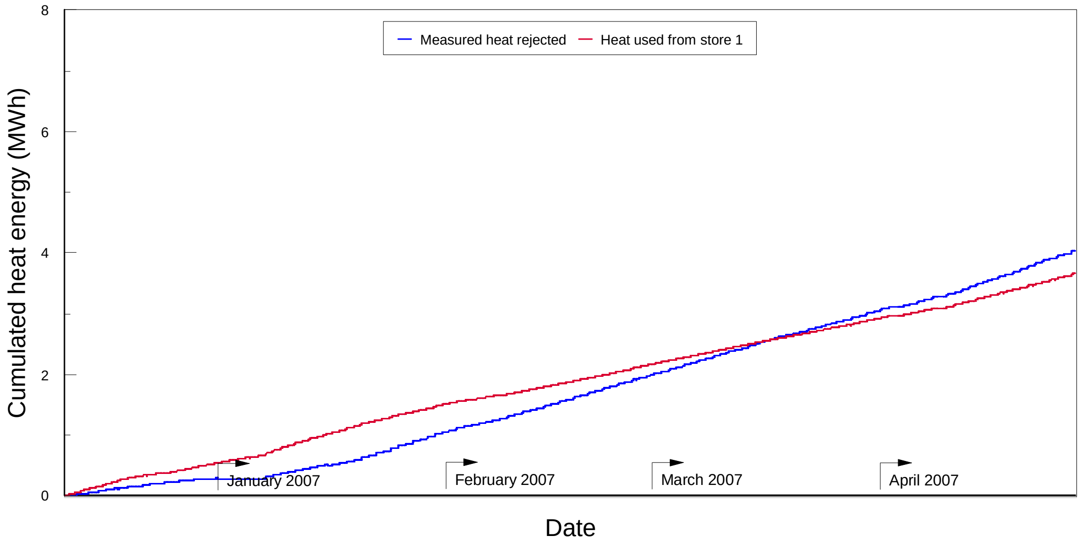


Figure 11.3. Comparison of measured heat rejected and store heat used during building heating simulation

11.3 Electrical energy used

An evaluation of the heat rejected against the electrical power used in running the pumps was carried out on an arbitrary date (1st February 2007) when rejecting heat at a planned rate of 10kW per hour over a 4 hour period. Measurements of flow rate and differential temperatures confirm that 40.7kWh was actually rejected for building heating purposes, whilst 12.7kWh was actually recovered from the ground heat store during the 4 hour period.

Current (RMS) measurements on the various pumps over the period from 12:00 to 16:00 on the 1st February confirm that the AC electrical power used was as follows:

- the heat pump used 14.812 kWh,
- pump 4 (circulating from the heat store to the heat pump) used 3.273 kWh,
- pump 3 (circulating between the heat pump and the buffer vessel) used 3.148 kWh.

The efficiency of a ground source heat pump system is measured by the coefficient of performance (CoP). This is the ratio of units of heat output for each unit of electricity used to drive the compressor and pump for the ground loop. From the figures above the CoP of the overall system at Toddington can be calculated from 40.7/(14.812+3.273+3.148) = 1.92. However it must be noted that this calculation includes the losses due to the addition of pump 3 and the buffer vessel, which may not be required in every situation or could be considered to be part of the building heating system. If allowance is made for these factors, it would be expected that the CoP of the heat pump would be between 3 and 4 as is normal.

The efficiency of the unit and the energy required to operate it are directly related to the temperatures between which it operates. In heat pump terminology, the difference between the temperatures where the heat is extracted and the temperature where the heat is delivered is called the “lift.” The CoP of the system will show some variation and the smaller the lift, the higher the efficiency will be.

In this prototype experiment, the required capacity of the heat pump was estimated using the best information available. Retrospectively it is considered that the heat pump was oversized for the application, a smaller heat pump would probably have cycled less frequently and hence been more efficient.

12 Building cooling simulation (1st May to 31st August 2007)

The procedure used for the building heating simulation reported in Section 11 was effectively reversed to simulate cooling of a building in the summer. The ability to cool a building is an important feature of any interseasonal heat transfer system in view of the increased temperatures likely in extended summer periods which are predicted to occur as a result of global warming.

The building cooling protocol works in a similar way to the heating simulation. Heat is moved from the simulated building (buffer vessel) to heat store 2 (via the heat pump). The rate of transfer of heat to the store attempts to match the cooling load entered into the pre-programmed look-up table and is measured by a heat meter which is used for control and monitoring. The fans pass outside air over the fluid circulating from the buffer vessel thereby raising its temperature, causing an increase in cooling demand to match the load defined in the look-up table.

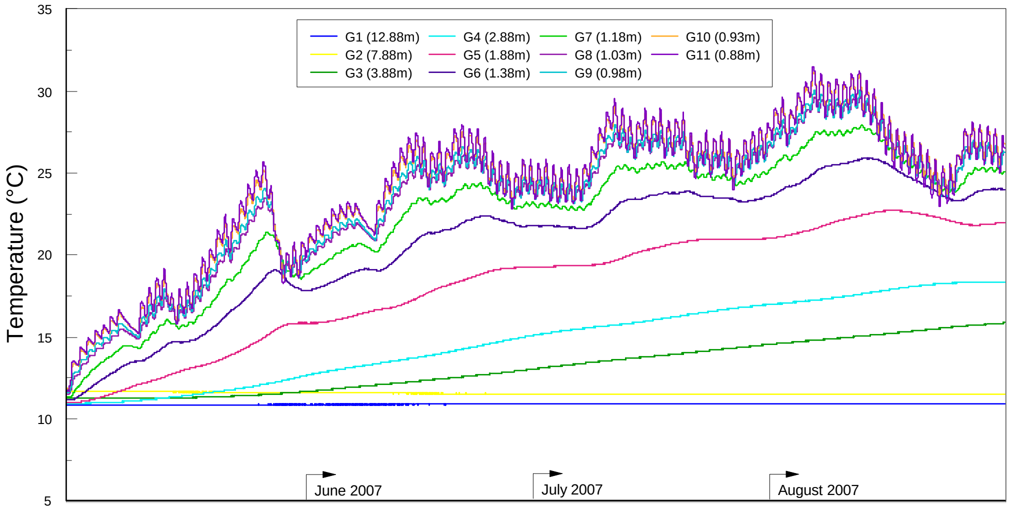
The building cooling simulation commenced on 1st May extracting heat under a load of 10kW from 2pm to 6pm for the first seven days with a subsequent break for the following two days to assess the preliminary results. Building cooling was then recommenced on the 10th May under a load of 10kW from 8am to 6pm on a daily basis until 31st August.

12.1 Ground temperature below the heat store

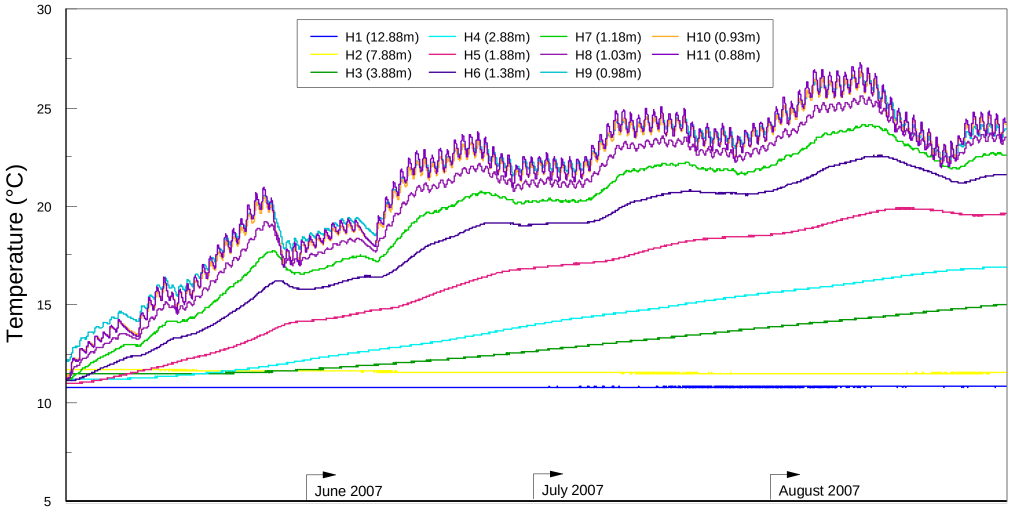
The ground temperatures below store 2 increased rapidly as heat was extracted from the air by the dry air coolers and passed to the pipe array comprising store 2. Figure 12.1 shows the subsurface ground temperatures measured below the pipe array. A steady build-up in ground temperature was recorded on the thermistors in boreholes G and H below the centre and edge of store 2 respectively. Only small changes in temperature were measured in borehole I below the insulation and at 2m from the edge of the store, this tended to confirm that heat leakage laterally from the ground store was relatively small. The increases in temperature in boreholes G and H show some peaks and troughs according to the ambient air temperature and how much heat could be successfully extracted by the dry air coolers.

The distributions of temperatures with depth in each borehole are shown in Figure 12.2. In boreholes G (centre of store) and H (edge of store), temperatures decreased in an exponential manner with depth from respective peak temperatures of 28.0^{o}C and 24.6^{o}C measured immediately below the store pipes on 18th July.

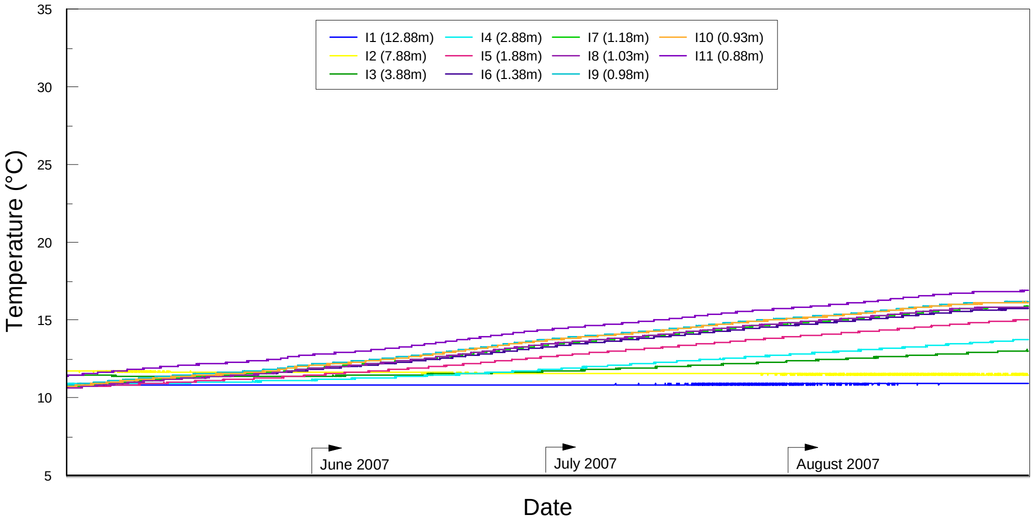
As would be anticipated the transfer of heat to store 2 during the building cooling simulation in 2007 was significant and it is therefore unsurprising that the temperatures of the ground recorded during the simulation exceeded those achieved whilst recovering solar heat from the road surface in 2006. For completeness this comparison is shown in Figure 12.3 for the thermistors in the borehole below the centre of store 2 for two dates, namely 27th July (as temperatures peaked then during solar heat recovery in 2006) and 31st August (on completion of the building cooling simulation in 2007). On 27th July, temperatures were not much different in 2006 and 2007 although temperatures between 2m and 8m depth were slightly higher in the latter case indicating more heat stored in the ground at these depths by the building cooling simulation. Figure 12.3(ii) shows that by 31st August the ground temperatures at all depths developed during the building cooling simulation exceeded that from solar heat recovery from the pavement. Clearly winter maintenance procedures would benefit from being coupled to a hotter store resulting from a building cooling regime in the summer; however in reality it would normally be preferred to operate building cooling and heating protocols together.



(a) Borehole G (centre of store 2)

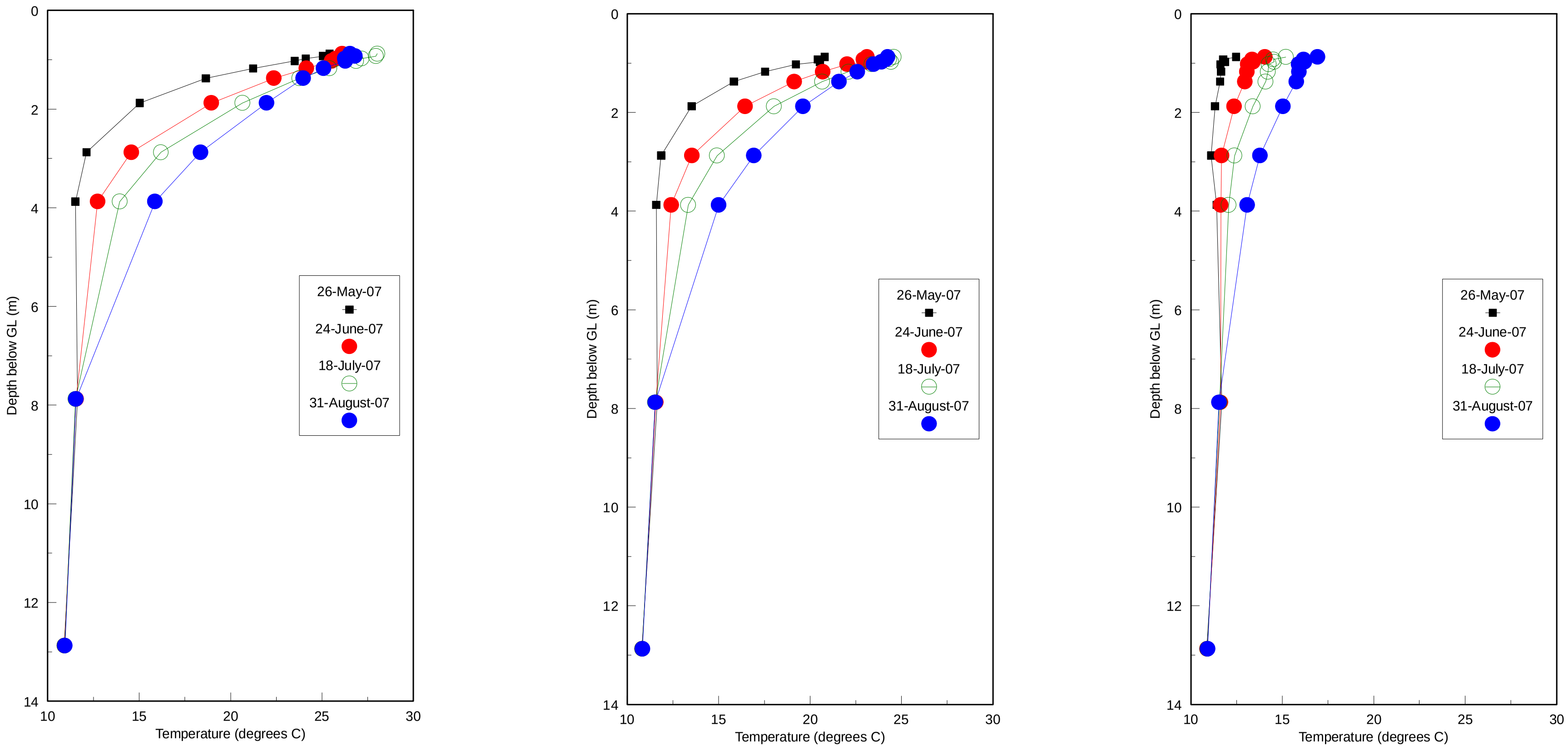


(b) Borehole H (edge of store 2)



(c) Borehole I (2m from edge of store 2)

Figure 12.1. Variation of ground temperatures with time below store 2 (building cooling)

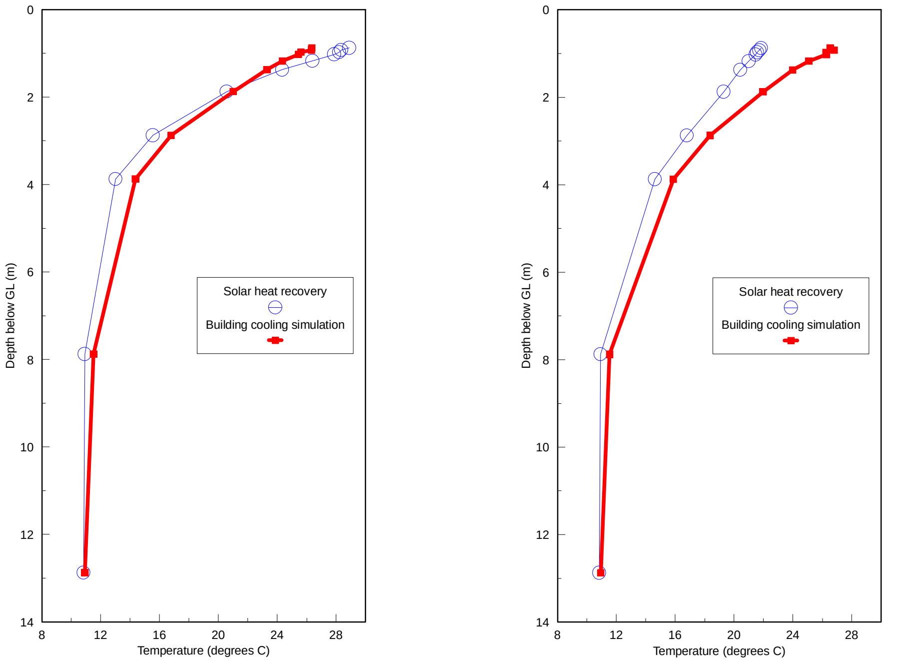


(i) Borehole G: Centre of Store 2 (Under-road)

(ii) Borehole H: Edge of Store 2 (Under-road)

(iii) Borehole I: Offset from Store 2 (Under-road)

Figure 12.2. Profiles of ground temperature with depth below store 2 during building cooling simulation



(i) Borehole G: Centre of Store 2 on 27th July 2006 & 2007

(ii) Borehole G: Centre of Store 2 on 31st August 2006 & 2007

Figure 12.3. Comparison of measured ground temperatures during solar heat recovery (2006) and building cooling simulation (2007)

12.2 Heat extracted from the dry air coolers and heat transferred to store 2

The heat extracted by the dry air coolers during the period from 1st May to 31st August is shown in Figure 12.4 and amounted to a total of 9.96MWh. Also shown is the rate of heat transfer to store 2 and a total of 10.01MWh was transferred over the period. As this process was assisted by appropriate operation of the heat pump where necessary, the quantity of heat transferred to the store slightly exceeded that extracted by the coolers.

