HYDROGEOLOGY AND HEAT ENGINEERING

3 December 2007
Burlington House, Piccadilly, London

PROGRAMME OF ORAL PRESENTATIONS

Convenors and oral session chairs:
Steve Buss (ESI), Mark Morton (Environment Agency) & Willy Burgess (UCL)

0930 Registration and coffee

1000 **Steve Buss**, *ESI*. Welcome by chair

1005 **David Banks**, *Holymoor Consultancy / University of Newcastle-upon-Tyne.* Subsurface heat flow: an introduction to thermogeology and the exploitation of ground source heat.

1030 **Mark Morton**, *Environment Agency.* Ground source heat pump policy and regulation.

1055 **Martin Preene**, *Golder Associates.* Groundwater use for heating and cooling – sustainable or not?

1120 Coffee

1145 **David Whittaker**, *ARUP.* Sustainability aspects of ground energy systems.

1210 **John Barker**, *University of Southampton.* Modelling doublets and double-porosity.

1235 **Catherine Gandy**, *University of Newcastle-upon-Tyne* **& Lee Clarke**, *CarbonZero Consulting.* Predictive modelling of groundwater abstraction and artificial recharge of cooling water.

1300 Lunch

Afternoon Session: Chaired by Willy Burgess

1400 **Mark Gropius & Zeb Etheridge**, *Zenith International.* Numerical groundwater flow and heat transport modelling of a large open loop geothermal system in London.

1425 **Ryan Law**, *University of Birmingham / ARUP.* Open ground energy systems in the Chalk aquifer of central London – methods of understanding and interpreting the impact of fracture flow.

1450 **David Birks**, *Parsons Brinckerhoff.* Groundwater cooling at the Royal Festival Hall, London.

1515 **Alan Herbert**, *ESI.* Modelling of groundwater cooling schemes in London.

1540 Tea

1605 **James Dodds, Lee Clarke & John Findlay**, *CarbonZero Consulting.* Thermogeological Risk Assessment.

1645 **Victoria Fry**, *Environment Agency.* Lessons from London.

1710 **Mark Morton,** *Environment Agency*. Review of meeting, followed by open discussion.

1730 Wine Reception

ABSTRACTS

Subsurface heat flow: an introduction to thermogeology and the exploitation of ground source heat

David Banks, Holymoor Consultancy, 8 Heaton Street, Chesterfield, Derbyshire, S40 3AQ, United Kingdom. Also: Senior Research Associate in Thermogeology, HERO Group, Institute for Research on Environment and Sustainability, University of Newcastle-upon-Tyne, United Kingdom

Our modern mathematical understanding of hydrogeology grew, thanks to the insight of Clarence Lubin in the early 1930s, directly from heat conduction theory. It should therefore be no surprise that equations describing subsurface heat conduction are directly analogous to those describing laminar ("Darcian") groundwater flow and that the equations describing advection of heat with groundwater are analogous to those for contaminant transport. These equations can be used to assess the performance of the two main options for utilising ground source heat – "closed loop" and "open loop" systems, respectively. The analogy between hydrogeology and thermogeology can be extended still further: we can consider the thermal budget of an "aestifer" in much the same conceptual terms as the water budget of an aquifer. We can even indulge in artificial recharge of heat during seasons of plentiful supply and low demand in order to enhance scheme sustainability and to provide readily accessed thermal storage during periods of high demand.

Groundwater policy aspects of ground source heat pumps

Mark Morton, Environment Agency, Rivers House, 21 Park Square South, Leeds LS1 2QG

Ground Source Heat Pumps (GHSPs) use constant ground/groundwater temperature to provide winter heating and summer cooling for buildings. They are relatively low carbon and more efficient than conventional heating systems but may have environmental impacts, depending on mode of operation and location. The public profile and demand for GHSPs is rising rapidly.

