Development of new ground loop sizing tools for domestic GSHP installations in the UK

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ABSTRACT

Commercially available software packages for designing closed-loop GSHP systems, such as Earth Energy Designer (EED), Ground loop designer (GLD) and GLHEPRO have been available in the UK for some time. However, these are rarely used by domestic ground-source heat pump installers owing to their complexity and availability. Until recently, installers were therefore dependent on specialist thermogeologists, manufacturers, or rules of thumb learned through experience or other sources. Consequently, when a UK field trial of domestic ground-source heat pumps showed that several systems were operating with excessively cold ground loops within four years of being installed, the UK Government and the GSHP industry identified a need to develop conservative design tools that were simple to use and readily available. A paper-based design methodology for closed-loop GSHP systems of less than 45kW heating capacity has now been brought into service through the UK Microgeneration Certification Scheme's Microgeneration Installer Standard for heat pumps MIS3005 (MCS 2012). The sizing methods for boreholes, horizontal loops and Slinkies encompasses the diverse geologies, and full extent of both ambient and ground temperatures encountered throughout the UK, over a range of domestic load factors. Supplementary guidance has also been provided on the hydraulic design of these closed-loop systems. This paper describes the underlying philosophy behind the new design tools and how the multi-dimensional task of sizing a ground loop was reduced to 3-dimensional set of tables that UK ground source heat pump installers could begin using with minimal training. With domestic GSHPs designed to these guidelines, or better, the intention is that future installations will meet the performance requirements of both the UK's Renewable Heat Incentive (RHI) scheme and the EU RES directive for renewable energy from heat pumps.

1. INTRODUCTION

For a variety of reasons, the UK has been a late adopter of ground source heat pump technology (GSHPs) (Curtis 2001). In recent years, with wider recognition of the technology, and with incentives from the "Clear Skies" microgeneration scheme, the EEC (Energy Efficiency Commitment) and CERT (Carbon Emissions Reduction Target) utility backed schemes, and the "Low Carbon Building Programme", the number of installations began to rise, to a level of about 4000 per annum. In numerical terms most of these were in the domestic sector, ranging in size from 3.5kW$_{th}$ in social housing installations to ~16kW$_{th}$, a limit determined by the single phase 230VAC electrical supply that is the norm for UK housing.

In 2008, the Energy Saving Trust, together with industry stakeholders, initiated a one year monitoring exercise on ~80 domestic heat pump installations, distributed throughout the UK (EST 2010). This study included 48 GSHP systems, and as well as monitoring the performance of the systems, also incorporated work by Open University researchers on user satisfaction and experience. Some of the data in this monitoring exercise has subsequently been reworked, and an updated report has been published by the Department of Energy & Climate Change (DECC) (DECC 2012). The exercise had two major outcomes:

i) it suggested that many UK domestic heat pump systems included in this monitoring study, were not performing as well as would be expected,

and

ii) that there were serious shortcoming in the selling, design, installation and operation of these systems. It was decided to extend the monitoring programme for an additional year, with remedial measures being undertaken on a number of the installations in an attempt to see if their performance could be improved. The monitoring was concluded in 2012, and a final report on the overall monitoring experience will be published later this year (ie 2013).

In the UK, the evolution of incentive schemes for microgeneration systems (ie domestic solar thermal, solar PV, micro-wind, small biomass and heat pumps) has been carried out in parallel with the development of UK national "standards" for the selling, design, installation and operation of these systems. The government has wanted to ensure that in providing fiscal support for these technologies, domestic customers will receive properly designed and installed, effective systems that will meet the required renewable energy and/or carbon targets. These standards have been developed under the Microgeneration Certification Scheme (MCS). See:

(http://www.microgenerationcertification.org/mcs-standards/mcs-standards)

Because the UK government is keen to promote a rapid acceleration in the installation of heat pumps in the UK as part of its 2030 and 2050 decarbonisation targets, DECC decided that the shortcomings shown up in the EST monitoring study needed to be rapidly addressed. A DECC technical working party, drawn from the UK heat pump industry, was established in February 2011 whose objective was to revise or expand any parts of the MCS process that applied to heat pumps, with a view to improving domestic heat pump performance, and the user experience.

The major areas that were identified for consideration for all heat pumps were:

i) the assessment of building energy loads - both in terms of worst day heat loss, and in annual energy consumption (of particular importance for GSHPs).

ii) the selection and sizing of appropriate heat emitter systems for use with heat pumps

and specifically for GSHPs

iii) the sizing of ground loop arrays

iv) the design of the hydraulic performance of closed loop ground arrays - to minimise parasitic pumping energy.