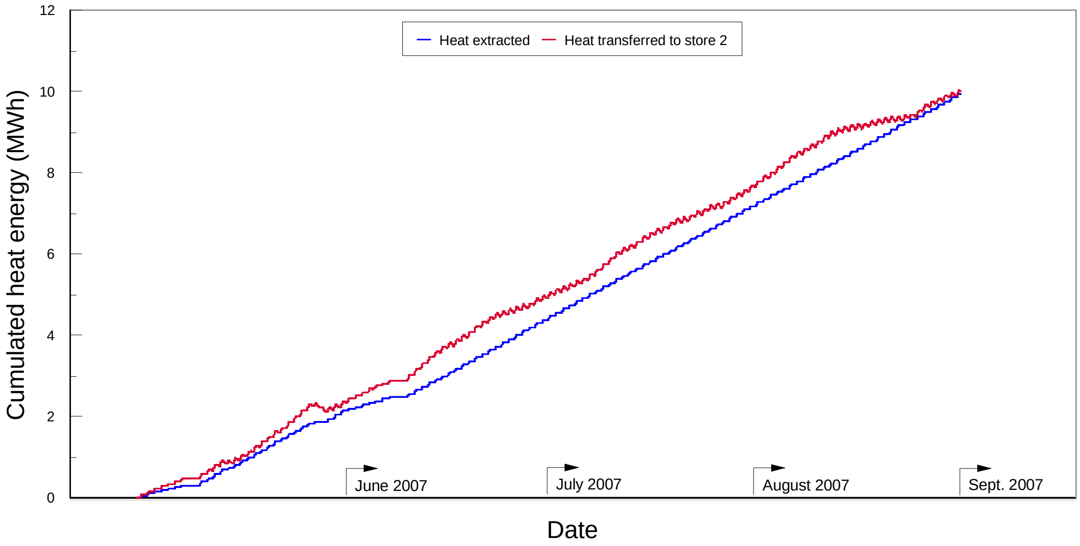


Figure 12.4. Comparison of measured heat extracted and heat transferred to store during building cooling simulation

12.3 Electrical energy used

An evaluation of the heat transferred to the store against the electrical power used in running the pumps was carried out on an arbitrary date (30th June 2007) when extracting heat under a load of 10kW from 8am for a 10 hour period. Measurements of flow rate and differential temperatures confirm that 88.1kWh was actually extracted from the simulated building for cooling purposes, whilst 137.7kWh was actually transferred to the ground heat store.

Current (RMS) measurements on the various pumps over the period from 8:00 to 18:00 on the 30th June confirm that the AC electrical power used was as follows:

- the heat pump used 76.833kWh,
- pump 5 (circulating from the heat store to the heat pump) used 3.725 kWh,
- pump 3 (circulating between the heat pump and the buffer vessel) used 8.216 kWh.

The efficiency of a ground source heat pump system is measured by the coefficient of performance (CoP). This is the ratio of units of heat output for each unit of electricity used to drive the compressor and pump for the ground loop. From the figures above the CoP of the overall system at Toddington can be calculated from 137.7/(76.833+3.725+8.216) = 1.55. However it must be noted that this calculation includes the losses due to the addition of pump 3 and the buffer vessel, which may not be required in every situation or could be considered to be part of the building cooling system. If allowance is made for these factors, as with the building heating simulation, it would be expected that the CoP of the heat pump would be better than this. Once again more appropriate sizing of the heat pump would have improved efficiency by reducing its cycling.

13 Conclusions

The use of interseasonal heat transfer systems incorporating solar energy collectors in the road and shallow insulated heat stores in the ground is currently innovative and at the forefront of technology. A major instrumented trial of the technique was undertaken on an access road near Toddington which involved constructing two solar heat collectors (pipe arrays each 5m wide by 30m long installed at 120mm depth below the road surface) and two insulated heat stores of similar dimensions but at 875mm depth. One store was beneath the road and the other beneath the verge to simulate new construction and retrofit installations respectively.

The solar heat recovered from the road surface was used to investigate the winter maintenance of the road surface and the heating of nearby buildings. The cooling of a building was separately simulated. The following main conclusions were reached.

Solar heat recovery in summer

1. Following commissioning in August 2005, about 1MWh of heat energy was transferred to each heat store (of 150m^2 area) during the limited solar heat recovery period from 23rd August to 14th November 2005. During this period, peak air and road surface temperatures of 30°C and 40°C respectively were recorded in the first few weeks, after that temperatures showed their expected seasonal reductions.
2. During a full season of heat recovery in 2006 measurements showed that 4MWh and 6.5MWh of heat energy were transferred to store 1 (off-road) and store 2 (under-road) respectively. This difference was not considered to be a consequence of the different store locations, but primarily a consequence of the thermal history in that store 2 was depleted by the previous winter maintenance schedule. During July when the air temperature peaked at 34°C, peaks of 50°C and 38°C were recorded at the road surface and at collector pipe level respectively.
3. Generally the major increases in ground temperature occurred at depths of up to 4m within the ground heat stores, although very small changes in temperature were measured down to about 8m depth.
4. Computational fluid dynamics using a stabilised model (related to winter maintenance demand) predicted a heat energy recovery of 4.9MWh per annum. The predicted value therefore showed good agreement with that measured and confirmed the validity of the model.

Winter maintenance of the road surface

5. Following the limited collection and storage of solar heat carried out during the late summer of 2005, the available heat in store 2 was used for a preliminary investigation of de-icing of the road surface during the following winter. For this purpose an operational protocol was employed which pumped fluid from the heat store to collector when the road surface temperature fell below 2°C for more than 15 minutes. Although the road temperatures over collector 2 did fall below zero on a few occasions, with only two exceptions the temperatures remained above -1.5°C. In actual practice sub-zero temperature does not necessarily mean that icing occurs as it will depend upon the relative humidity and the dew point.
6. A more extensive study operating from a fully charged heat store was carried out in the winter of 2006/07. When the road surface temperature fell below 2°C and the heating was activated, this section of road was generally maintained at a temperature about 3°C hotter than that of the unheated control area. Almost without exception the heated area of road remained above freezing until the period of extremely cold weather in early February 2007. On February 7th extreme surface temperatures of -6°C and -3°C were measured for a few hours on the unheated and heated sections respectively. On the following morning snow fell and briefly settled although the road surface was being maintained between 0°C and +0.5°C at the time. Following this incident, no further issues were encountered in keeping the road surface above

freezing. About 2.5MWh of heat energy was used to heat the test section (150m^2) of road in the generally mild winter of 2006/07, more generally it is considered that 3MWh is typically needed per winter.

7. It is believed that fine tuning of the system in one or a combination of the following ways could prevent the snow settling on future occasions:
    - having the heat pipe array at a shallower depth would improve the efficiency of both the heat collection and winter maintenance procedure[3],
    - smarter sensing of atmospheric conditions and refinements in the control protocols would prevent unnecessary triggering and hence heat wastage on occasions when sub-zero temperatures do not result in ice formation. For example, the under-road heating was activated on 16 more days than the 28 days on which salting took place on the nearby motorway.
    - by using techniques of temporarily boosting the heat output in extreme weather conditions, such as employing a heat pump.
8. Numerical modelling (CFD) of the summer solar heat recovery was extended to investigate winter maintenance performance. The simulation confirmed that the heat output to the road surface increases with the starting temperature of the heat store and decreases with depth of the pipe array beneath the road surface. A change in pipe invert depth from 140mm to 90mm increased heat output by 20% when starting from a cool store temperature of 5^{o}C. An increase of about 8% occurred when store temperatures were elevated to 19^{o}C. The calculated performance from the modelling slightly under-predicted the measured uplift in road surface temperature.
9. The whole life costs of a winter maintenance system (incorporating summer heat recovery) evaluated over a 30 year accounting period was found to be £164,293 for 100m length and two lanes. Taking account of the annual discount rate of 3.5% this means that a saving of £8,631 per annum needs to be made for break even over the 30 year period for this section of road. The costs of operating a renewable energy system, electrical under-road heating, and salt spreading were compared. At first sight, the operating costs of salt spreading are lower than those of an interseasonal heat transfer system, and both are an order of magnitude lower than those of a totally electrical system as might be expected. However allowance needs to be made for the fact that operating costs derived for salt spreading take no account of the time of supervisory staff and weather forecasting for which no figures are readily available. It was concluded that treatment of well-known cold spots on the highway network or treatment of slip roads and interchanges may provide cost effective locations for initial implementation of interseasonal heat transfer systems.

Building heating simulation

10. An investigation of the performance when heating a nearby building using interseasonal heat transfer was carried out from December 2006 to April 2007. Solar heat recovered during summer 2006 was used in response to the simulated demand for building heat. This simulation protocol extracted heat from the stores, and delivered it (via a heat pump) to a buffer vessel. The buffer vessel simulates the heat load of a building by losing heat to the atmosphere at a rate determined by a pre-programmed look-up table.
11. During this investigation 4.05MWh of heat was rejected in the building heating simulation and of this 3.66MWh was extracted from the heat store prior to boosting the fluid temperature using the heat pump. Some electricity was used to drive the pump circulating fluid from the

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[3] Apart from the effect this would have on the pavement maintenance schedule and the associated cost implications in replacing the collector pipe array if planing occurred to pipe depth, there are concerns about the presence of the pipe array at shallower depth increasing the risk of reflection cracking of the pavement surface.

heat store to the heat pump, and the heat pump itself, and this needs to be taken into account in assessing the coefficient of performance (CoP) of the system. The system CoP varied but was typically about 2, whereas the CoP for the heat pump alone would be expected to be at least twice this value. However a higher CoP would probably have been achieved with a smaller heat pump.

12. By the end of April 2007 the solar heat recovered during the summer had been depleted and continued operation, although feasible, was probably extracting naturally occurring geothermal heat from the ground rather than stored solar heat.

Building cooling simulation

13. The procedure used for the earlier building heating simulation was effectively reversed to simulate cooling of a building in the summer (May to August 2007 inclusive). The ability to cool a building is an important feature of any interseasonal heat transfer system in view of the increased temperatures likely in extended summer periods due to global warming. For the purpose of the simulation, a programmable amount of heat was extracted from outside of the pump house by the dry air coolers and passed to the buffer vessel. This heat in turn was transferred to one of the heat stores which heated up as a consequence. This process was assisted by operation of the heat pump where necessary.
14. During the 4 month period from May to August 2007, 9.96MWh was extracted by the dry air coolers to simulate building cooling. A total of 10.01MWh was transferred to the ground heat store during this process. As with the building heating simulation, electricity was used to drive the reversible heat pump, and the coefficient of performance (CoP) of the overall system utilising a buffer vessel and associated pump was calculated at 1.55. The buffer vessel and associated pump can be considered to be part of the building system and then the CoP of the heat pump would increase to above 3 as is normal. Once again more appropriate sizing of the heat pump would have improved efficiency by reducing its cycling.
15. Higher subsurface temperatures in the ground heat store, primarily in the uppermost 3m of the ground below the store pipe array, were measured at the end of August 2007 than after the solar heat recovery in summer 2006. This reflected the fact that nearly twice the quantity of heat was passed to the store during the building cooling simulation.
16. There are significant advantages in providing a self-sufficient building system incorporating both heating and cooling capability. In this way heat recovered during the cooling period can be re-used for building heating purposes in the winter. There may be merit in boosting the heat recovery by the recovery of solar energy recovery from asphaltic surfaces (road or carpark) particularly during cold summers when building cooling is not required so frequently.

Recommendations

17. The interseasonal heat transfer system acted to successfully recover solar heat from the asphalt pavement surface in the summer and to store it in shallow insulated ground heat stores for subsequent re-use. The carbon footprint of such renewable energy technologies is less than those of vehicle-operated salt spreading systems used for road winter maintenance and traditionally powered building heating and cooling systems. There is therefore merit in continued research and development on the topic, particularly as renewable energy systems are likely to become more important as other energy sources become depleted.
18. Re-use of the stored heat for winter maintenance successfully elevated the temperature of the road surface by about 3^{o}C, however some uncertainty remains about the capability of this particular system to cope with extreme cold weather incidents. Fine tuning of the system may improve the capability, but the main improvement in performance is likely if the heat pipes

below the road surface were at shallower depths of cover than 120mm. There are then perceived concerns that the presence of pipes could give rise to “reflection cracking” of the surface, these could be allayed by trafficking trials in the pavement test facility. Alternatively, methods of temporarily boosting the heat in cold spells could be investigated although these slightly reduce the energy efficiency.

19. The interseasonal heat transfer system investigated in this trial used a shallow insulated ground heat store. In terms of wider implementation of this particular system for winter maintenance of a highway, the significant quantity of insulation required is expensive and additional land-take is required to insulate to either side of the road to prevent leakage out sideways from the heat store. There may be merit in looking at other forms of heat storage utilising borehole heat exchangers where land-take is not an issue as the boreholes can be below the road structure and no insulation is required. Where land availability is good, it may still be a convenient option to have the borehole heat exchangers alongside the road.
20. In terms of using the summer solar heat recovered from the road surface for winter heating of nearby buildings (by incorporating a heat pump into the system), the operating principles were clearly demonstrated although further validation of the efficiency of the process is needed. The viability of the technique is clearly better when the system incorporates building cooling too. In this case both solar heat from the road and the heat extracted during the building cooling cycle combine to build-up the temperature of the ground store in the summer providing more available energy for heating the building when it is needed. It is recommended that further investigation of these aspects could await the outcome of a concurrent project to heat a school being undertaken by Hertfordshire CC and icax^{TM} Limited.

14 Acknowledgements

The work described in this report forms part of the research programme of Infrastructure and Environment Division of TRL Limited and was funded by Safety, Standards and Research (Asset Performance Division) of the Highways Agency (Project Officers, Mr L Hawker and Mr C Christie). In addition to the authors the TRL team comprised Mr J Bradford, Mr A Dunford, Mr K Green, Mr J Harper, Mr R J Owen and Mr A Scarman. Dr A Parry and Dr R J Woodward acted to ensure the technical quality of the project.

TRL was responsible for the overall management of the project and organisation of the supply chain of specialists required for the diverse aspects of the study. Development of the civil engineering aspects of the design and the procurement and installation of instrumentation was solely undertaken by TRL.

Design of the interseasonal heat recovery system, pump house construction, control of protocols, and numerical modelling was undertaken by icax^{TM} Limited and in addition to the authors, their project team included Mr A Ford. It must be noted that certain aspects of this design are protected by current patents and for this reason should not be employed or reproduced for commercial purposes without written approval from icax^{TM} Limited.