Key Issues
- Rapid increase in new proposals and installations.
- Legislative framework incomplete and responsibilities unclear.
- Concerns over potential interference between systems and with other water users, particularly in Central London.
- Potential multiple site applications.
- Lack of science and understanding of new technology and its operation in the UK.

Drivers for growth in GSHP installation
- Good efficiency and low carbon footprint.
- Policy initiatives – e.g. Ken Livingstone's CO_2 reduction commitments and the proposal to cool the London underground system in time for the Olympics.
- Grants from Low Carbon Buildings Programme for public sector buildings (including schools, hospitals, housing associations and local authorities) and charitable bodies and for domestic installation of low carbon systems.

Legal uncertainties.
We have some control over open loop systems via existing abstraction licence and discharge consent procedures. Warm water discharged to ground is trade effluent. However, the transfer of heat alone does not appear to be covered by UK legislation. Although the Groundwater and Water Framework Directives indicate that heat can cause pollution, heat is not a pollutant and is not subject to permitting or other statutory controls.

It is unclear if the impact of warm water or heat alone on another GSHP, so reducing efficiency or preventing operation, is pollution and something that can be controlled. Closed loop systems appear to be beyond current regulatory controls.

Knowledge, understanding and science

Policies for GSHP are now in part 4 of the Groundwater Protection: Policy and Practice (GP3) document. However, there is limited experience and understanding of the risks from heat input to the ground under UK conditions. Most proposed GSHP systems are to provide cooling. The result is discharge of warm water (around 18-25ºC) into the aquifer. The long-term effect of this on the aquifer and other abstractors is unclear. The risks are that aquifers may become clogged due to chemical or biological action or flow directions changed. There may be down-gradient impacts on surface water ecosystems.

It is clear that consistent and streamlined procedures and legislation are needed for GSHP applications.

Groundwater use for heating and cooling – sustainable or not?

Martin Preene, Golder Associates UK Limited, Golder House, Station Road, Tadcaster LS24 9JF

Open loop groundwater source energy systems can provide a low carbon source of heating and cooling, and offer corresponding environmental benefits. However, a key question is – does it automatically follow that groundwater source systems are sustainable? This is not a straightforward question because clear definitions of sustainability targets for such systems do not currently exist.

Sustainability considerations rightly must address the short term and long term quantity of energy that is extracted from or rejected to the aquifer. However, true assessment of sustainability of a groundwater source system also requires that the wider 'system' be assessed.

Breaking down a groundwater source energy system into its principal components, as below, can aid the understanding of the system:

i. The building and its cooling and/or heating demand;
ii. The source of groundwater (the aquifer and the engineering infrastructure, boreholes, pumps etc used to exploit it);
iii. The disposal route of waste stream of warmer or cooler water (examples of disposal routes include discharge to surface waters, groundwater or to urban sewerage networks).

Only the second of these components is normally within the remit of the hydrogeologist, but in the future hydrogeologists must learn to understand, and influence, the other components.

This presentation will address the interactions between the system components and how the hydrogeological design element can be affected. A series of tests to determine whether a groundwater source cooling system can be considered 'sustainable' are identified.

Sustainability aspects of ground energy systems

David Whittaker, ARUP

Open and closed loop borehole systems and energy foundations are all methods of exploiting the thermal capacity of the ground. Design calculations for ground energy systems usually omit reference to the ultimate source of the net energy abstraction. This is in contrast to groundwater supply engineering, in which a hydrogeological evaluation of sustainable resources is as important as the design of the abstraction system. The natural geothermal gradient in most parts of the world is insignificant in the context of ground sourced energy, and solar radiation is remote from deep strata. Groundwater flow rates are seldom large enough to carry a significant part of the temperature deficit or surplus beyond the site boundaries. The long term stability of all ground energy systems therefore depends upon adoption of an operating regime which substantially maintains a balance between heat rejection and abstraction. This is not as widely appreciated as it should be.