The working party needed to work rapidly and was only in existence for a period of six months. It managed to achieve a significant amount of development work in terms of revised MCS guidance and design documentation. Interested readers will find the revised versions of the GSHP related MCS documents on the UK Ground Source Heat Pump Association's web site:

(http://www.gshp.org.uk/pdf/MIS_3005_Heat_Pump_Systems.pdf)

As well as revised guidance provided in the heat pump design document MIS 3005, three other documents have been generated:

i) an emitter design guide,

(http://www.gshp.org.uk/pdf/MIS_3005_Heat_Emitter_Guide.pdf)

ii) ground loop sizing charts,

(http://www.gshp.org.uk/pdf/MIS_3005_Ground_loop_sizing_tables.pdf)

iii) hydraulic pressure loss design charts.

(http://www.microgenerationcertification.org/images/GSHP_Hydraulics_Design_Guide_v1.0.pdf)

This paper specifically addresses the development of items ii) and iii) which are of relevance to domestic closed loop GSHP systems.

(All of the MCS documentation, for the various microgeneration technologies can be found at: http://www.microgenerationcertification.org/mcs-standards/mcs-standards)

2. GROUND LOOP SIZING

2.1 Previous practice

In the absence of any UK guidance documents or standards, installers of domestically sized closed loop GSHPs systems used several approaches to designing ground arrays:

1) In some cases, design software such as the US based GLHEPRO from the International Ground Source Heat Pump Association (IGSHPA), and the European based EED (Earth Energy Designer) has been used by the more knowledgeable designers. In more recent years the US based GLD software from Gaia Geothermal has been adopted in the UK. Whilst GLHEPRO and EED are reasonably low cost, they may be beyond the reach of small companies, but more importantly they are too complex for them to use, at least without a significant investment in training. In the case of GLHEPRO the heat pump libraries do not include data on European heat pumps, although this can be added. Gaia Software have begun to include data on a significant number of European heat pumps into GLD. EED does not provide a heat pump model, but relies on the designer inserting a required SPF.

2) In a few rare cases, designers have made use of CLGS, the US based domestic design software from IGSHPA. This package can be used for small borehole based, U-tube systems and for North American style 2, 4, 6 pipe-per-trench horizontal systems. The disadvantage is that it uses Imperial units, requires bin style temperature data (°F!) which is not commonly available in the UK, and does not include data on European heat pumps.

3) VDI 4640 (VDI 2001) is either used directly, or has been adopted and adapted by a number of European heat pump manufacturers and incorporated into their own technical design manuals, eg Viessmann, Dimplex, Stiebel Eltron.

4) Other manufacturers (primarily Scandinavian) provide in-house design tools for their installers.

Whilst codes such as EED, GLHEPRO and GLD are extremely flexible, they are dependent on the correct input data from the designer, and the number of variables to be considered is far more complex than the designer of small domestic systems is generally familiar or comfortable with.

The issue of concern around VDI 4640 and design tools provided by European manufacturers was whether these had been designed for use in UK conditions of geology, climate and building design. Specific issues associated with VDI 4640 are the use of double U-tubes in boreholes, a practice which is not common in the UK for small domestic systems, the variability in the allowed minimum Entering Water Temperature, (EWT) (ie to 10°C below the equilibrium ground temperature), and queries over the design depth for horizontal systems, and the associated annual temperature swing.

2.2 Underlying philosophy

It was decided that a sizing methodology would be developed that encompassed borehole and trench based closed loop GSHPs, up to 45kW (heating/hot water only), under all UK geological and climatic conditions.

The system would be paper based, and would produce a conservative design. The approach being that if an installer rigorously followed the procedure, they would be assured of a GSHP system that would deliver a satisfactory SPF. Designers with more sophisticated knowledge or with access to, and an understanding of, ground loop sizing software, would in principal be able to achieve less conservative (and possibly lower cost) systems. Thus the objective was to provide an "open source", non-proprietary, freely-available design tool that would allow any installer to design a GSHP system up to 45kW that would deliver a satisfactory performance, anywhere in the United Kingdom. There is complete independence from any computer operating system, computer hardware, software or software versions, which isolates the MCS delivery organisation from any future software or hardware "upgrade" issues.

In principle the methodology would be suitable for software or at least spread-sheet style adaptation. It is also possible that the approach adopted here could be replicated to other "national" climates and geologies, both within the EU and beyond.

The ground loop sizing tables would be the additional design item that is required for GSHP design, above and beyond design principles required for air source heat pumps. The methodology now laid down in MIS3005 is:

1) Determine the worst day heat loss of the property, and the annual load factor (or full load equivalent run hours). This has to be done using a room-by-room heat loss sizing calculation based on EN12831

2) Select the heat emitter system using the Heat Emitter Guide (specifically developed as part of this working party). This guide has been developed to cover underfloor heating, radiators and convector radiator heat emitters and is designed to assist an installer in explaining to a potential customer the improvement in operating efficiency (SPF) that can be achieved by using lower temperature emitter systems. The chart provides the designer with the expected space heating SPF of the system.