The Principal Contractor for the civil works was Carillion-URS and the help of Mr J Harris and Mr R Pegg and, in particular, Mr G Hurst and Mr H Jones who managed the site is gratefully acknowledged. The assistance of ForwardSpread Ltd (Mr I Juniper and Mr A McColl) who carried out the civil works, McCann Ltd (Mr R Cupples) who organised the electrical work, and Aggregate Industries (Mr P Evans) who carried out the asphalting is also acknowledged.

The heat collector and store arrays were installed by Infowork Engineering and the assistance of Mr G Rhodes was especially appreciated. The advice of pipe manufacturers Wirsbo and Rehau is also acknowledged.

The advice of Mr A Walker of Vencel Resil on the polystyrene insulation, and the loan of a hot wire cutter, is gratefully acknowledged.

Pump house construction was subcontracted to Constant Air Systems Ltd (Mr D Green, Mr M Jones) and the pump control system was constructed by Silchester Control Systems (Mr C Vibert, Mr D Jones). Special thanks are due to the latter organisation for their continued assistance throughout the project.

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Design Manual for Roads and Bridges

HD 24/96 Traffic assessment (DMRB 7.2.1)

HD 25/95 Foundations (DMRB 7.2.2)

HD 26/01 Pavement design (DMRB 7.2.3)

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16 Appendix A. Schedule of construction operations

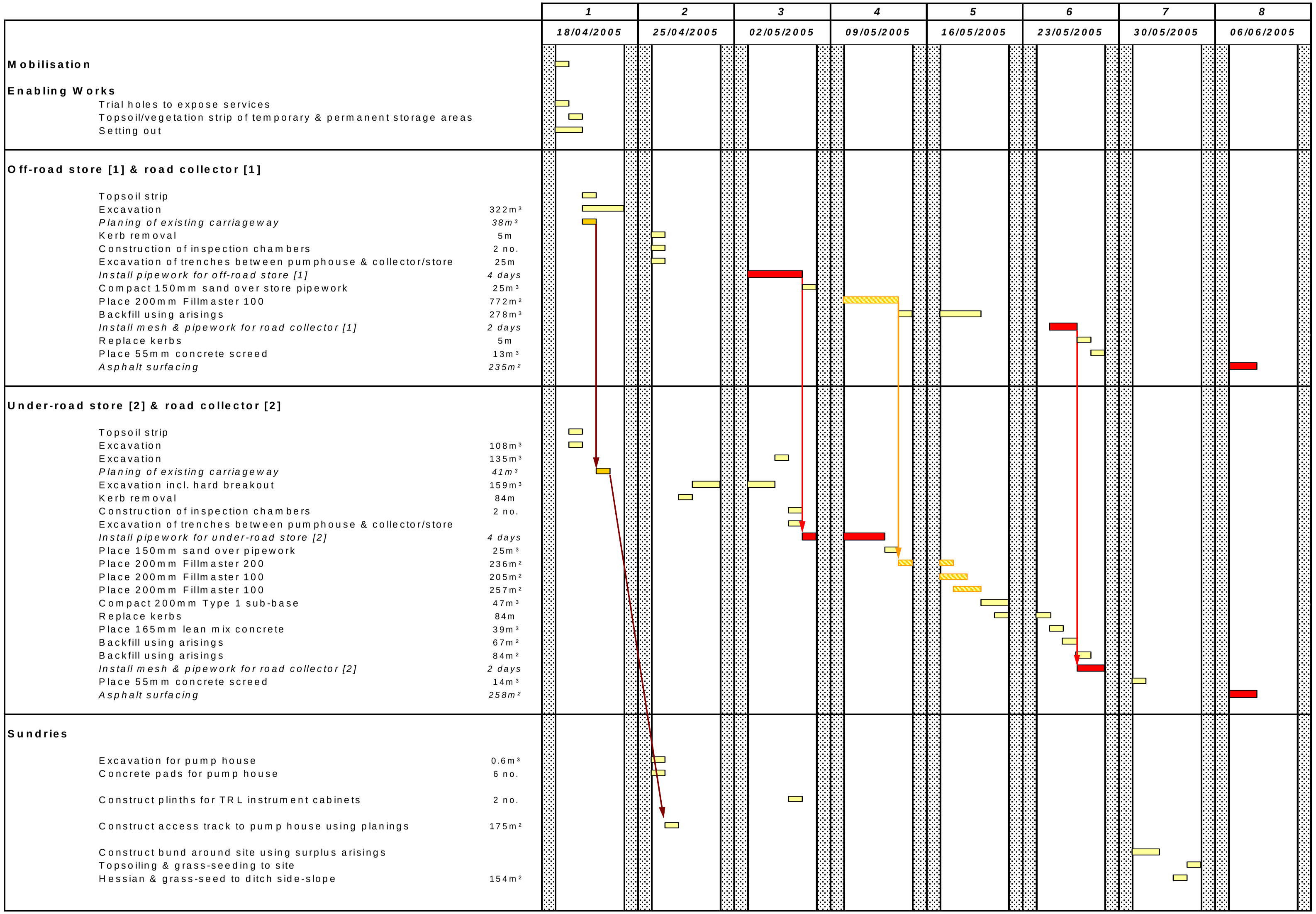


Table 16.1. Schedule of construction activities

17 Appendix B. Further advice on construction and operational issues

During the course of the demonstration trial, much experience was gained in construction and operational issues and, to assist in the construction of future systems of this type, this is now considered.

17.1 Installation of collector and storage pipe arrays

Much advice on these issues was given in the contractor feedback on the construction process given in Section 4.8. Some of the main issues which arose are as follows:

> (i) the store pipe arrays should also be laid on well-prepared flat ground. In many cases a clay foundation is acceptable provided that it contains no significant stones, flints, etc. Where the available surface is deemed unsuitable, a compacted layer of sand is advisable before placing the pipes.
>
> (ii) at this trial the collector pipe arrays were wired to a steel mesh before placement of a concrete screed to provide all-round support to the pipes. The pipes were pressurised with water during the concrete pour and subsequently cooling water was circulated to avoid damage to the collector pipes during the asphalting. The direct placement of hot asphalt onto the plastic pipes is not advised without carrying tests to assure that no damage occurs.
>
> (iii) pipe loops in the store and collector should be continuous with no joints. Pipe connections to manifolds should be arranged so that future access is available so that an individual loop beneath the road can be isolated in the event of an unexpected failure. Valves connecting the pipes to manifolds are however better avoided, particularly if in manholes, to minimise potential problems with leakage and frost damage.

17.2 Pumping system

The design of the pump house at Toddington is more complex than would normally be required because of its experimental nature and the need to switch between two store and two collector arrays to investigate protocols for the winter maintenance of roads and also the heating and cooling of buildings. Nevertheless the following advice is generally applicable.

> (i) In early life, considerable air will continue to come out of the pipe arrays and associated header pipes. For this reason design of the pumping system needs to consider practical issues such as:
>
>> (a) positioning the circulating pump at low elevations following normal good practice to ensure that it always pumps water,
>>
>> (b) providing suitable means for the trapping and release of air. If a mains water supply is available this may include a water pressurisation system,
>>
>> (c) including an expansion vessel to accommodate thermal expansion.
>
> (ii) The simpler the system, the better it is likely to perform. Where possible the use of valves should be avoided.
>
> (iii) Consideration needs to be given to the frost protection of all external systems.
>
> (iv) If using a heat pump to boost fluid temperatures for building heating purposes, particular attention needs to be given to the electrical characteristics of the pump and in particular to start-up electrical load.

18 Appendix C. Thermal imaging during winter maintenance on 25 February 2006

A preliminary investigation of the road surface temperature using thermal imaging was carried out during the evening of 25 February 2006 when air temperatures were predicted to be sub-zero.

It must be noted that the heat stores were not at their full operational temperature after the limited solar heat collection carried out at the end of summer 2005 and for this reason the winter maintenance operation in heating the road surface was not at its full efficiency.

18.1 Experimental procedure

All images were taken using a Jade infrared camera capable of detecting wavelengths in the region 2.5 to 5.1µm.

The thermal imaging camera was fixed to a telescopic mast (4m above road level) which was positioned just inside of the road kerb and midway between the near edges of collectors 1 and 2 (Figure 3.1). This location meant that the camera could be swivelled by 180^o to aim at either collector 1 or collector 2. The angle of the camera on the mast was adjusted to about 30^o from the horizontal to enable an area of unheated road and the near area of collector to be viewed in each case. As collector 2 had been extensively used for winter maintenance trials its heat was depleted, and collector 1 provided the main data.

Prior to the investigation, the pump house control system was switched to manual mode and all pumps were switched off. This enabled a datum set of images to be taken at 16:30 on both collectors 1 and 2. Following this, the requisite motorised valves and pumps were activated to separately pass fluid from collector 1 to store 1 and from collector 2 to store 2.

Photographs of collector 1 were then taken at 30 minute intervals until 22:30 at which time the air temperature warmed slightly and the investigation was therefore terminated with final photographs at 22:45. Because the temperature of the fluid being passed through collector 2 was lower, photographs were only taken at 16:30, 18:00 and 22:45.

On completion of the photographs at 22:45, the mast was lowered to about 1.5m height and a long distance photograph of collector 1 taken to show the complete collector and the unheated road to either end.

18.2 Observations

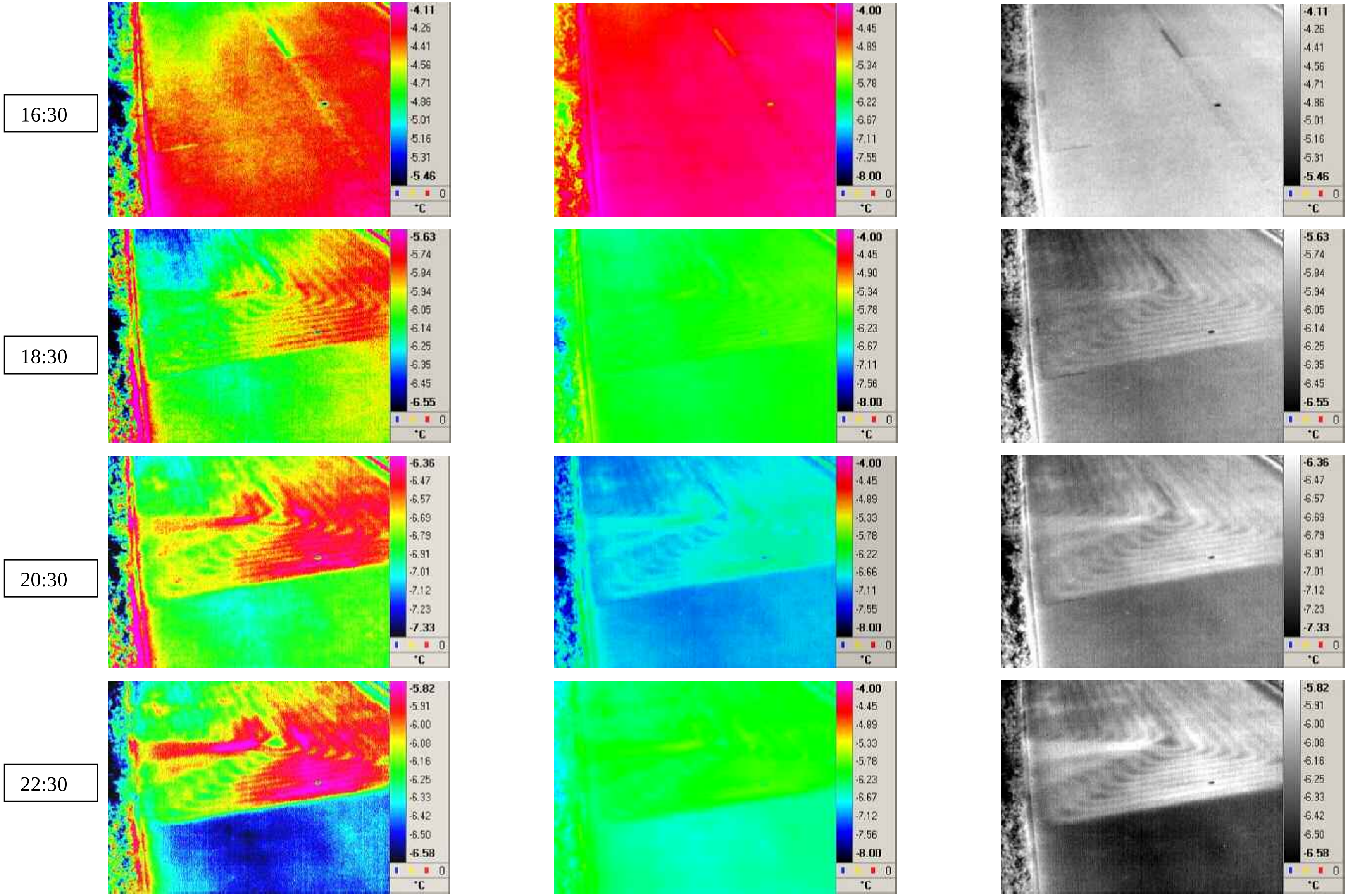
Figure 18.1 shows a summary of the same four photographs (ie. at 16:30, 18:30, 20:30 and 22:30) of collector 1 produced using different picture settings, namely:

- colour – automatic gain control,
- colour – fixed scale,
- grey – automatic scale.

In all cases, with the exception of the control at 16:30 before heating the road, the thermal images of the heated pipes can be seen at the road surface.

Although the apparent temperature scales are included in Figure 18.1 these must not be considered as absolute temperatures for the following reasons:

- the apparent temperature will depend on the angle of viewing. The calibration of the camera assumes a perpendicular view, and in the colour images this accounts for the apparent decrease in temperature as the angle of viewing moves further from the perpendicular, ie. more distant from the camera.



Colour: automatic gain control Colour: fixed scale Grey: automatic gain control

Figure 18.1. The same thermal images of collector 1 at 16:30, 18:30, 20:30 and 22:30 using different picture settings

- infrared does not transmit through water so the accuracy of the temperature readings will be affected as the road surface was damp (although not wet). The thermal properties (in terms of reflectivity and emissivity) will therefore change with time as the road surface dries out or becomes wet.

With the above caveats, it is considered that differences in temperature over a small localised area may nevertheless be real.

In Figure 18.1 the colour (fixed scale) image at 22:30 shows a slight warming from 20:30, this relates to a change in air temperature possibly as a cloud briefly passed over. The same effect is not so evident in the images taken using automatic gain control.

Figure 18.2 shows the images obtained at 22:45 when the mast was lowered to about 1.5m height above road level and a long distance photograph taken of collector 1. Once again both colour and grey picture settings are included for the same image. As well as showing the outline of the heated pipes below the surface, the colder areas of road to either end of the collector can be seen.