It is quite possible that there have been many ground energy schemes which are in effect over-abstracting heat or coolth. While the consequences of over-pumping of groundwater to the operator of a water supply abstraction are water level lowering, falling well yields and increased pumping costs, in the case of ground energy schemes the effects are seen as increasing (or decreasing) temperature of entering flow and reduced efficiency of heat pumps. The wider environmental costs are, of course, also significant in both cases. The Environment Agency in the UK is adopting a precautionary approach to the licensing of open borehole schemes, although it has no jurisdiction over closed systems.

Modelling doublets and double-porosity

John A. Barker, School of Civil Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ.

The use of two-well systems for the exploitation of geothermal energy has been considered for a variety of scenarios. For example, during the UK geothermal research programmes of the 1970s and 1980s, doublets were investigated in principle, for extracting heat from sedimentary basins, and in practice in the Hot Dry Rock (HDR) experiment in Cornwall.

The obvious advantages of a doublet over a single well are the avoidance of discharge and the reduction in pumping costs. But a significant concern is always that of the breakthrough of the injected water at the abstraction well and the associated fall (or rise) in temperature. Both the breakthrough time and the subsequent temperature breakthrough curve need to be predicted for effective design and management of these systems.

The mathematics of flow and advective transport between well doublets is available in standard texts but it is worth reflecting on what those formulae tell us in practice. Starting from those formulae, a semi-analytical model has been developed for simulating heat-transport across a well doublet in a double-porosity medium, with the Chalk particularly in mind.

Given the uncertainties of flow in fractured rock, this modelling tool was specifically intended to be calibrated using tracer-test data and then applied to heat. This takes advantage of fact that the transport of heat and of solutes (e.g. tracer dyes) are described by the same equations and involve in common parameters characterising the aquifer. Due to the different time scales of heat and solute diffusion, a tracer test carried out over just a few days can help us predict the behaviour of heat transport on a timescales of the order of months to years.

Predictive modelling of groundwater abstraction and artificial recharge of cooling water

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Well doublet ground-source heating and cooling systems are rapidly becoming a popular alternative to conventional heating and cooling systems in the UK, principally due to the substantial reduction in carbon emissions which can be achieved. The sustainability of such systems, and their expected lifetime, is largely governed by the fate of the waste heat following re-injection into the aquifer. Numerical modelling using the reactive transport model SHEMAT (Simulator for HEat and MAss Transport), has been undertaken to determine the feasibility of a groundwater based cooling scheme to remove heat generated by a UK laboratory. The proposed scheme involves the use of groundwater, pumped from a single abstraction borehole drilled into a sandstone aquifer, to feed a heat exchanger cooling system with re-injection back into the aquifer via three injection boreholes. A series of simulations have been undertaken to determine the optimum configuration of the abstraction and recharge boreholes in order to minimise the effects on the aquifer. To prolong the thermal breakthrough time at the abstraction well, it is concluded that the abstraction borehole must be located up the hydraulic gradient from the three recharge boreholes. It is predicted that a cooling load of 3 MW is achievable.

Numerical groundwater flow and heat transport modelling of a large open loop geothermal system in London

Mark Gropius & Zeb Etheridge, Zenith International Ltd., 7 Kingsmead Square, Bath BA1 2AB

The Greater London Authority planning requirement for 10% of building energy to be obtained from renewable sources has led to extensive development of open loop geothermal systems in central London.

Open loop geothermal systems are used for building heating and cooling with varying energy loads and balances over an annual cycle.

Numerical groundwater flow and heat transport modelling is a useful tool for predicting the hydraulic and thermal impacts of such schemes in order to investigate whether proposed schemes are likely to impact on existing licensed abstractions or other open loop systems and whether thermal interference is likely to reduce the efficiency of the system over time. Potential hydraulic impacts can also be assessed as part of this process.

The presentation will focus on case studies showing and discussing the results of the feasibility stage numerical modelling of open loop geothermal scheme with up to 10 borehole pairs within the London Chalk as well as a validation of the modelling results against data from an operating open loop scheme.

Sustainability and licensing issues will be addressed, as along with geological and numerical issues.