3) Select a heat pump that can meet 100% of the total worst day heat loss of the property (in kW) for 99% of the hours in an average year. (Note that it is now a requirement, under the MCS standard, that mono-energetic domestic heat pumps have to be sized to meet the worst day heat loss of a property. This is to prevent significant increases in electrical demand at times of cold weather, and to achieve reasonable SPFs and running costs. Only bivalent systems that use non-electrical heat sources can employ heat pumps sized to less than 100% of worst day heat loss.)

4) From the desired SPF in the heat emitter guide, and the thermal power of the selected heat pump, the designer can compute the required heat extraction rate required from the ground for a GSHP system.

Thus the objective was to generate charts (at least initially) for single U-tube borehole systems, horizontal systems and Slinky systems, that provide the permitted ground extraction rates from which a designer can compute the size of a ground loop array (ie total borehole length, total horizontal loop length, or total length of Slinky pipe and trench.)

For all systems, the minimum ground loop entering water temperature to the heat pump from the ground (EWT) is required to be not less than 0°C after 20 years of operation.

This was adopted to ensure that good, long term SPF's are achieved by GSHPs, and to ensure that installers cannot gain significant competitive advantage by designing (lower cost) systems with shorter ground arrays that operate at significantly lower EWTs.

The major variables that have to be addressed are:

i) Thermal conductivity

ii) Ground "rest" or "equilibrium" temperature

iii) Required annual energy delivery, eg load factor / Full Load Equivalent run hours.

After investigating relationships between the variables in this multi-dimensional space, it was decided that it was possible to produce tables for a given annual load factor, that relate the permitted ground heat extraction rate to the mean ground temperature, and the ground thermal conductivity.

Given the significant impact that the annual thermal energy requirement has on the size of ground loops, an initial exercise looked at the potential impact of different load profiles in the UK environment. Load profiles for three UK locations, Plymouth, London and Aberdeen were generated, for heating only and for heating and hot water generation. It was found that the variation in the shape of these annual load profiles, for domestic heating GSHPs, was relatively minor, compared to the much larger impact of the total annual energy requirement. In all of the work that followed, a common annual load profile was adopted for a set of annual full load equivalent run hours (FLEQs) of 1200, 1800, 2400, 3000 and 3600 hours.

2.3 Boreholes

Determining the permitted extraction rates for borehole based systems was more straightforward than for the horizontal options.

2.3.1 Borehole fixed parameters:

HDPE single U-tube 32mm OD, SDR11 with a thermal conductivity of 0.420W/mK. 52mm pipe centre-to-centre shank spacing.

130mm diameter boreholes. Thermal resistance of borehole/grout/U-tube completion 0.1 mK/W

6m minimum spacing, boreholes in a line.

25% mono-ethylene glycol heat transfer fluid. Re > 2500 in active elements of ground loop array.

2.3.2 Borehole variable parameters:

Mean ground temperature: 6.0°C to 15.0°C

Ground conductivity: 1.5 - 4.5 W/m/K,

Load factors: 1200, 1800, 2400, 3000, 3600 full load equivalent (FLEQ) run hours.

The borehole values were computed with these parameters using GLHEPRO, and EED. A selection of the results were cross checked with results both from GLD, and from VDI 4640 (albeit with a correction factor for double U-tubes vs single U-tubes). The values derived from the code runs were then transformed into the sizing tables using an extrapolation algorithm developed in MATLAB. An example of a completed Borehole Heat Extraction Table is shown in the Appendix, Figure A3.

2.4 Horizontal / trenched systems

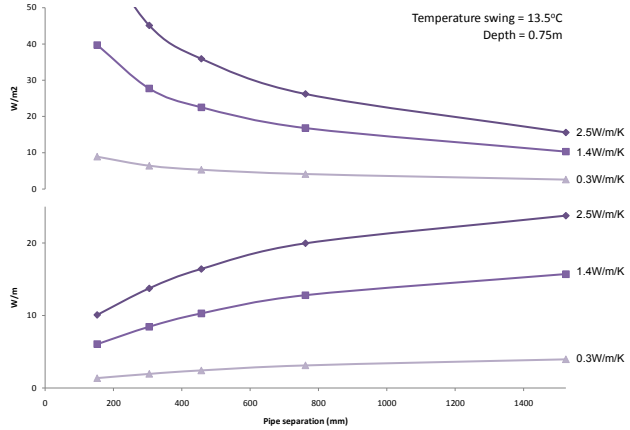
The permitted heat extraction values for horizontal systems were more difficult to generate because there are additional parameters and design considerations compared to boreholes. As well as ground equilibrium temperature, data is required on the annual temperature swing. In addition the designer could vary the depth and spacing of the pipework. In order to keep the number of tables to a practical minimum, the variance in these parameters was investigated.