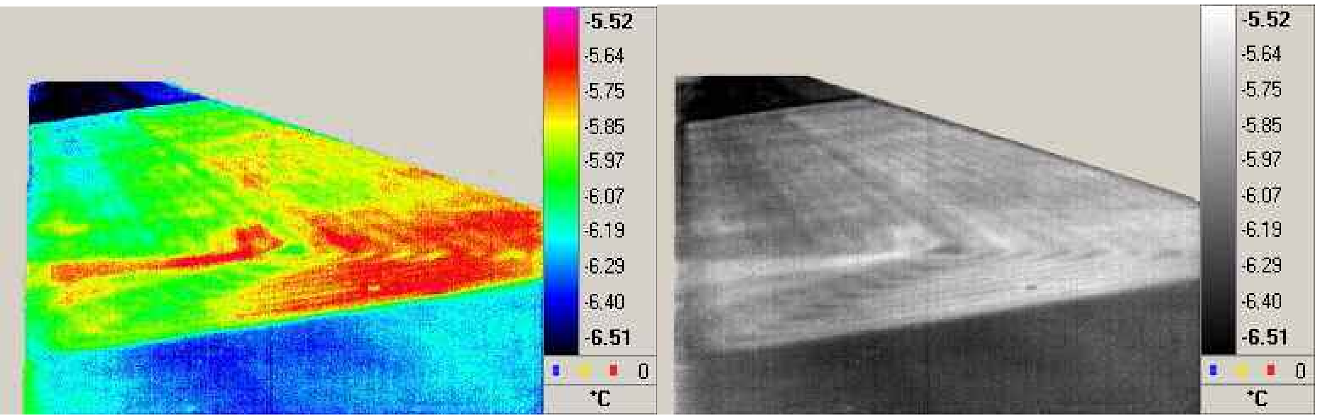
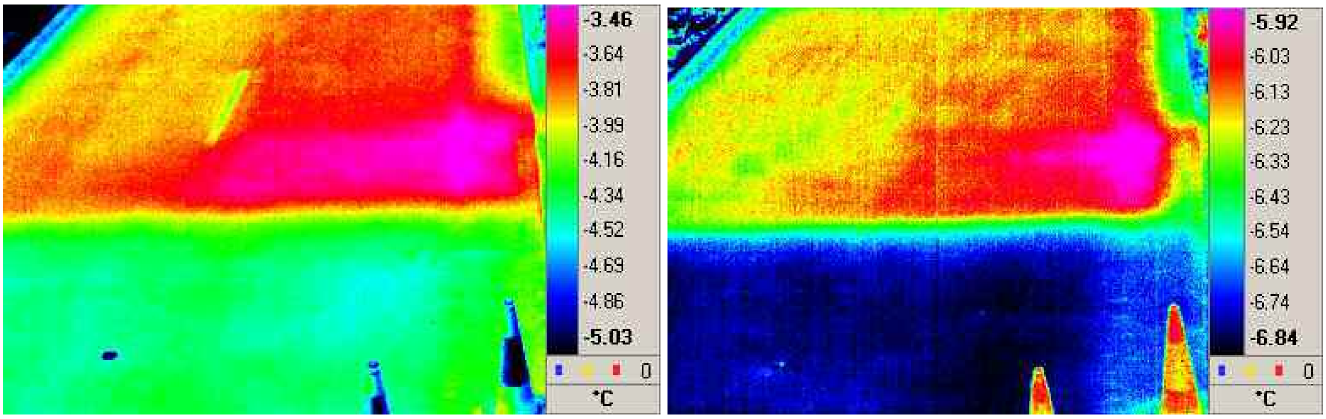


Figure 18.2. Images showing the complete length of collector 1

The colour images obtained when viewing collector 2 are less useful as fluid temperatures from the depleted heat store 2 were much lower (~5°C). Nevertheless one point of interest is apparent from the image in Figure 18.3 taken at 16:30 prior to the commencement of the winter maintenance protocol, namely the apparent



16:30 22:45

Figure 18.3. Images of collector 2 at the beginning and end of the test

temperature in the collector area is already about 0.5°C above that of the adjacent untreated road. This is most likely to be because of minor heating effect from the insulated heat store below the collector array, but could be due to the residual effect from the winter maintenance protocol operated in this area during the previous nights. With this collector the outline of the array pipes is only faintly evident at the end of the test at 22:45, whereas it was a lot clearer with collector 1.

18.3 Comparison with measured data

The measured temperature data whilst thermal imaging was taking place are shown in Figure 18.4.

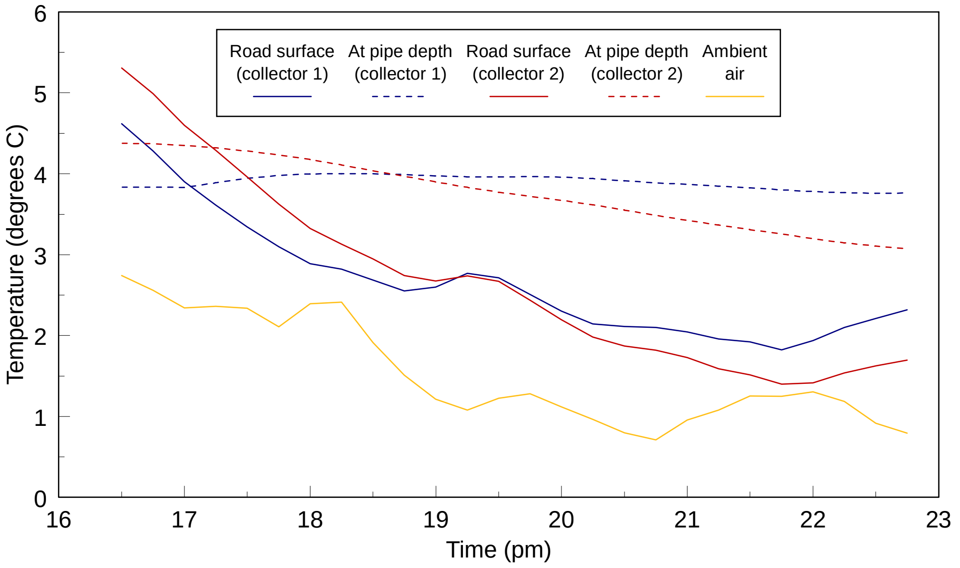


Figure 18.4. Temperatures measured by the thermistors

During the evening of the 25th January the air temperature dropped to below 1°C. At this time the temperatures at the top of heat stores 1 and 2 were about 10°C and 5°C and fluid was passed around collectors 1 and 2 at temperatures of about 7°C and 4°C respectively. As shown in Figure 14.4, this process maintained the temperature of collector 1 pipe array at about 4°C whilst that of collector 2 pipe array fell to nearly 3°C in response to the fall in air and road temperature. Over the period of the thermal imaging, heat was transferred to collectors 1 and 2 at average rates of 6.2kW and 1.7kW respectively.

Measurements at the respective road surfaces indicated that the heating protocol had some effect in maintaining road temperatures above that of the ambient air temperature, although clearly the effectiveness of the winter maintenance protocol needs to be assessed over a severe winter when operating from a fully charged heat store. The results in Figure 14.4 demonstrate that collector 1 operated more effectively than collector 2 as would be expected because of the heat available in the respective stores. It is also worth noting that the changes in road temperature lagged behind those of the air temperature by approximately an hour.

The measurements confirmed that the apparent temperatures obtained during the thermal imaging were not real. The reasons for this have been discussed in Section 18.2.

18.4 Summary

The thermal imaging successfully detected the presence of the pipe array comprising collector 1 at shallow depth below the surface. The temperature differences will be more pronounced when circulating fluid from a heat store which had been fully warmed by a complete summer of heat recovery.

The findings demonstrate that thermal imaging is an effective “trouble-shooting” tool when operating under-road heating systems and in particular can assist with:

(iv) detecting fluid leaks if they should arise,

(v) detecting cold spots which might present a safety hazard to road users,

(vi) detecting heating pipe locations to avoid subsequent damage during road maintenance operations or installation/repair of buried services.

19 Appendix D. Numerical modelling

by D Ritter and M G Hewitt (icax^{TM} Limited)

19.1 Principles of analysis

Analyses were carried out using computational fluid dynamics (CFD) to predict the solar heat energy recovered during the course of the trial and the use of this energy for the winter maintenance of a road surface. The analyses were performed using a general-purpose software package (PHOENICS) which predicts quantitatively:

- how fluids (air, water, oil, etc) flow in and around engines, process equipment, buildings, natural-environment features, and so on;
- the associated changes of chemical and physical composition;
- the associated stresses in the immersed solids.

The package simulates the prescribed physical phenomena by:-

- expressing the relevant laws of physics and chemistry, and the "models" which supplement them, in the form of equations linking the values of pressure, temperature, concentration, etc which prevail at clusters of points distributed through space and time;
- locating these point-clusters (which constitute the computational grid) sufficiently close to each other to represent adequately the continuity of actual objects and fluids;
- solving the equations by systematic, iterative, error-reduction methods.

For the purpose of this study, the analysis model comprises both three dimensional (3D) and one dimensional (1D) components. The analysis of heat flow through the ground is achieved using a 3D grid of cells, whereby, in simple terms, the heat flow between each cell and its neighbour is calculated at each iteration and totalled to establish overall heat flow.

The heat transfer from the collector to the store is calculated using a 1D model, assuming a flow of water through a circuit with heat inputs and outputs from the surrounding ground. Therefore the water circuit 1D model links with the 3D model so that the heat transferred into the pipe system equals the heat transferred from the ground zone immediately surrounding the pipes.

The algorithms that are used to calculate the heat input into the 3D or 1D components of the model may be summarised as follows:

- Heat transfer between the collector surface and the ambient environment:
    - solar radiation;
    - convective heat transfer (wind-forced);
    - re-radiative heat loss to night sky.
- Heat transfer from the ground into the pipes:
    - internal heat transfer to the fluid flowing through the pipes;
    - heat transfer through the tube material;
    - heat transfer to surrounding ground material.
- Heat transfer through the ground:
    - conductive heat transfer.

The model has been set up to calculate the heat transfer between a single collector and a single store. The selected arrangement of collector and store is equivalent to the off-road store arrangement at the Toddington Trial.

19.2 Mesh development

The three-dimensional mesh for both the collector and store were designed to ensure a high level of accuracy for the heat flow calculation, particularly for heat flow in the vertical direction. The mesh was generally finer nearer to the collector and store areas where changes in temperature were expected to be more pronounced. Both the collector and store mesh were 30m long and 5m wide.

19.2.1 Collector mesh

The depth spacings between horizontal grid lines were as follows:

- 0.02m apart for the first 0.2m depth,
- 0.1m apart for the following 0.8m depth,
- 0.2m apart from 1m to 2m depth,
- 0.5m apart thereafter.

Figure 19.1 shows a screen snap of a vertical section through the 3D collector mesh.

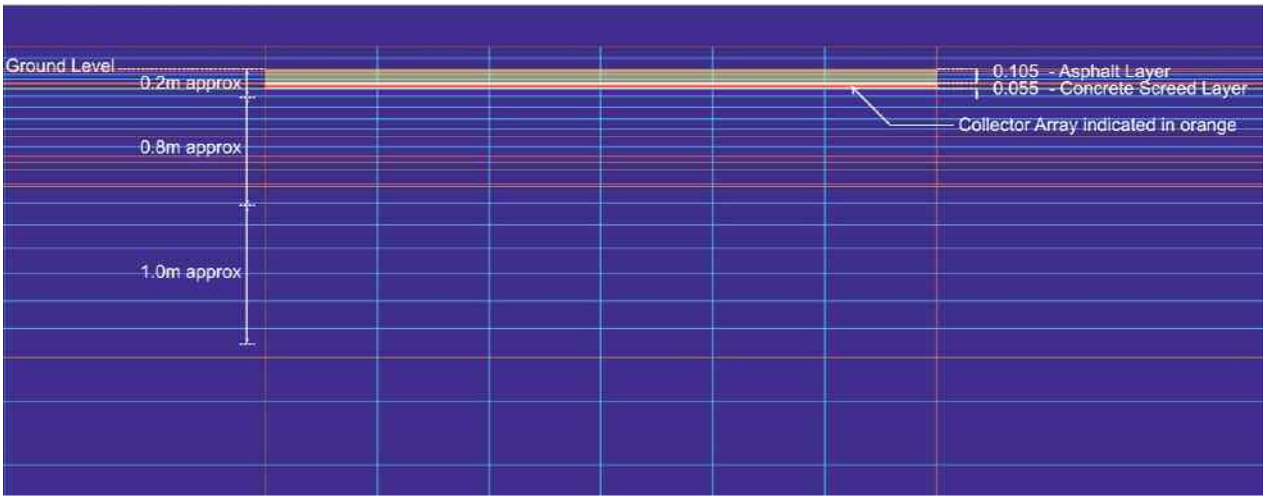


Figure 19.1. Vertical section through the collector mesh

Since most of the heat transfer through the ground will take place in the vertical direction, the horizontal spacing of grid lines has been simplified to 6 cells set across the 5m wide collector array as shown in Figure 19.2. Outside of the road surface, the horizontal spacing is 3m, as these areas are not so critical for the analysis.

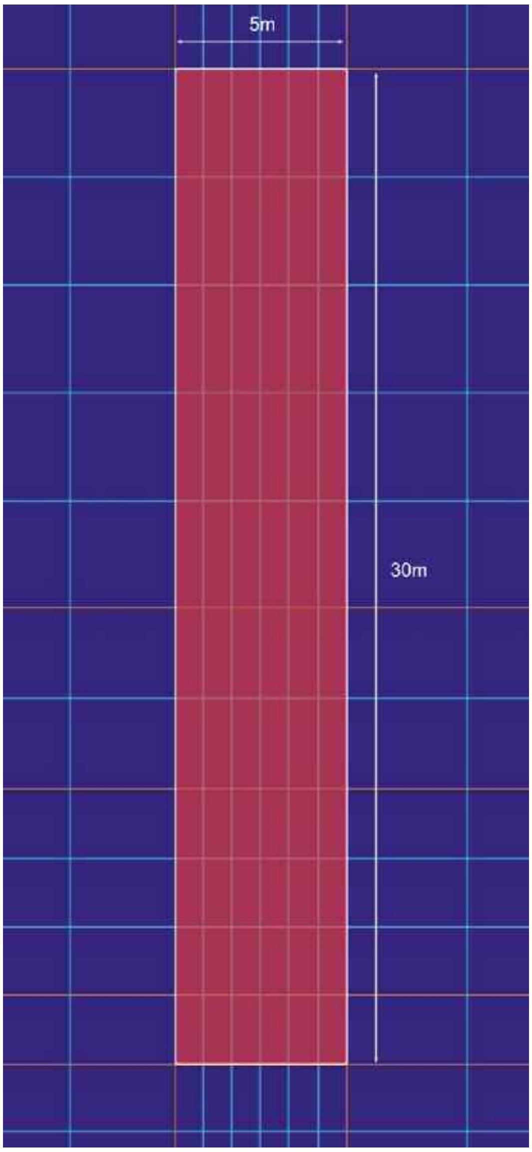


Figure 19.2. Plan view of the collector mesh

19.2.2 Store mesh

The store mesh has a similar design to that of the collector. In this case however energy transfer to and from the pipe array is not so critical so the grid lines immediately around the array do not need to be so closely spaced. For this reason a grid line separation of about 0.1m has been used as is shown in the section in Figure 19.3. The layout of the store array, the sand, insulation and overlying backfill are also identified.

The insulation cover above the store array is a strip 18m wide, extending 6.5m to either side of the store array as is shown in Figure 19.4. It should be noted that the proportions and locations of the mesh outside of the insulated area are only approximate because of the nature of the screen dump from the CFD package.