Open ground energy systems in the Chalk aquifer of central London – methods of understanding and interpreting the impact of fracture flow

Ryan Law, ARUP & University of Birmingham

A significant number of open ground energy systems are under construction in central London, the majority of which use the Chalk aquifer as a water source. Current Environment Agency regulation stipulates that such schemes within London must re-inject a significant proportion of the abstracted water back into the aquifer. This water is at a different temperature to the aquifer and, if the system is to continue functioning in the long term, must not interfere with the temperature of the water at the abstraction borehole/s.

Groundwater flow within the Chalk is predominantly through fractures. The nature of the fracturing and thus the thermal transport beneath a proposed site will be variable. One approach to predicting the long term behaviour of a proposed open system has been to treat the chalk aquifer as a homogenous medium. However, this method may not be appropriate for all sites and may lead to inaccurate predictions of thermal breakthrough times at the abstraction borehole/s. The nature of the thermal transport beneath any proposed site must be properly understood and interpreted before any ground energy system is put into operation.

This paper discusses two methods that were used to assess a proposed open ground energy system in central London

1) Tracer testing – Fluorescein transport between an injection and abstraction borehole.
2) Thermal testing – The injection and abstraction of heated water within a single borehole.

Preliminary results suggest that the flow beneath the site is dominated by a small number of relatively large fractures. The implications of this have been analysed using numerical models that take into account the nature of the fracture flow and the results used to design an appropriate system for the site.

Groundwater cooling at the Royal Festival Hall, London

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Acknowledgments: Stephen Wells (Lend Lease Projects), Steve White (Max Fordham LLP) & Ian Blackburn (South Bank Centre)

A heated groundwater extraction - injection trial was undertaken over a five week period in June – July 2007 at the Royal Festival Hall on London's South Bank. The trial was jointly funded and managed by London Underground Ltd and the South Bank Centre to inform design development for groundwater assisted cooling using water drawn from and returned to the Upper Chalk aquifer.

Cooling systems which extract groundwater from the Chalk Aquifer and discharge the effluent (warmed) water to surface water courses are an established and proven technology in Central London and elsewhere. This kind of system has been operating successfully at the Royal Festival Hall since 2004 providing in the region of 1.2MW of cooling. There is, however, an upper-bound limitation on the number of these kinds of cooling systems which can be operated in a sustainable way. In view of this and in response to heightened interest in groundwater assisted cooling, the Environment Agency now requires that proposed groundwater cooling schemes consider returning some or all the groundwater to the originating aquifers.

The operation of hydraulically balanced groundwater cooling systems in London and elsewhere in the UK is a largely unproven technology and there exist some significant uncertainties with regard the optimum design and long term operation of such systems. The trial at the Royal Festival Hall utilised two existing abstraction wells (144m apart) and existing heat input sources to simulate the operation of a hydraulically balanced groundwater cooling system of approximately 300KW over a period of five weeks. Following a day of step testing, a constant rate extraction – injection test was carried out continuously over a 4 week period at an average flow rate of 8.3 l/sec. The ambient groundwater temperature was 14ºC and the average temperature of injected water was 24ºC. Throughout the trial temperature was monitored continuously at the extraction well, the injection well and interconnecting pipe-work for direct measurement of heat input and detection of heat breakthrough at the extraction well. Groundwater movement between the extraction and injection wells was simulated using fluorescein and sodium chloride tracers. Tracer breakthrough occurred within approximately 6 hours.

The Royal Festival Hall trial addresses some fundamental uncertainties relating to the design and long term operation of hydraulically balanced groundwater cooling systems in the Chalk Aquifer. The trial has informed upon the mode and vigour of heat dissipation in the Chalk aquifer in response to sustained heat injection; optimum spacing between extraction and injection wells; and hydraulic response and head changes within the extraction and injection boreholes.