Whilst there is no underlying physical relationship, a review of data from the UK Meteorological Office suggested that there was at least an approximate linear correlation between annual average temperature (and hence ground equilibrium temperature) and the annual temperature swing (Appendix, Figure A1). It was therefore decided to eliminate annual temperature swing as a variable, but to take account of it over the range of ground equilibrium temperatures adopted for the UK tables. The linear relationship shown in Figure A1 produces conservative designs in most cases.

An investigation was also carried out into the optimal depth placement for horizontal pipework. There was concern that calculation methods developed for the US, Canada or Scandinavia could have adopted allowances for snow cover in the winter. This encourages the use of shallower depths to take advantage of solar input in the summer, whilst being insulated by snow cover in the winter. This does not apply to the UK as the period and extent of any snow cover is generally very limited. The series of graphs shown in Figure A2 in the Appendix illustrates the complex variation in predicted extraction rates for a range of thermal conductivities, at different depths, for differing swing temperatures. After investigating the optimal placement depth based on thermal performance, primarily driven by a combination of ground equilibrium temperature and annual temperature swing, it was found that practical considerations vis-a-vis depths of other services (eg water electricity, cable, telephone etc), protection from other shallow ground excavations, frost protection and Health and Safety requirements, indicated a depth of 0.8 - 1.2m for developing the horizontal tables. This is an example where a designer with access to more sophisticated modelling software, and knowledge of the local temperature swing, may be able to come up with a more optimal (possibly lower cost) solution.

Investigations were also made into the variation in extraction rate, either as a W/m value or a W/m^2 value, with horizontal pipe spacing. This exercise revealed issues relating to the computation of the "effective area" to be used for a W/m^2 calculation, and is why the Tables give a W/m of pipe length value for horizontal pipes, for a specified pipe separation, rather than a W/m^2 value. Figure 1 is an example, generated during this study, of the variation in extracted W/m or W/m^2 values for a range of pipe separations, at different thermal conductivity values.

Figure 1: Horizontal loops: variation in predicted heat extraction rates with separation distance, for a range of thermal conductivities.



The horizontal pipe extraction values were generated using the IGSHPA CLGS code, with cross checks being made against VDI 4640 in the parameter space where the latter overlays the work described here.

The more difficult exercise was in the generation of values for Slinkies. The only code that the authors are aware of that treats Slinkies is GLD. They are not covered by VDI 4640. Upon investigation, it appears that the method used in GLD is based on the technique described in the IGSHPA Slinky Installation guide (IGSHPA 1995) which employs a modified form of the algorithms used in CLGS for horizontal pipework.

After an exploratory study, it was concluded that it was possible to represent a Slinky in the CLGS code as four equally spaced pipes with a separation of d/3 between pipe centres, where d is the diameter of single Slinky loop (Figures 2a and 2b).

Figure 2a: Slinky geometry

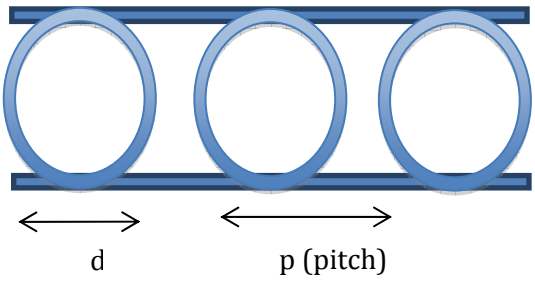
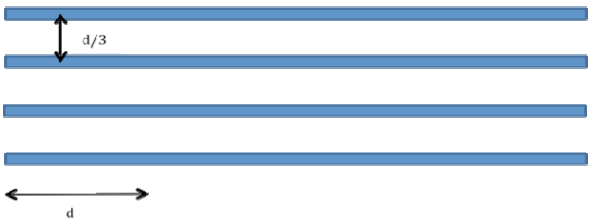


Figure 2b: Equivalent horizontal loop geometry



A comparison was made of horizontal and vertical Slinkies, pitch, and trench separation. Modelling of Slinky geometry is not straightforward, and all of the work carried out here was done within the confines of the analytical modelling employed in CLGS. However, there are some interesting mind exercises that can be undertaken when exploring the extremes of pitch. At a pitch of zero, the installation simply becomes a coil, or roll of pipe in the ground. In this configuration there are obviously extreme cases of pipe overlap, with only the two extreme (ie outer) coils actually being in contact with the ground. At the other extreme, ie as pitch tends to infinity, there is minimal pipe cross over and practically all pipe is in contact with the ground. Comparisons were made with analogous horizontal pipe layouts in order to develop consistency between the Slinky and horizontal loop sizing values. In this case the extraction tables are quoted as W/m of trench length for a specified pitch and loop diameter.

Once again, designers with access to more sophisticated modelling software may be able to arrive at ground loop arrays based on different Slinky geometric parameters.