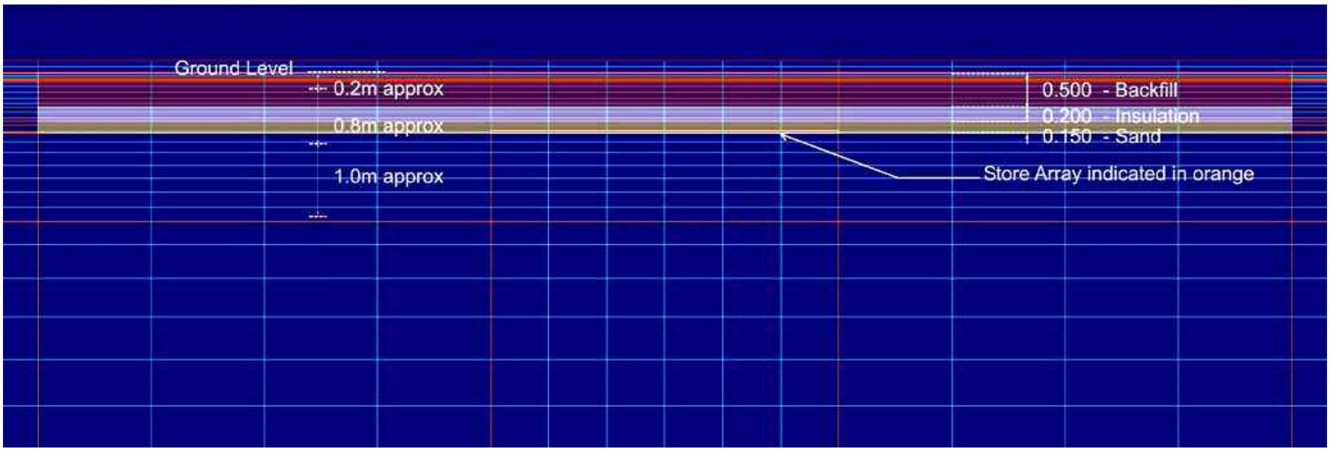


Figure 19.3. Vertical section through the store mesh

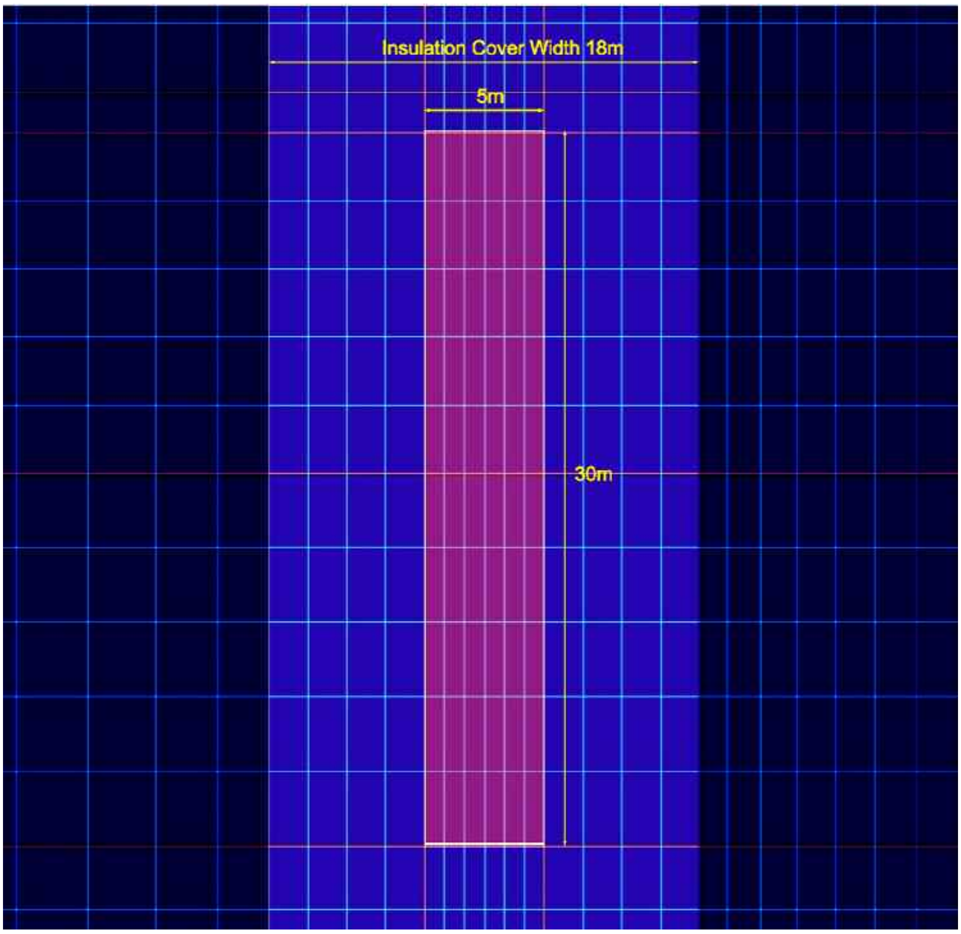


Figure 19.4. Plan view of the store mesh

19.3 Thermal properties

Table 19.1 gives the thermal properties for the various layers comprising the pavement structure in which the collector pipework was installed. As described in Section 3.2 the pipework was installed with a depth of cover of about 120mm in the concrete screed.

Table 19.1. Thermal properties used for modelling the collector

Layer	Type	Thickness (m)	Density (kg/m^3)	Specific heat capacity (J/kg)	Thermal conductivity (W/mK)
1	Asphalt[1]	0.105	2400	850	0.85
2	Concrete screed[2]	0.055	2100	840	1.40
3	Silty clay[2,3]	9.600	1960	840	1.21

1. Values calculated from constituent values of asphalt.

2. Default parameters from the Phoenics 3.5.1 package.

3. It must be noted that the materials comprising the road base have not been separately designated within layer 3, as the performance of the underlying clay is deemed to dominate.

The thermal properties used for the three-dimensional modelling of ground heat store performance are shown in Table 19.2. The layer construction relates to the off-road heat store, although the performance of the under-road store is expected to be very similar. The pipework forming the store array was installed directly on the silty clay within the sand layer.

Table 19.2. Thermal properties used for modelling the ground heat store

Layer	Type	Thickness (m)	Density (kg/m^3)	Specific heat capacity (J/kg)	Thermal conductivity (W/mK)
1	Backfill[1]	0.500	1960	840	1.21
2	Polystyrene insulation[2]	0.200	30	1130	0.034
3	Sand[1,3]	0.150	2240	840	0.33
4	Silty clay[1]	9.000	1960	840	1.2 or 2

1. Default conductivity of 1.2 from the Phoenics package, although a value of 2 was also investigated.

2. Parameters supplied by Vencel Resil Ltd.

3. Thermal conductivity taken from reference to ASHRAE Fundamentals, 2005.

The pipes, which were 25mm in external diameter with a 2.3mm wall thickness, had a thermal conductivity of 0.4W/mK (Wirsbo, 2002). The fluid within the pipes comprised 90% water and 10% ethylene glycol by volume, values for fluid specific heat capacity, fluid density and kinematic viscosity of 4kJ/kg, 1009.7kg/m^3 and 9.6×10^{-7}m^2/s respectively were considered appropriate for the modelling based on these constituents. Total flow rate was 1.4l/s between the collector and store pipe arrays, i.e. 0.14l/s through each of the ten flow and return pipes.

19.4 Comparison of predicted and measured solar collection data during Aug/September 2005

The objective of the first simulation run was to calibrate the CFD numerical model against the measured results during the initial period of solar heat collection in August and September 2005. Although the heat collection period actually continued until 14th November, only a nominal amount of heat was collected after the end of September. The analysis therefore focussed on the period between 24th August and 30th September.

19.4.1 Weather data

Real weather data gathered from the Toddington site over this period was used for the simulation. For simplification of the calculation process, the climate data were averaged for each fortnightly period.

The data were therefore separated into 3 sets of hourly data comprising mean air temperature, mean wind speed, solar radiation and this is summarised in Table 19.3.

Table 19.3. Summary of the meteorological data used in the simulation

Fortnight 24th August- 6th September				**Fortnight 7th September-20th September**				**Fortnight 21st September - 4th October**			
Time	mean air temp (^{o}C)	mean radiation (w/m2)	mean wind speed (m/s)	Time	mean air temp (^{o}C)	mean radiation (w/m2)	mean wind speed (m/s)	Time	mean air temp (^{o}C)	mean radiation (w/m2)	mean wind speed (m/s)
0:00:00	14.7	-0.2	0.0	0:00:00	12.3	0.0	0.1	0:00:00	11.6	0.0	0.3
1:00:00	13.8	-0.1	0.0	1:00:00	12.4	0.0	0.2	1:00:00	11.0	0.0	0.1
2:00:00	13.4	0.0	0.0	2:00:00	12.0	0.0	0.2	2:00:00	10.4	0.0	0.1
3:00:00	13.1	0.0	0.0	3:00:00	11.6	0.0	0.2	3:00:00	9.9	0.0	0.1
4:00:00	12.7	0.0	0.0	4:00:00	11.6	0.0	0.2	4:00:00	9.5	0.0	0.1
5:00:00	12.6	0.0	0.0	5:00:00	11.4	0.0	0.2	5:00:00	9.3	0.0	0.2
6:00:00	12.5	0.1	0.0	6:00:00	11.3	0.0	0.1	6:00:00	9.1	0.0	0.2
7:00:00	12.7	16.8	0.2	7:00:00	11.5	3.8	0.2	7:00:00	8.9	0.7	0.2
8:00:00	13.7	107.1	0.5	8:00:00	12.0	59.6	0.4	8:00:00	9.1	32.0	0.2
9:00:00	15.2	229.7	0.8	9:00:00	13.4	133.9	0.4	9:00:00	10.4	129.4	0.1
10:00:00	17.0	377.4	0.8	10:00:00	14.6	217.5	0.6	10:00:00	12.2	240.5	0.1
11:00:00	18.7	523.6	0.8	11:00:00	16.1	321.3	0.7	11:00:00	13.6	324.9	0.3
12:00:00	20.0	592.7	1.0	12:00:00	17.4	405.2	0.6	12:00:00	14.9	413.0	0.3
13:00:00	21.1	634.6	0.8	13:00:00	18.3	404.4	0.7	13:00:00	15.8	448.2	0.4
14:00:00	21.6	617.6	0.9	14:00:00	18.7	398.0	0.7	14:00:00	16.5	447.1	0.4
15:00:00	21.8	521.9	0.8	15:00:00	19.2	362.2	0.8	15:00:00	16.4	340.4	0.4
16:00:00	22.0	440.5	0.8	16:00:00	19.4	326.0	0.9	16:00:00	16.4	301.5	0.5
17:00:00	22.1	363.7	0.7	17:00:00	19.4	233.8	0.8	17:00:00	16.4	214.0	0.4
18:00:00	21.7	237.3	0.6	18:00:00	18.8	145.9	0.3	18:00:00	16.0	123.5	0.1
19:00:00	20.6	114.1	0.1	19:00:00	17.8	58.8	0.1	19:00:00	15.0	30.4	0.1
20:00:00	19.2	26.7	0.0	20:00:00	16.3	5.5	0.1	20:00:00	13.3	0.4	0.2
21:00:00	17.4	0.7	0.0	21:00:00	14.8	-0.1	0.1	21:00:00	12.5	0.0	0.2
22:00:00	16.1	-0.2	0.0	22:00:00	13.9	0.0	0.1	22:00:00	12.0	0.0	0.2
23:00:00	15.3	-0.2	0.0	23:00:00	12.9	0.0	0.1	23:00:00	11.7	0.0	0.3

19.4.2 Results

Reference data for the conductivity of silty clay indicates that typical values vary between 1 and 3W/mK. Since a soil conductivity test was not carried out at this site to determine the exact conductivity, the sensitivity of the analysis was investigated using two separate CFD simulations adopting a different value for soil conductivity in each case.

Simulation 1: Using silty clay conductivity of 1.2W/mK

The predicted distribution of temperature with depth in the ground heat store is shown in Figure 19.5 for five dates in September. The general shape of the profiles resembles that measured and shown in Figure 7.6. Little change in either measured or predicted temperatures was observed below a depth of 8m as would be expected because of the limited duration of the heat collection period.

Figure 19.6 shows the simulated cumulative energy transfer from the collector to the store from the 24th August to 30th September when a value of 1.2 W/mK was used for the conductivity of the clay. A total of 0.74MWh of heat is transferred to the store over this period.

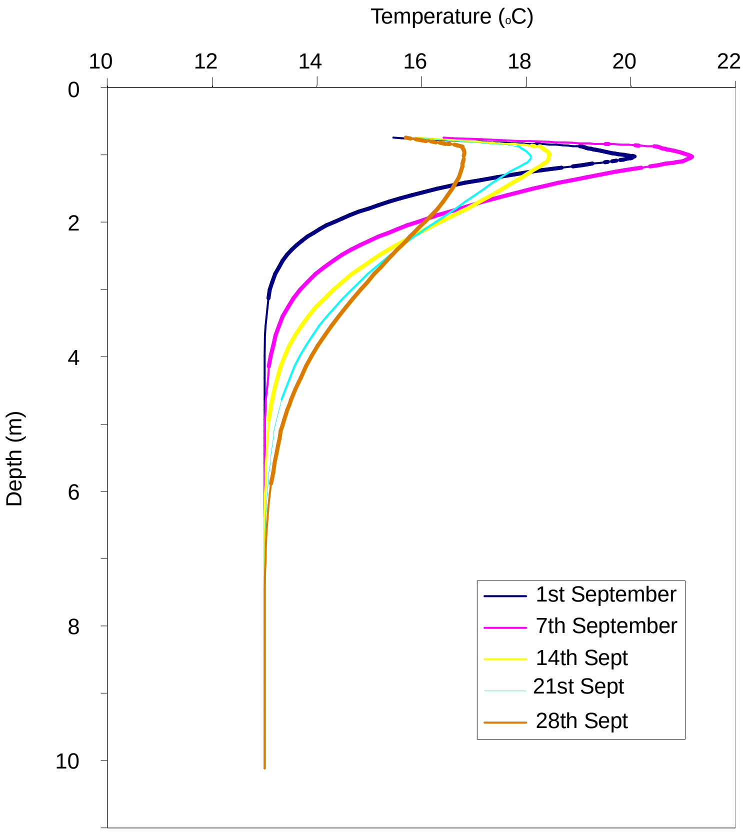


Figure 19.5. Variation of temperature with depth in the ground store at selected dates

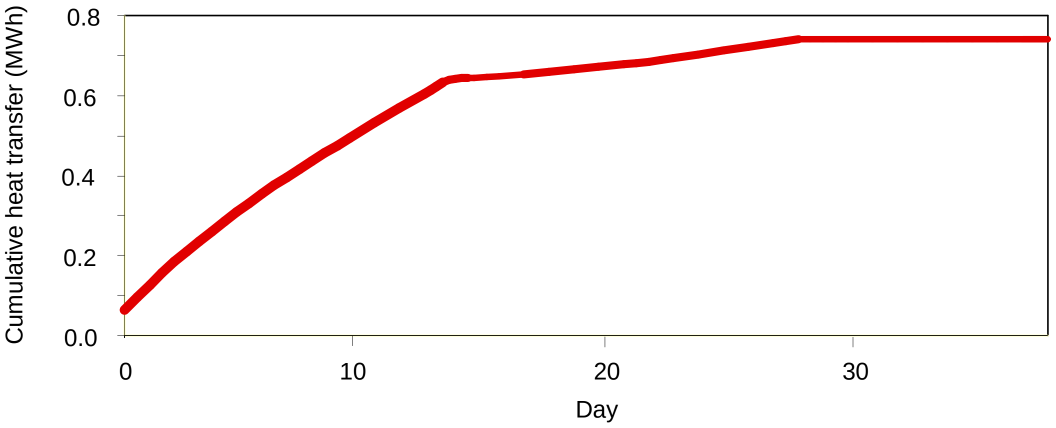


Figure 19.6. Predicted heat recovery during August/September 2005 (clay conductivity of 1.2W/mK)

<u>Simulation 2: Using silty clay conductivity of 2W/mK</u>

Very similar distributions of temperature with depth are predicted to those shown in Figure 19.5. An illustration of the small differences is shown in Figure 19.7 which compares the temperature profiles for the final step in the sequence (ie. 28th September) when different soil conductivities are used.

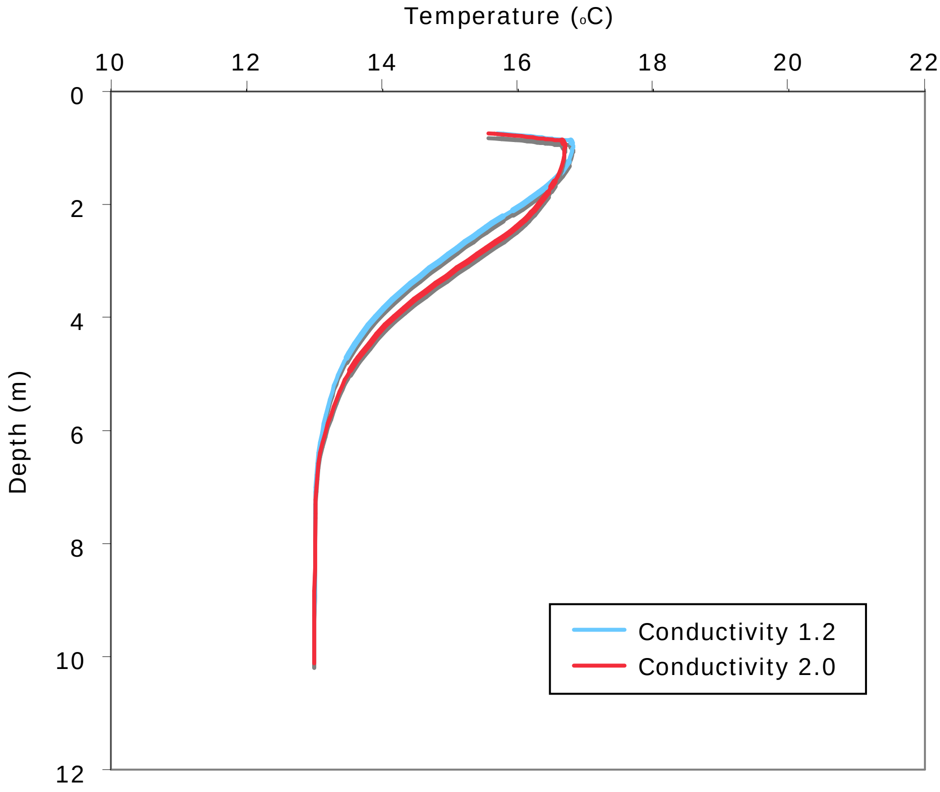


Figure 19.7. Comparison of temperatures predicted on 28th September for different conductivities

The lower soil conductivity leads to slightly higher peak soil temperatures adjacent to the array pipes, but lower temperatures at depth. The area contained by the temperature curves is proportional to the overall energy transfer into the store and more energy is therefore transferred when assuming the higher conductivity.