Modelling of groundwater cooling schemes in London

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The Tunnel Cooling Programme was set up to implement London Underground's intention to mitigate future heating of the underground system and to reduce platform temperatures to a maximum of 29°C. As part of this programme, proposals have been developed to use groundwater from the Chalk as one of the options for tunnel cooling. The Environment Agency considers the water resources of the Chalk aquifer in London to be broadly in balance at present, thus the proposals are for non-consumptive use of the water: the abstracted groundwater will be passed through cooling pipework within the Underground tunnel network and returned to the aquifer via injection boreholes.

It is currently envisaged that groundwater cooling solutions could be used at about 20 stations, mostly in central London. It is certain that some of these locations will interact hydraulically and possibly also thermally with each other. There are also a few existing groundwater cooling schemes, with a significant number of similar schemes under consideration. It is likely that the current London Underground proposals will interact hydraulically and thermally with some of the existing or future schemes.

London Underground has been commissioned a programme of groundwater modelling to assess the potential hydraulic and thermal effect of these proposed schemes. This presentation provides an overview of the approach to modelling taken and some of the interim findings in terms of critical factors that need to be taken into account when modelling the groundwater system under London and the key parameters that are likely to control the long term efficiency of such schemes.

Thermogeological risk assessment

James Dodds, Lee Clarke & John Findlay (CarbonZero Consulting)

We have experienced a degree of misconception within the building services industry that any amount of heating or cooling energy can be obtained from a ground source, whether it is an open or closed loop scheme. In assessing sites at an early stage of project development it is important that the thermogeologist gives confidence to the building services designer on the sustainable energy availability at the site. The building design process may need to evolve to match that energy availability.

Within the field of hydrogeology there is long experience of the impact of abstraction and recharge of water, and the risk associated with contaminants. Such a legacy of experience does not exist within the field of UK thermogeology and the recharge of heat or coolth. Within the developing regulatory regime relating to ground source heating and cooling in the UK, the assessment of the risk of impact on the wider environment and other beneficial users of water is increasingly important.

In fact, as in groundwater development, the energy availability of and risk of a ground source scheme will be dependent on the hydraulic properties of the underlying strata together with their thermal properties. The values of hydraulic characteristics are statistically log normally distributed, with hydraulic conductivities ranging over 6-7 orders of magnitude, while those of thermal properties are distributed over only one order of magnitude. Therefore errors in hydraulic parameter estimation have a far greater effect on both the energy availability and the risk assessment than those in thermal parameter estimation.

This paper will examine the principal areas of risk that relate to open loop systems and the tools that are readily available for assessment. The risk will be described in terms of consequence and probability and this will be used to discuss the level and focus of any particular assessment.

Discussion also focuses on the natural controls that define the practical limits of energy recovery and the processes and design considerations that interact to increase or decrease the energy availability, such as doublet separation and hydraulic characterisation. The paper will be illustrated by UK case studies relating to different geological settings and aquifers, undertaken within the last 12 to 18 months.

Based on the presentation the need for better tools will be discussed.

Lessons from London

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Much of the Environment Agency's recent experience of Open Loop Ground Source Heat Pumps (GSHPs) has come from the increasing number of systems being installed into the Confined Chalk of Central London. Information collected through a Consent to Investigate a Groundwater Source demonstrates the likely well yields and the impact on other protected rights or water bodies, data which is then included in an abstraction licence application. Due to London's licensing polices, the majority of systems return heated water back to the aquifer, thus requiring a Discharge Consent. Consented activities must therefore also provide enough information to examine the effects of re-injecting heated water into the Confined Chalk in order to gain a Discharge Consent.

In the last three years, valuable lessons have been learnt as the Environment Agency has had to adapt existing processes to manage the environmental impacts of these systems. For example, consented re-injection tests have resulted in a revised approach to the types and lengths of test pumping. However, as GSHPs increase in number and proximity within London, applications become increasingly complicated for both the applicant and the Environment Agency. It can be concluded that the granting of future licences and consents will depend upon the quality and thoroughness of supporting assessments.