Having explored the factors affecting the design of these <45kW heating only, closed loop GSHP ground arrays, the sizing tables were generated for single-U boreholes, horizontal loops, and Slinkies,

2.4.1 Horizontal and Slinky fixed parameters:

25% mono-ethylene glycol heat transfer fluid. Re > 2500 in active elements of ground loop array.

Horizontal pipe: 25mm OD MDPE SDR11, horizontal pipe spacing at least 0.75m, pipe depth 0.8 - 1.2m

Slinkies: 32mm OD MDPE SDR11. Trench spacing at least 3m. Mean slinky depth 0.8 - 1.2m. Pipe length to trench length ratio at least R > 4. (For 900mm diameter = 1250mm pitch)

2.4.2 Horizontal and /Slinky variable parameters:

Mean ground temperature 6.0°C to 12.0°C

Ground conductivity: 0.4 - 2.4 W/m/K

Load factors; 1200, 1800, 2400, 3000, 3600 full load equivalent (FLEQ) run hours.

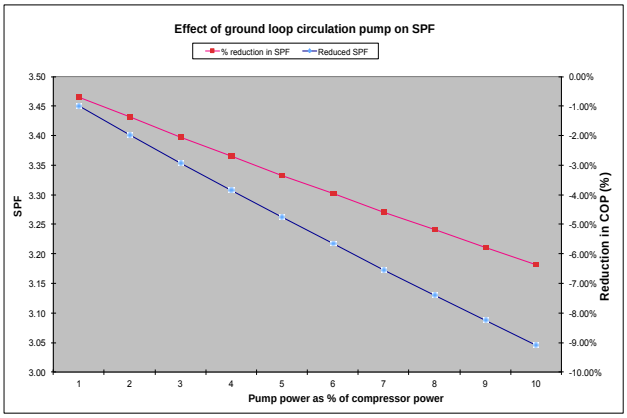
Examples of completed Horizontal Loop and Slinky Heat Extraction Tables are shown in the Appendix, Figures A3 and A4.

3. Hydraulics design

Having prepared the ground loop heat extraction tables, it was recognised that an additional topic that needed to be addressed was in the hydraulic design of closed loop GSHP ground arrays. Systems were being encountered where the parasitic pumping energy of

the ground loop pump was significant, and badly affecting the SPF of the installation. For many designers this appears to be a neglected component of the design. Figure 3 shows the impact on the SPF of a heat pump with increasing power of the ground loop circulating pump as a fraction of the heat pump compressor power.

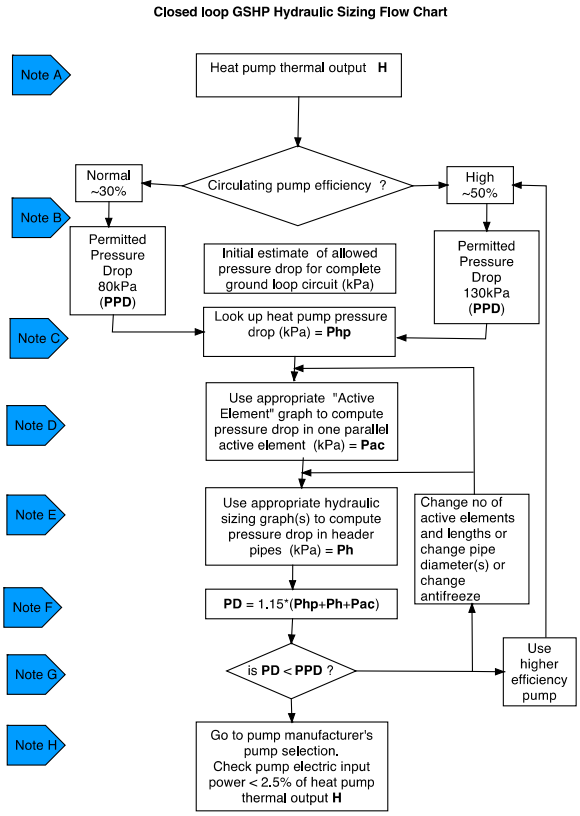
Figure 3: Impact of ground loop circulation power on overall SPF of a GSHP system



To address this, it was decided, using the same reasoning as was applied to the Heat Extraction Tables, to develop a paper based sizing procedure for the hydraulic design of closed loop GSHP systems up to 45kW$_{th}$.

The guidance document combines an iterative flowchart based design process, with paper charts giving head loss vs flow rates for commonly used pipework that make up the various ground loop elements. The underlying requirement is to achieve a minimum head loss across the entire ground loop array, whilst maintaining turbulent flow (Re>2500) in the thermally active elements of the array. The overarching flow chart is shown in Figure 4, which points at two further flow charts, one for the thermally active components and one for the header components. An example of a head loss chart is shown in the Appendix, Figure A6. The design guide (available at: www.microgenerationcertification.org /images/GSHP_Hydraulics_Design_Guide_v1.0.pdf) has been developed for three heat transfer fluids, viz monoethylene glycol to freeze protection levels of -10°C and -15°C, and mono propylene glycol to a freeze protection level of -10°C. The charts provide pressure drop values for active elements constructed from 25mm, 32mm and 40mm OD, SDR11 and SDR17, and for header pipework in 25mm, 32mm 40mm, 63mm and 90mm SDR11 and SDR17. These encompass practically all of the pipework sizes used in domestic systems up to 45kW$_{th}$.