The predicted cumulative energy transfer from the collector to the store over the same period from 24th August to 30th September is shown in Figure 19.8. When using the higher conductivity of 2W/mK, 0.85MWh of heat was estimated as being transferred to the store: this was about 15% more than recovered using the lower value of conductivity.

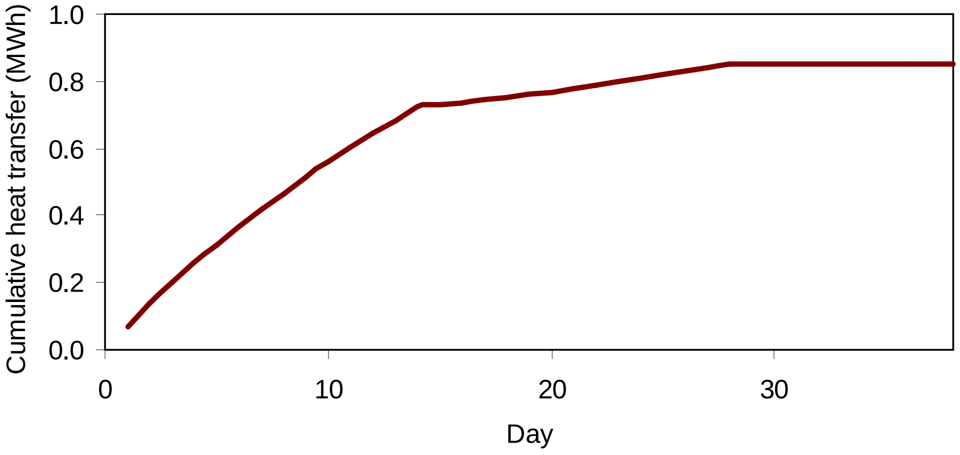


Figure 19.8. Predicted heat recovery during August/September 2005 (clay conductivity of 2W/mK)

These predicted values showed good agreement with the measured cumulative heat transferred to store 1 of about 0.85MWh by the end of September (Figure 7.9), particularly when a clay conductivity of 2W/mK was used in the predictions.

On this basis, the model appeared to be reasonably validated and an attempt was therefore made at predicting the annual heat collection.

19.5 Predicted annual solar collection

Following the above model validation, a CFD analysis was undertaken to estimate the annual heat collection capacity for a system implementing a road winter maintenance protocol only. For this analysis, the conductivity value of 2W/mK was preferred for the silty clay as this appeared to show better correlation with the measured data during the summer collection period 2005.

In this simplified scenario, the system collects heat between March 21st – September 22nd and releases heat back to the road during the winter season (September 23rd – March 20th). The experimental protocol for heat collection to take place is for the temperature difference between the road collector and the store to be greater than 2°C and for heat rejection to occur when the road surface temperature drops below 2°C.

Although the analysis does not simulate precisely the winter maintenance protocol, it provides a means of rejecting residual heat within the store via the pavement surface so that the store is ready for heat collection the following season.

The system has been run repeatedly for a number of iterations in order to reach a stable condition, where annual heat collection equals annual heat rejection. Figure 19.9 shows the solar collection curve (energy transferring from the collector into the store) as q_{hot}. Likewise, q_{cold} represents the transfer of heat in the opposite direction. The area contained by each curve is equal, as the annual heat collection equals the annual heat rejection for this stabilised model.

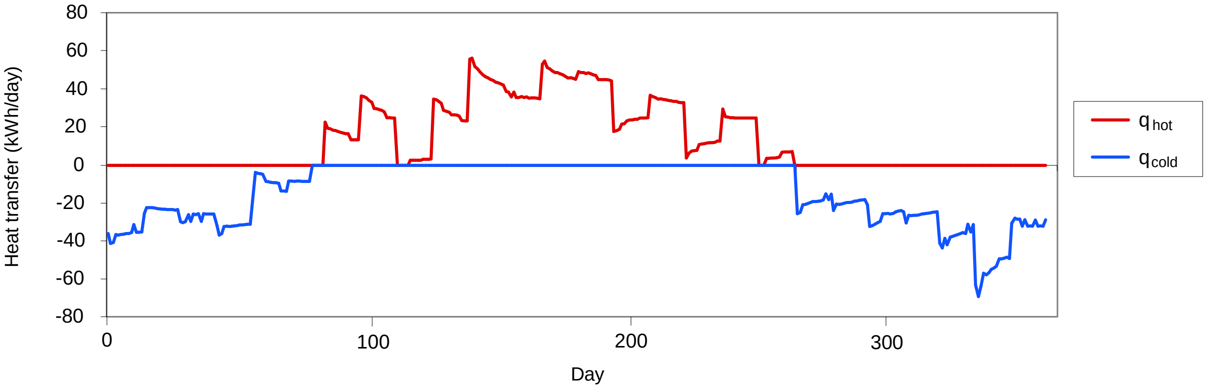


Figure 19.9. Heat flow using the stabilised model

The cumulative heat collection curve calculated from the heat flow data is shown in Figure 19.10. On the basis of this stabilised model, the total annual solar heat transfer calculated is then approximately 4.9MWh/annum.

This prediction can be compared with the measured values of heat energy recovered in summer 2006 and shown in Figure 9.10. The measurements showed that more heat was generally transferred to store 2 than store 1, i.e. about 6.5MWh as opposed to 4MWh respectively. The predicted value of 4.9MWh therefore showed good agreement with the measurements.

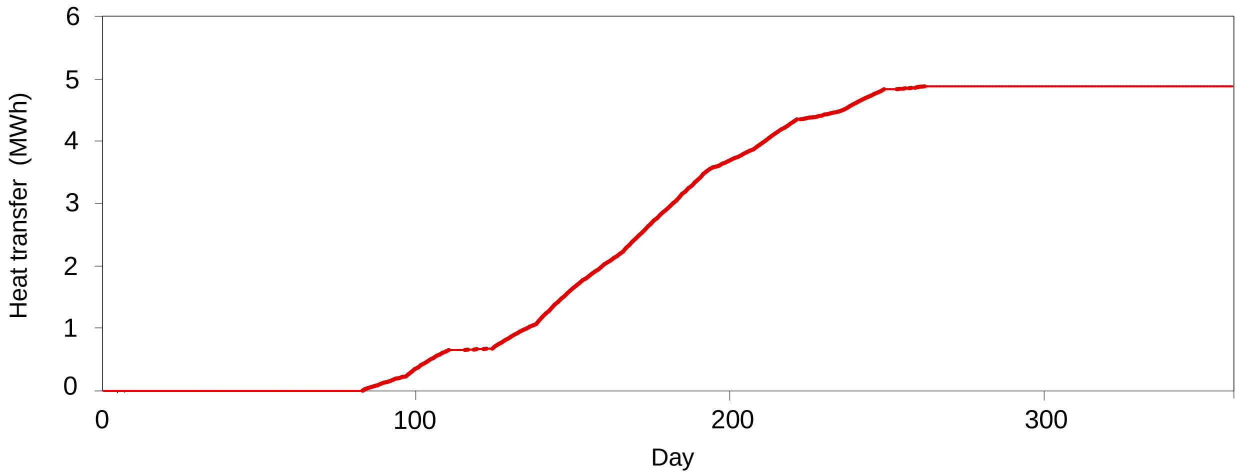


Figure 19.10. Annual cumulative heat collection using the stabilised model

19.6 Winter maintenance heat output capability

Following the simulation of annual solar heat collection the CFD model was used to simulate the maintenance of winter road surface temperatures for the prevention of ice and snow formation. In this mode the solar energy that has been collected in the store over the summer is then recovered and used to warm up the road surface. The CFD simulation has been carried out by inputting the monitored January 2006 weather data into the model and comparing this with the actual performance of the system at site under the same temperature conditions.

At Toddington the experimental protocol is activated when the temperature of the road surface drops below 2^{o}C using the temperature sensors in the road surface. The same control sophistication of the site trial cannot be built into the CFD model. It is more simply simulated as ‘the heat collection system in reverse’, i.e. rejecting the heat from the store to the collector. This process is not activated by any temperature control parameters in the model.

The CFD model is also limited to an analysis of surface temperatures rather than any complex modelling of ice and snow melting.

The thermal properties that have been used in the simulation of the winter maintenance protocol are generally identical to the properties used in the initial summer and annual heat collection simulation exercises. The exception to this is the value for the thermal conductivity of the sand layer adjacent to the store pipe arrays. The assumption is made that some water will accumulate in this layer during the cold and damp winter weather. The thermal conductivity for damp sand (1.1W/mK) rather than that for dry sand (0.33W/mK) is therefore used in this analysis.

The importance of collector pipe depth in providing effective road surface heating has been assessed using two different depths:

- 140mm invert depth (as installed at Toddington),
- 90mm invert depth.

19.6.1 Weather data

For simplification of the calculation process, the climate data that is input into the numerical model is averaged for each fortnightly period (as with the solar collection and storage simulation previously). This enabled input into the model of a set of daily readings taken from the monitored weather data at Toddington that represents a typical cold weather snap. In this case a weather pattern was chosen where the air temperature and road surface temperatures dipped below freezing overnight. The data that have been selected for this purpose are the readings from site on the 12th January 2006. This was selected as a cold night during the first fortnight in 2006, when the simulated performance can be compared to the actual performance.

Table 19.4 shows the air temperatures, solar radiations, and wind speeds which have been used to represent the first fortnight of weather data.

Table 19.4. Data from 12th January 2006 representing fortnight 1

Time	Air temperature (^{o}C)	Solar radiation (W/m^{2})	Wind speed (m/s)
0:00	0.1	-0.21	0.77
1:00	-0.5	-0.30	0.63
2:00	-1.0	-0.38	0.65
3:00	-1.6	-0.55	0.55
4:00	-1.8	-0.61	0.54
5:00	-1.3	-0.58	0.57
6:00	-0.6	-0.56	0.71
7:00	-0.5	-0.51	0.77
8:00	0.6	0.32	1.17
9:00	1.1	37.01	1.20
10:00	3.1	92.94	1.98
11:00	4.5	172.20	1.89
12:00	4.6	116.44	2.58
13:00	4.6	92.77	2.27
14:00	4.2	43.73	1.88
15:00	3.9	2.50	2.14
16:00	4.0	0.00	2.16
17:00	4.2	0.00	2.01
18:00	4.3	0.00	2.41
19:00	4.4	0.00	2.76
20:00	3.6	0.00	2.06
21:00	2.7	0.00	1.98
22:00	1.8	0.00	1.96
23:00	0.9	0.00	2.24

19.6.2 Results with collector pipe inverts at 140mm and 90mm

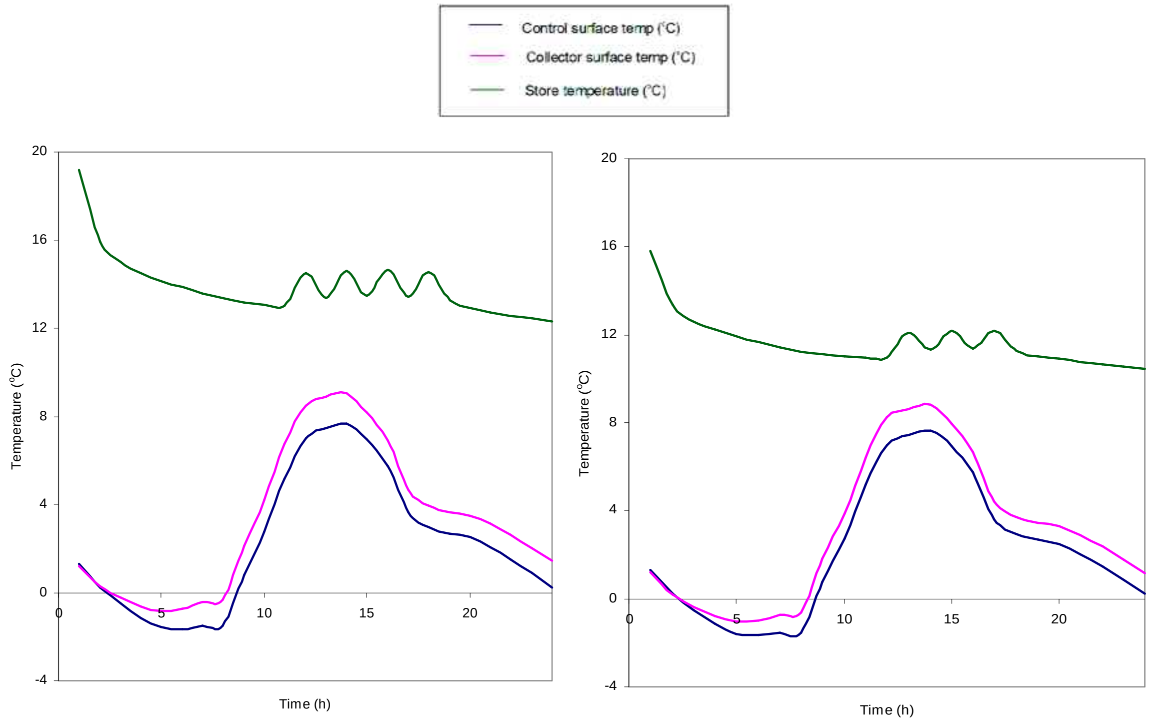
The main variable that has been investigated for the simulated operation of the winter maintenance protocol is the initial temperature of the store. At the beginning of the winter season, the temperature of the store in the region of the store pipes will be highest (at around 19^{o}C), while at the end of the winter maintenance season it will be at its lowest (at around 5^{o}C).

For this reason, a range of initial temperatures of 5^{o}C, 10^{o}C, 16^{o}C and 19^{o}C for the store have been simulated in the analyses. The control and collector surfaces were both exposed to the same weather parameters for each initial store temperature, although it must be noted that the modelling to achieve these initial store temperatures is not straightforward and slightly different thermal histories had to be employed. The effect of these differences is minimised by considering “temperature uplift” as a measure of performance.

The results in Figure 19.11 for a collector depth of 140mm are displayed for a 24 hour simulation of the winter maintenance protocol under the different conditions to give a comparison of the different system performances.

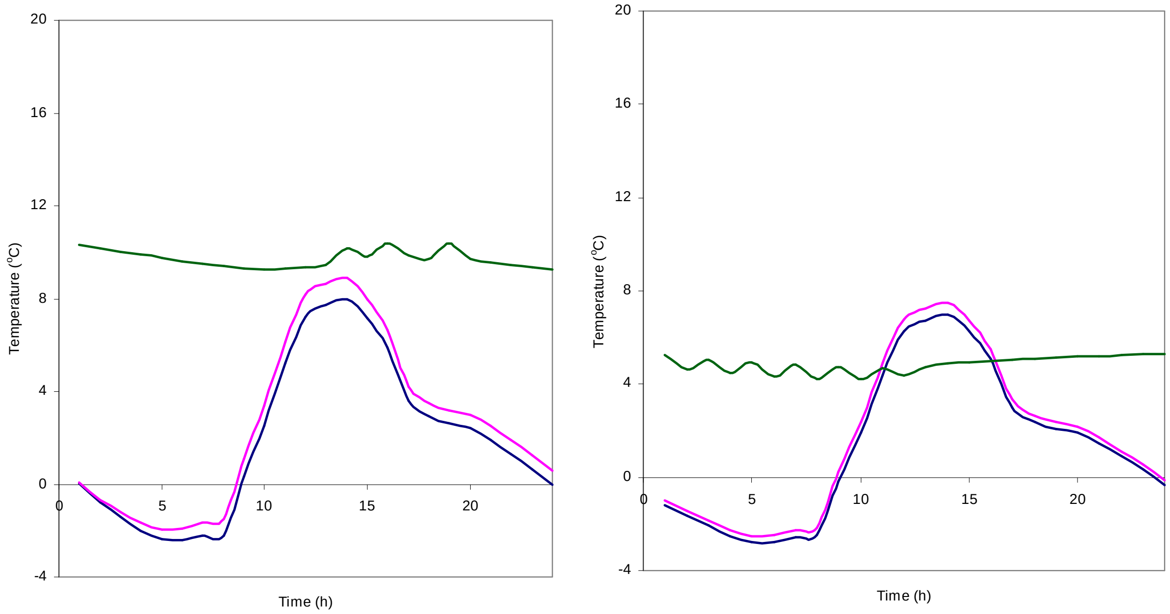
It should be noted that the store temperature curves in Figure 19.11 show some fluctuation with minor peaks and troughs. This is a result of simulated stop/start behaviour as the temperature differential between the store and the collector becomes less than 2^{o}C and pumping stops.

Similar plots are shown in Figure 19.12 for the various temperatures when the collector pipe inverts are at 90mm.



(a) 19^{o}C initial store temperature

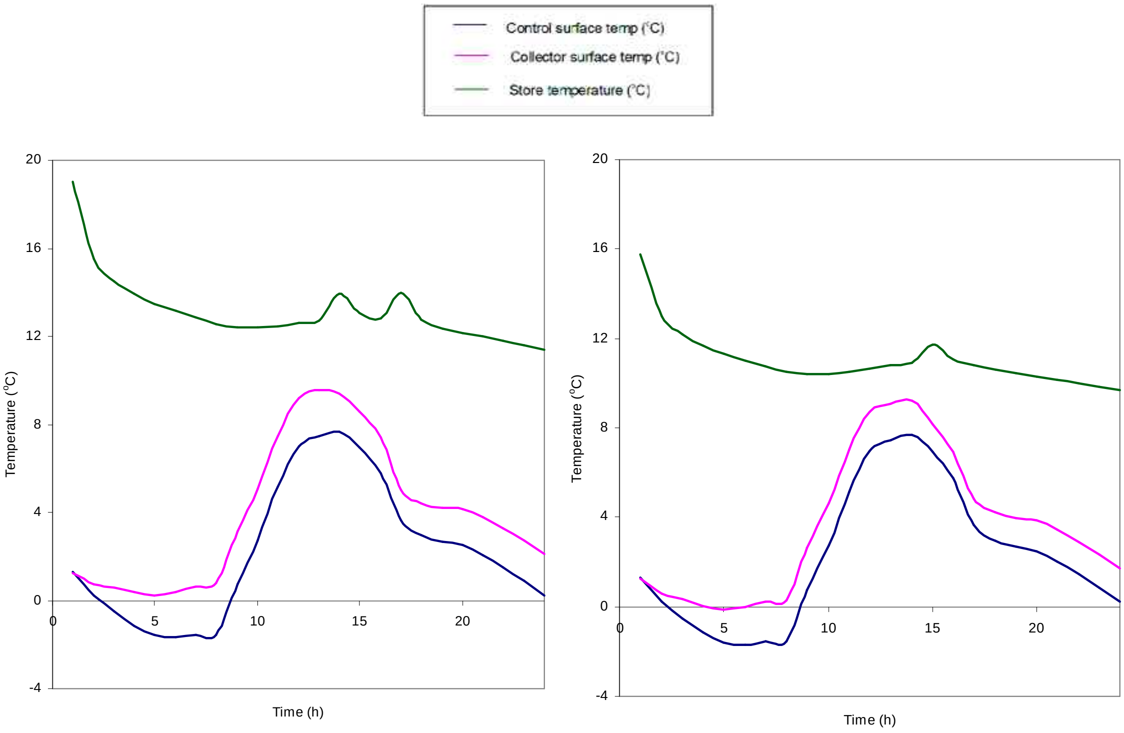
(b) 16^{o}C initial store temperature



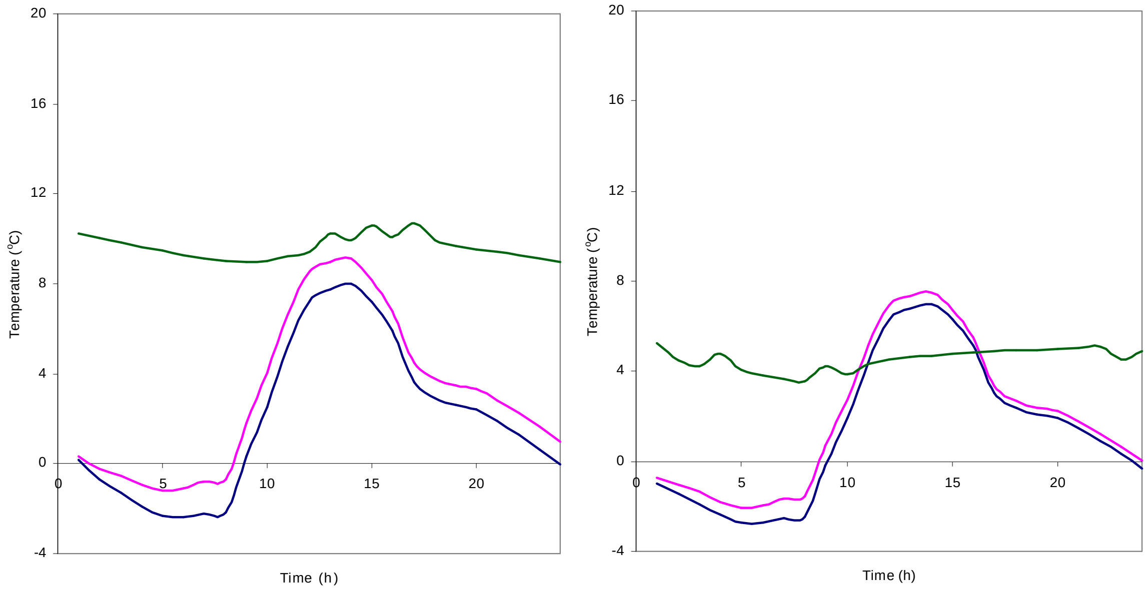
(c) 10^{o}C initial store temperature

(d) 5^{o}C initial store temperature

Figure 19.11. Results with a collector depth of 140mm and various initial store temperatures



(a) 19^{o}C initial store temperature (b) 16^{o}C initial store temperature



(c) 10^{o}C initial store temperature (d) 5^{o}C initial store temperature

Figure 19.12. Results with a collector depth of 90mm and various initial store temperatures

The results from Figures 19.11 and 19.12 are conveniently summarised in Table 19.5 which gives the peak uplift temperature differential between the heated and unheated road surfaces. The associated peak heat output is also given for each case.

Table 19.5. Summary of temperature and heat output data

Pipe invert depth 90mm				
Initial store temperature (°C)	**5**	**10**	**16**	**19**
Minimum collector temperature (°C)	-2.05	-1.19	-0.14	0.25
Peak uplift temperature during de-icing (°C)	0.89	1.51	1.92	2.36
Peak heat output (kW)	-5.24	-11.13	-15.68	-19.92
Pipe invert depth 140mm				
Initial store temperature (°C)	**5**	**10**	**16**	**19**
Minimum collector temperature (°C)	-2.54	-1.96	-1.06	-0.84
Peak uplift temperature during de-icing (°C)	0.46	0.87	1.14	1.45
Peak heat output (kW)	-4.37	-9.70	-14.06	-18.38

The results in Table 19.5 are represented graphically in Figures 19.13 and 19.14. Figure 19.13 demonstrates that for the same initial store temperature, an improved temperature uplift of between 0.4°C and 0.9°C occurs when the collector array is at the shallower depth. The associated peak heat outputs are shown in Figure 19.14 and as would be expected the outputs are higher when the collector array is shallower.

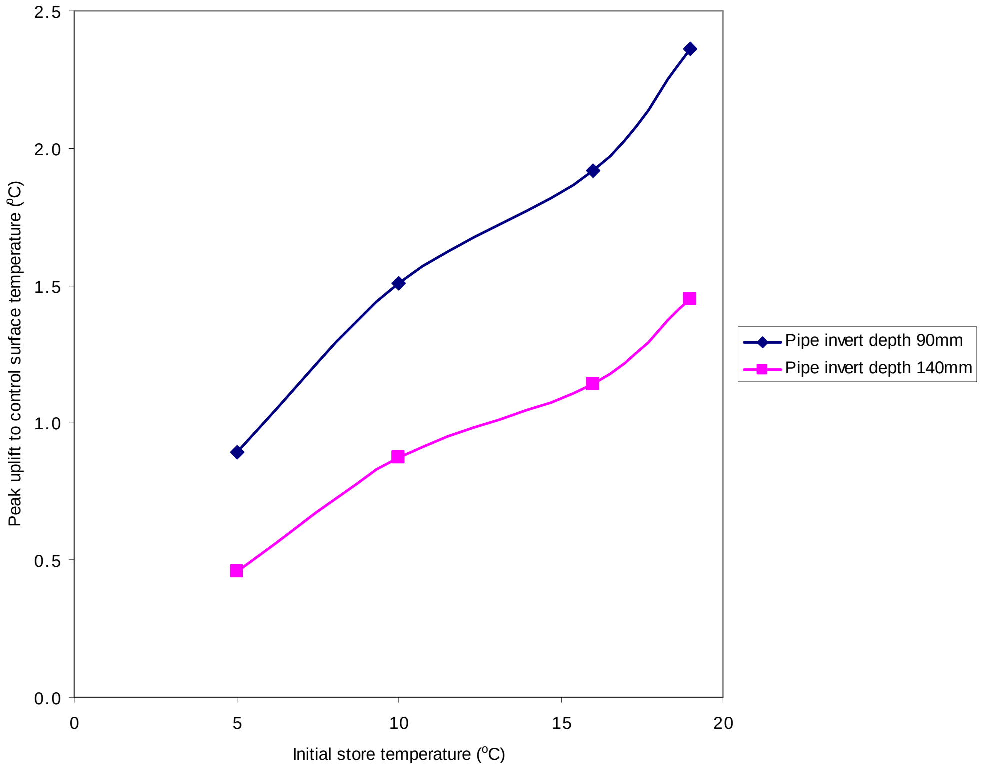


Figure 19.13. Relation between initial store temperature and peak uplift temperature

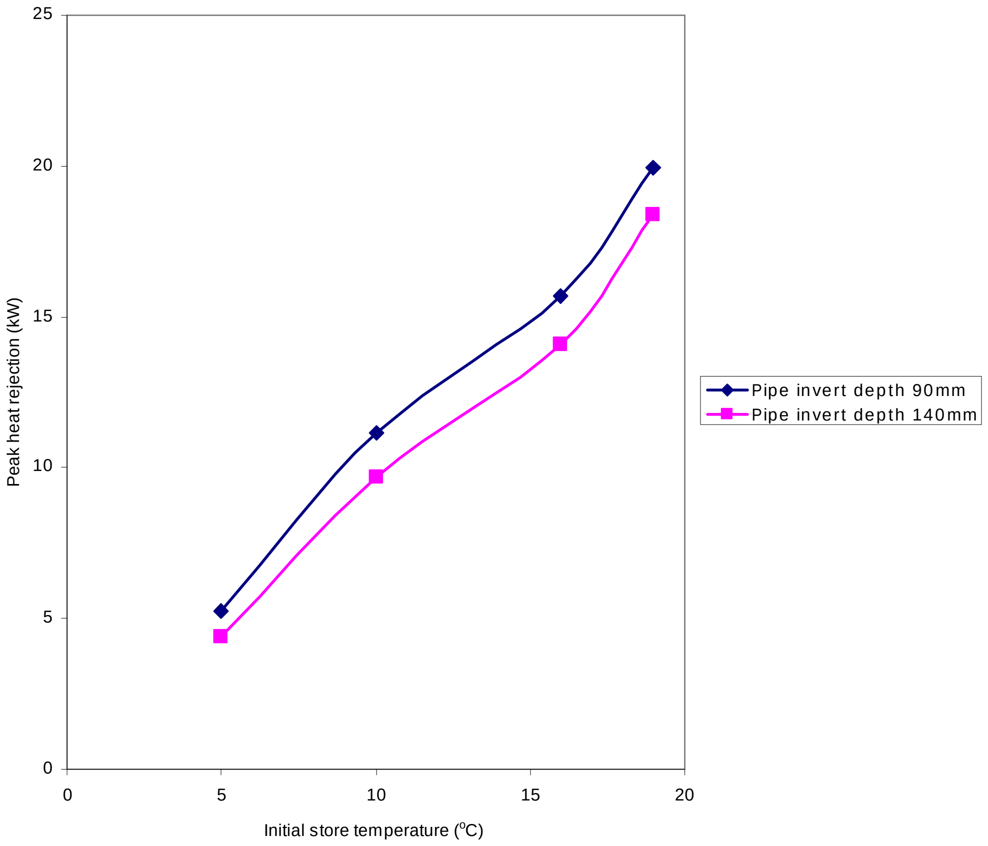


Figure 19.14. Relation between initial store temperature and peak heat output

19.6.3 Summary

The simulation of the winter maintenance protocol reveals that the performance, (i.e. the heat output and the ability of the system to raise the temperature of the collector surface relative to the control surface) increases with the starting temperature of the store and decreases with the depth of the collector pipe beneath the road surface.

With the initial store temperature at 19°C and at a collector invert depth of 90mm the collector surface is successfully maintained above freezing over the 24 hour period. The heat output under these circumstances is approximately 20kW. If the initial store temperature is 10°C, the collector surface temperature drops to a minimum of -1.19°C and remains below zero for two hours. The heat output under these circumstances is reduced to approximately 11kW.

The simulation shows that a pipe invert depth of 90mm shows an improved heat output relative to a system with a pipe invert depth of 140mm as given in Table 19.6.

Table 19.6. Improved heat output if collector pipe invert depth is reduced from 140 to 90mm

Initial store temperature (°C)	Improved heat output (%)
5	19.7
10	14.7
16	11.5
19	8.4

It must be noted that the calculated performance from the CFD modelling under-predicts the measured performance of the road-heating system at Toddington. The measurements given in Section 8 indicate that generally the heated road surface remained at least 2^{o}C hotter than that in the control area at a time when the store temperature was at the low end of the modelled range.

20 Appendix E. Whole life costing of a highway winter maintenance system

A detailed whole life costing (WLC) of interseasonal heat storage was reported by Carder (2005) in the initial feasibility study prior to commencing the trial at Toddington and the findings were based on the best estimates at that time.

Following the trial, the opportunity existed to refine the whole life cost study using real costs, etc. The main differences from the earlier study are:

- the current WLC study was carried out assuming the installation was solely for a highway winter maintenance system, no provision was made for re-use of the recovered energy to heat nearby buildings. The inclusion of a heat pump or heat exchanger in the system and associated motorised valves was therefore deemed unnecessary.
- the operational cost savings in reduced deployment of salt spreaders was taken into account in two ways, that is by considering:
    - treatment of well-known cold spots on the highway network. These tend to trigger spreading activity significantly in advance of it being generally needed over most of the network.
    - treatment of slip roads and interchanges which necessitate separate journeys by spreaders[4].
- the depth of cover to the collector pipe array below the road surface was 120mm. This allowed for planing of the road surface to 100mm depth which occurs as part of typical maintenance treatments of motorways and trunk roads. Installations on less heavily trafficked and local roads may permit collectors to be installed at shallower depths for improved heat recovery.

In common with the earlier whole life cost study, it was assumed that:

- the interseasonal heat storage system would be installed only during new construction or major reconstruction of the highway so that pavement construction costs are not considered.
- some additional costs may be incurred due to the extra time required to install the collector and heat store during the construction or reconstruction process. These are not quantified as they would be either site specific or possibly avoidable by careful construction scheduling.
- the heat store would be below the collector within the carriageway. If the alternative of the heat store adjacent to the highway is required, the site specific costs of the additional land-take would need to be considered.

20.1 Cost data

Where possible the data in Table 20.1 are actual costs for the Toddington trial where the actively heated section of the test road was 60m long and 5m wide. It must be noted that because the trial was a prototype and there were experimental requirements, some costs exceeded those that would be expected in a construction situation and this is indicated where applicable.

In Table 20.1 the data are then normalised to two lanes each of width 3.65m and of length 100m to simulate the treatment of slip roads and cold spots on the highway network. The multiplication factor for normalisation in most cases was related to the relative area of the heated sections of road (ie. 730/300), although in some cases the relative lengths (ie. 100/60) were considered more appropriate. For example, when considering insulation to the side of the road, the same width of insulation is required regardless of the number of traffic lanes and it is the length of road that is important. It has also been arbitrarily assumed that an insulation thickness of 100mm would be adequate rather than the 200mm thickness used at Toddington.

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[4] The whole life costing, if treating significant lengths of motorway or trunk road, would be especially complex in view of the logistics in installing pipe arrays and insulation, and programming the operations into the construction progress. A separate whole life costing, which is considered beyond the scope of this report, would therefore be needed to cover this eventuality.

20.2 Performance data

The trial at Toddington has indicated that the solar heat recovered in the summer is broadly compatible with that needed to prevent ice and snow formation during the winter period.

The following other issues are also considered in the analysis:

- the cost of the electricity in running the circulating pump(s),
- the service life of the pipework and circulating pump(s).

The whole life costs are also considered in relation to the main issue of *cost savings in the reduced deployment of salt spreaders.*

20.3 Discount rate data

In accordance with the current Treasury rules, an annual discount rate of 3.5% has been assumed in the model.