Figure 4: Main flow chart from the Hydraulic Design Guide.



Conclusions

Following the deliberations of the DECC working group and after review and approval from the MCS committees, the MCS Microgeneration Installer for heat pumps, MIS2005 was revised and reissued in September 2011. A series of awareness days and training sessions were carried out to make existing heat pump installers aware of the significant changes that have been incorporated into the new guide.

It is hoped that the implementation of these new guidance document will result in an overall improvement in the performance of newly installed domestic heat pumps systems in the UK. DECC is currently running a large-scale heat pump monitoring exercise based on experience gained during the EST monitoring project. The objective is to demonstrate whether heat pump installations are now capable of meeting the target requirements of both DECC and the EU RES directive in terms of delivering low carbon renewable heat at a reasonable running cost to users. This will also provide information that the Government can use to evaluate the anticipated value for money of the domestic Renewable Heat Incentive (RHI) for heat pumps

In generating the GSHP heat extraction tables described here, it is believed that a robust basis has been put in place for evaluating how ground loops can be sized for the climatic and geological conditions that arise throughout the whole of the UK. It will now be possible to test sizing methodology and software from various other sources to check that that they also cover all conditions of relevance to the UK. It is suggested that the methodology adopted here could be replicated to other countries within the EU, and beyond.

The entire set of new design documents (ie MIS 3005 and related) have now been in use for over a year. A number of comments and queries have been received, but so far no major flaws have been reported. It is anticipated that any comments will be taken into account, and some of the basic design requirements may be reviewed. For example, there is a possible case to be made that a minimum EWT of 0°C could be relaxed for GSHP systems with low load-side temperatures. It is also possible that the various heat extraction and hydraulic tables will be expanded to cover other pipework layouts and geometries.

Given the requirement for EU-wide training and certification for GSHP installers as called for in the EU RES directive, There may be useful lessons to be incorporated from this exercise into schemes such as GEOTRAINET and EUHP Cert.

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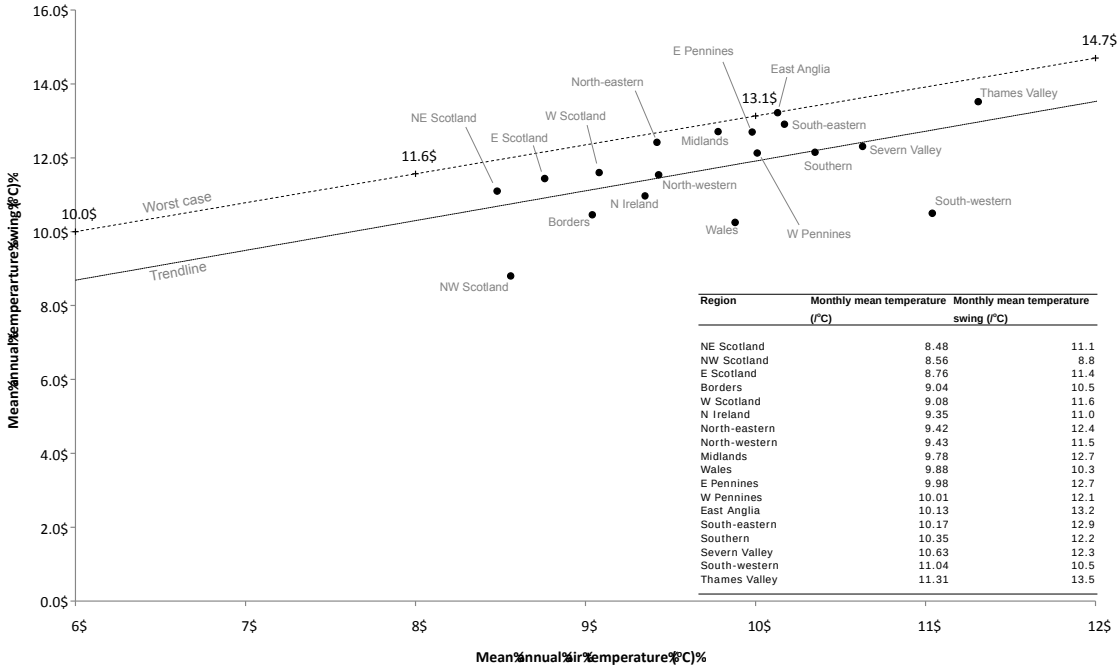
The authors would like to acknowledge the assistance provided by other members of the DECC technical sub-group that was established to revise the MCS domestic heat pump design and installation documents.

APPENDIX

Figure A1: Collection of UK locations showing mean annual air temperature, and annual temperature swing.



Region	Monthly mean temperature (°C)	Monthly mean temperature swing (°C)
NE Scotland	8.48	11.1
NW Scotland	8.56	8.8
E Scotland	8.76	11.4
Borders	9.04	10.5
W Scotland	9.08	11.6
N Ireland	9.35	11.0
North-eastern	9.42	12.4
North-western	9.43	11.5
Midlands	9.78	12.7
Wales	9.88	10.3
E Pennines	9.98	12.7
W Pennines	10.01	12.1
East Anglia	10.13	13.2
South-eastern	10.17	12.9
Southern	10.35	12.2
Severn Valley	10.63	12.3
South-western	11.04	10.5
Thames Valley	11.31	13.5

Figure A2: Example graphs showing variation in horizontal loop ground extraction rate with temperature swing, depth and thermal conductivity.

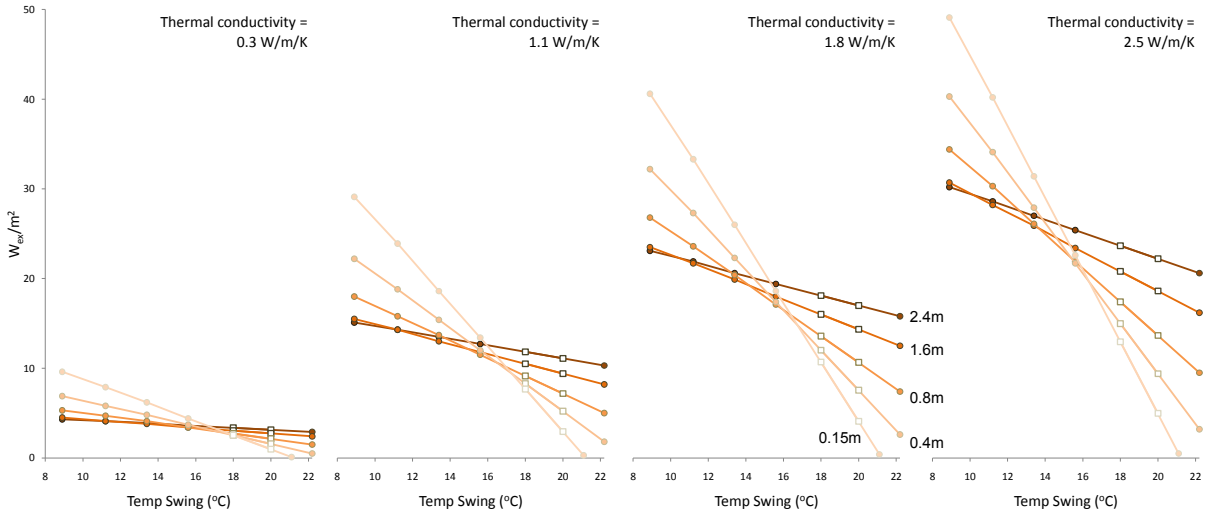


Figure A3: Borehole heat extraction table as published in MIS 3005 for 2400 FLEQ hours load.