20.4 Operation and maintenance costs

Operation and maintenance costs would be incurred for:

- cost of electricity to power the pumps,
- routine maintenance and de-airing of the circulating pump system,
- routine electrical testing,
- replacement of circulating pump(s) and any control valves at end of useful life,
- replacement of control system at end of useful life,
- replacement of connecting pipework, cabling and data link at end of useful life,
- replacement / maintenance of plant room at end of useful life.

These costs have been evaluated for two lanes of 100m length (i.e. they relate to the normalised values in Table 20.1.

Electricity for the pumps and control system

The measured electrical power consumptions at Toddington for a heated area of 150m^2 were as follows:

- An overall consumption of 369kWh during the summer heat recovery in 2006 based on the mean measurements from pump 4 (collector 1/store 1) and pump 5 (collector 2/store 2). It is anticipated that refinements in heat transfer protocols could reduce this to 200kWh.
- An overall consumption of approximately 95kWh during the winter maintenance period (November 2006 to March 2007). This was based on the hours of operation given in Table 10.1, although it should be noted that these will vary depending on the severity of the winter.

If the summer electricity consumption is costed at 6p/kWh and the winter consumption at an off-peak tariff of 4p/kWh, the cost of running the pumping system at Toddington is calculated as £15.8/annum. Therefore for 100m length of two lane carriageway, this would be equivalent to a total power consumption of 1.43MWh and a cost of £77/annum.

Table 20.1. Construction costs (under-road store for new construction) based on Toddington data

ELEMENT	COMMENTS	TRIAL COSTS (£) 5m×60m	NORMALISED COST (£) Two lanes×100m
Design and supervision	Allowance for detailed design and daily site supervision of all construction tasks	10,000	15,000
Civil engineering works			
Pump cabinet(s)	Supply and install cabinet for pumping system.	2,000	3,000
Extra excavation and backfilling within carriageway(1)	Excavate extra 250mm depth for store pipe array and insulation; backfill with 150mm depth of sand over store array.	5,010	12,191
Supply insulation above ground heat store(2)	100mm thick expanded polystyrene (Fillmaster grade 200) to insulate heat store. Gross volume of 30m^3 at rate of £60/m^3.	1,800	4,380
Install insulation above ground heat store	Installation of 30m^3 at rate of £30/m^3. This rate takes account of filling voids with sand to provide even bedding.	900	2,190
Excavate to 1m depth on both sides of the heat store for insulation. Backfill with arisings	Excavate 720m^3 at rate of £10/m^3; backfill 648m^3 with arisings at rate of £10/m^3; disposal of 72m^3 at rate of £10/m^3. These rates are higher than given by Spon (2006) to account for the need to produce a reasonable finish by laser levelling and for the need to stockpile in a confined space. *(Rates at Toddington were twice as high because of the presence of buried utilities in the construction zone).*	14,400	24,000
Supply insulation to both sides of the heat store	100mm thick expanded polystyrene (Fillmaster grade 100) to insulate 6m width of surrounding ground to both sides of store. Gross volume of 72m^3 at rate of £44/m^3.	3,168	5,280
Install insulation to both sides of the heat store	Installation of 72m^3 at rate of £30/m^3. This rate takes account of filling voids with sand to provide even bedding.	2,160	3,600
Electricity supply	Contingency for connection of local supply *(it is assumed that cable laying is undertaken during the excavation rather than by separate trenching).*	1,000	1,667
Mechanical installation			
Supply and install distribution pipes	Distribution pipework to be high density polythene.	3,000	5,000
Supply and install pipe arrays for collector and store	High density cross-linked polyethylene	20,364	49,552
Supply and install pump system in cabinet	Variable speed pump, expansion vessel, automatic air separator, electrical isolator.	4,000	6,000
Supply and fill system with anti-freeze	Ethylene glycol (10% by volume) protects down to -5°C. Given that road heating will be active at sub-zero temperatures, this is considered adequate(3).	1,500	3,650
Supply and install control system	Temperature sensors in the road surface, collector and store pipe arrays. Logging and control system with alarm feedback to Regional Control Centre by either mobile phone or cable link.	8,000	11,000
Testing and commissioning		2,000	4,867
TOTAL		***79,302***	***151,377***

Notes: (1) No additional excavation or backfilling activities are assumed when placing the collector pipes at 120mm depth within the road structure. Care is needed during construction of the pavement structure to ensure the plastic pipes remain undamaged.

(2) Polystyrene insulation should be protected from possible accidental contact with petroleum or solvents using a suitable polymer barrier, where necessary.

(3) Anti-freeze based on refined vegetable extracts with non-toxic corrosion/scale inhibitors may be used in future installations.

Maintenance of heat pumps etc.

It has been assumed that the circulating pumps, control valves, control system etc. would require maintenance by a heating engineer. The system would also require a check on the de-airing system at the same time. It is anticipated that inspection and any maintenance would require half-day visits by a heating engineer at approximately three monthly intervals. This cost is estimated at £600 per annum. It has been assumed that the time taken for maintenance would not have any impact on the heat recovered or used.

It has also been assumed that if fluid levels of the system need topping up, a pre-mixed anti-freeze solution would be available. A contingency of £20 per annum has been allowed for purchase of the fluid.

Electrical testing

It has been assumed that electrical testing is done on an annual basis during the regular maintenance visits identified above.

Replacing pumping system components

It has been assumed that the circulating pumps would be replaced after 25 years, provided the collector pipes have not been removed during pavement maintenance. It has been estimated that the time taken to replace the circulating pump(s) has no significant impact on the heat recovered/used.

It has been assumed that the service life of the heat store pipework and the insulation would be 30 years.

Replacing/maintaining plant room, cabling and data links, control system

It has been assumed that the useful life of the pump cabinet/enclosure would be 100 years, and that no maintenance would be required during the accounting period.

It has been assumed that the useful life of the control system, cabling and data links would be 60 years and that no maintenance would be required during the accounting period.

20.5 Decommissioning and salvage

No account has been taken of decommissioning costs at the end-of-use. It has been assumed that individual components in the ground or road have no significant value and that the only item of value to salvage would the circulating pump and possibly the pump enclosure. An allowance of £1000 has been made for salvage of these items. It is assumed that the control system although operational would be obsolete and of no value due to technological progress so no account has been taken of this.

The only operation on de-commissioning is to turn off the electrical power to the installation.

20.6 Results

The whole life costing for this particular study has been carried out on a simplistic basis by assuming that there is no damage and therefore no need to replace the collector pipe array during routine pavement maintenance treatments. This is likely to be true for a pipe array installed at a depth of 100mm or greater as is the case at Toddington.

It must be noted that a *very significant* increase in the overall effectiveness of the interseasonal heat transfer system is expected to occur if the collector pipe array is at a shallower depth in the road. However apart from the effect this would have on the pavement maintenance schedule and the associated cost implications in replacing the collector pipe array if planing occurred to pipe depth, there are concerns about the increased risk of reflection cracking of the pavement surface. Currently, for this latter reason alone, it is not envisaged that the depth of cover to the pipes can be reduced below 100mm on UK motorways and trunk roads subjected to heavy trafficking. The situation is clearly different for local roads, car-parks, etc. where trafficking is lighter. In cases where the collector array is installed at shallower depths and its replacement is necessary when maintenance options of planing to 100mm are unavoidable, more detailed whole life costings are given by Carder (2005).

Because the system is based on using renewable energy and complex components are not required, the whole life costs are primarily the capital costs of installing the system as maintenance and operational costs are relatively low.

The whole life costs evaluated using the above factors over a 30 year accounting period was found to be £164,293 for 100m length and two lanes. Because of the low maintenance and operational costs, this value was only slightly higher than the capital costs of installation of £151,377 given in Table 20.1. Taking account of the annual discount rate of 3.5% this means that a saving of £8,631 per annum needs to be made for break even over the 30 year period for this section of road.

20.7 Comparison of operational costs

The costs of operating under-road heating using the interseasonal heat system as reported in Section 20.4 were compared both with the cost of salt spreading and also that of running conventional electrical under-road heating.

20.7.1 Salt spreading

The whole life costs can be compared with the approximate costs of salt spreading although, exact data on these operations and costs are difficult to obtain, the information in Tables 20.2 and 20.3 provides some relevant information.

Table 20.2. Length of salting runs and salt used

Region	Typical length of salting run (km)	Typical time for each (hours)	Amount of salt used at 10gm/m^2 (tonne)
Local Authority 1	59	3	~5
Local Authority 2	44	2	n/a
Local Authority 3	56	3	n/a
HA MAC (i)	60	1.5	10.8
HA MAC (ii)	51-95	1.5	1.3* - 6
HA MAC (iii)	35	>2	3.74

* lower value applies where slip roads and interchanges are treated separately.

Table 20.3. Approximate cost data per salting run and per kilometre

Region	Length of road treated (km)	No. salting routes	Typical length of each route (km)	Cost per single complete treatment at 10g/m^2	Cost per route at 10gm/m^2	Cost per km using typical length*
Local Authority 2	2,400	54	44	£27,500	£509	£11.6
Local Authority 3	2,480	44	56	£22,000	£500	£8.9
Local Authority 4	-	61	35	£33,208	£544	£15.5
HA MAC (i)	1,248	29	60	£11,000	£379	£6.3
HA MAC (iii)	1,316	38	35	£15,000	£395	£11.3

* Calculated by dividing cost per route by its typical length.

The information in Tables 20.2 and 20.3 should be treated with some caution as the data are very situation and process dependent. For example, Local Authority roads will be of different widths to motorways and different salt spreading procedures will be adopted. On motorways it is common practice to have one spreader running the main carriageway, whilst a second does all the slips and junctions. Interchanges are a little more complex as an off and on diversion from the main line may not be possible. If the road is two-lane dual carriageway, one spreader load will be able to salt about double the length it could do on a motorway. Also, the type of salt and whether it is pre-wetted, together with the spreader capacity will all have an impact on the costing.

For the purpose of this report it has been assumed that the direct cost of spreading salt is of the order of £10/km run. This cost does not take into account the support staff, which run the operation from the HA Managing Agent Contractor (MAC), and also the cost of weather forecasting which would not be needed if a road heating operation were adopted as it would be sensor controlled. Vehicle maintenance and depreciation is also not included as it is difficult to quantify as many vehicles are multi-purpose. A more detailed breakdown of costs is not readily obtainable from HA MACs as winter maintenance generally forms a lump sum activity within the MAC pushing the onus for efficiency on to the service provider.

There are known cold spots on the highway network such as exposed areas, areas where water seepage onto the carriageway occurs, and bridge decks which are colder than the surrounding roads. Approaches on the separate treatment of cold spots vary between regions according to the number of problem areas which exist. Potentially some savings in treatment could occur if the coldest spots were treated separately, particularly if they are in close proximity. However, in many instances, as the majority of the cost is in mobilising plant and labour it can be argued that a full treatment of that route might as well be carried out.

Information on triggering protocols was also obtained during this part of the study and is of relevance to the control of interseasonal heat systems. Generally sophisticated weather forecasting relevant to salt spreading is carried out by service providers using meteorological data and data from local weather stations on the highway network, some of which incorporate cameras and road surface temperature measuring devices. The primary trigger is normally low road surface temperatures tempered with humidity considerations. Road surface temperature trigger points vary by region but are typically when the temperature falls below either 2^{o}C or in some cases 1^{o}C.

20.7.2 Conventional electrical under-road heating

From winters 2005/06 and 2006/07 it was concluded that at Toddington about 3MWh heat energy is needed for the winter maintenance of a section of road 30m long by 5m wide. Although this was heat energy, it is presumed that a near identical amount of electrical energy would be required if under-road electrical heating[5] was employed at the same depth rather than heating using renewable energy.

Therefore a 100m length of road (two lanes) would consume about 14.6MWh/annum. This equates at off-peak electrical tariffs of £40/MWh to an electricity cost of £584/annum for the 100m length.

20.8 Summary of cost implications using different systems

Table 20.4 summarises the known costs of operating a renewable energy system, electrical under-road heating and salt spreading.

A direct comparison of the costs given in Table 20.4 is difficult to make and the findings must be treated with extreme caution. At first sight, the operating costs of salt spreading are lower than those of an interseasonal heat transfer system, and both are considerably lower than those of an electrical system as might be expected. However allowance needs to be made for the fact that operating costs derived for salt spreading take no account of the time of supervisory staff and weather forecasting. No figures are readily available for these cost items.

All techniques require a significant investment in infrastructure and, for salt spreading, the level of investment cannot be easily identified, particularly within the HA MACs which mainly operate on a lump sum basis.

It must also be noted that no allowance has been made in Table 20.4 for a standby engineer in the event of an electronic warning of an unexpected failure of a section of under-road heating. It could be argued that a battery-

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[5] It should be noted that a fluid-filled road-heating system driven from a boiler system is likely to have similar running cost to that of an electrical system.

backed "icy road" warning could be automatically activated in the event of either a localised failure or more general power interruption on the HA network.

Table 20.4. Cost implications using different systems

Winter maintenance technique	**100m × 2 lanes**		
	Operational cost	**Whole life cost of infrastructure over 30 year accounting period**	**Maintenance**
Interseasonal heat system (renewable energy)	£ 77/annum	£164,293[a]	£615/annum
Electrical under-road heating	£584/annum	Cost of installation of heating cable beneath the road and suitable transformation is likely to be similar to that of a renewable energy system. Additional costs may however be incurred in upgrading the HA electricity network to handle the heavy power requirement.[a]	Costs are expected to be less than those of a renewable energy system.
Salt spreading	£ 30/annum[b] (based on 30 out-turns[c])	Significant investment in salt spreaders, depot facilities, MAC/Local Authority staff, and weather forecasting.	Vehicle depreciation and maintenance costs.[d]

Notes: a. Sensors incorporated into these systems mean that weather forecasting is not required.

b. This cost includes drivers/operators, but not the time of supervisory staff and weather forecasters.

c. More out-turns may be required in the event of a bad winter.

d. These are not readily quantifiable as many salt spreaders are multi-purpose vehicles.

The comparisons in Table 20.4 with salt spreading costs are not necessarily definitive for the following reasons:

- *Treatment of well-known cold spots* on the highway network may prevent the triggering of a complete salt treatment run significantly in advance of it being needed. Although generally the contacted MACs/Local Authorities reported that salt spreading of cold spots did not happen very frequently, when it does occur there is an associated cost saving. The cost of salting a cold spot(s) is directly proportional to the length of dead running of the spreader as this is the most significant element of the task, the cost of salt being low. For example if a run of 30km was necessary to treat cold spots, a single run would cost approximately £300. If the total length of cold spots within this run was less than about 400m, the operational costs in Table 20.4 suggest that an interseasonal heat system might then be competitive. If specific cold spot treatment was initiated more than once per winter, the cost benefits clearly increase *pro rata*.
- *Treatment of slip roads and interchanges* which necessitate separate journeys by spreaders are also expensive in terms of salt spreader deployment as once again the length of dead running is the major cost factor. Installation of an interseasonal heat transfer system on slip roads and interchangers may therefore be beneficial. For example if the spreader travelled 30km to treat such locations, this would cost about £300 per run and, based on 30 treatments per winter, about £9,000 per annum. This sum would permit operation of under-road heating over about 12km of 2 lane carriageway (one direction), i.e. about one third of the salting route and probably most if not all of the associated slip roads and interchanges.

20.9 References

Carder D R (2005). *The feasibility of trials of renewable energy generation in highways.* TRL Published Project Report PPR032. TRL Limited, Wokingham.

Abstract

The use of interseasonal heat transfer systems incorporating solar energy collectors in the road and shallow insulated heat stores in the ground is currently innovative and at the forefront of technology. A major instrumented trial of the technique was undertaken on an access road near Toddington which involved constructing two solar heat collectors (pipe arrays each 5m wide by 30m long installed at 120mm depth below the road surface) and two insulated heat stores of similar dimensions but at 875mm depth. One store was beneath the road and the other beneath the verge to simulate new construction and retrofit installations respectively. The solar heat recovered from the road surface was used to investigate the winter maintenance of the road surface and the heating of nearby buildings. The cooling of a building in the summer was also separately simulated.

This report describes the design, construction, operation and performance of the instrumented test facility to recover heat from the road surface. The performance was monitored over a two year period which gave the opportunity for full seasonal assessments of the recovery of solar heat from the road surface, its re-use for ice-free winter maintenance of the road surface, and protocols simulating the winter heating and summer cooling of a nearby building. Numerical modelling and whole life costing of the recovery of heat for winter maintenance of a highway was included in the study.

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Performance of an interseasonal heat transfer facility for collection, storage, and re-use of solar heat from the road surface