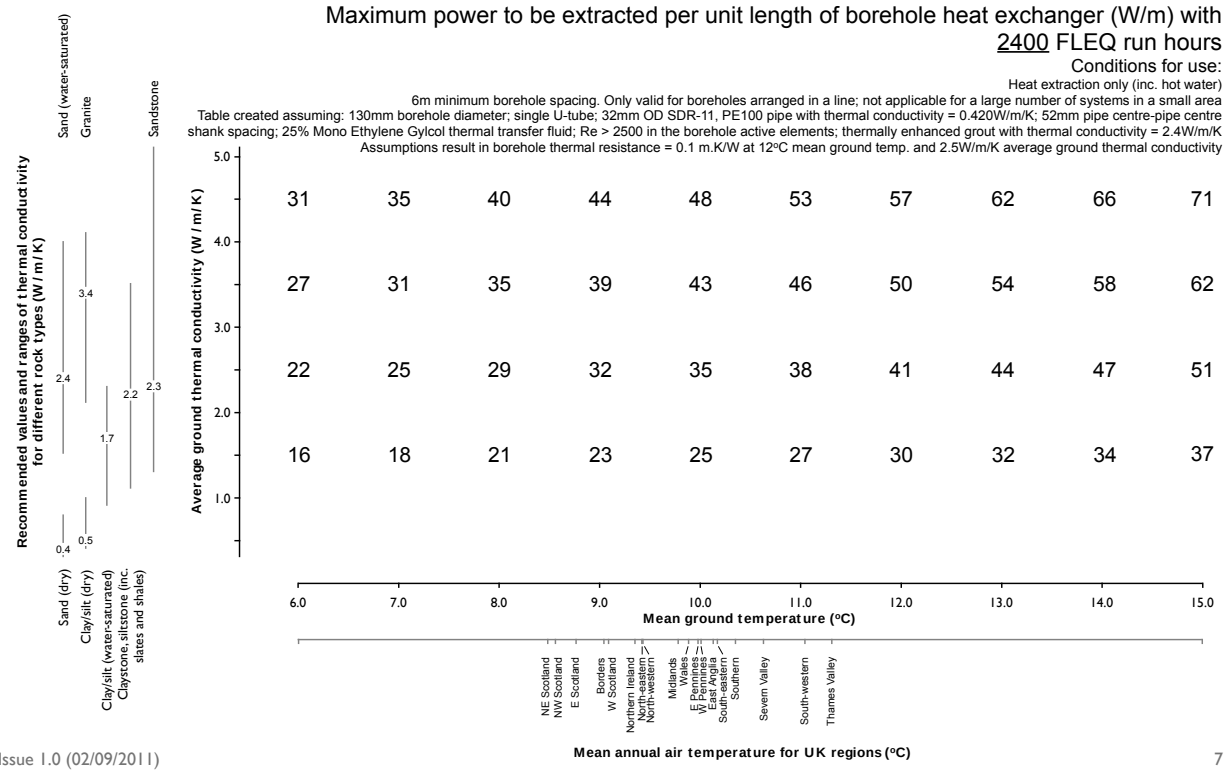


Figure A4: Horizontal loop heat extraction table as published in MIS 3005 for 2400 FLEQ hours load.

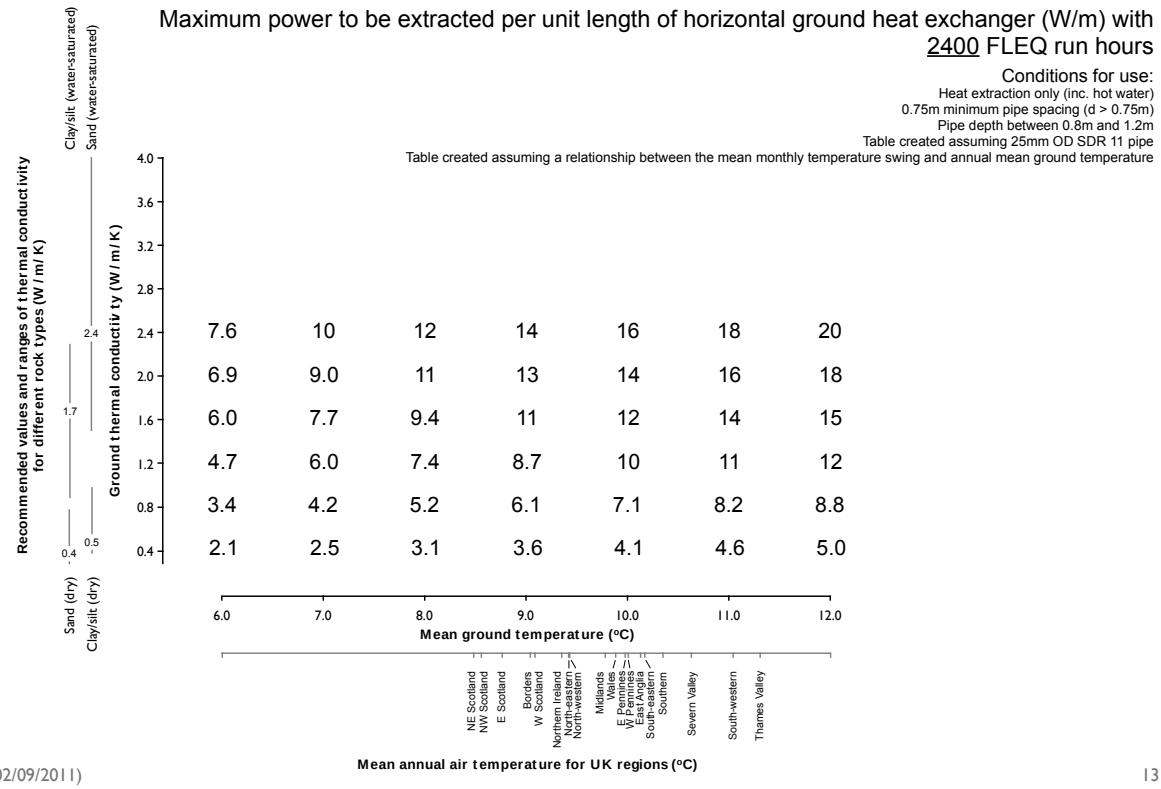


Figure A5: Slinky heat extraction table as published in MIS 3005 for 2400 FLEQ hours load.

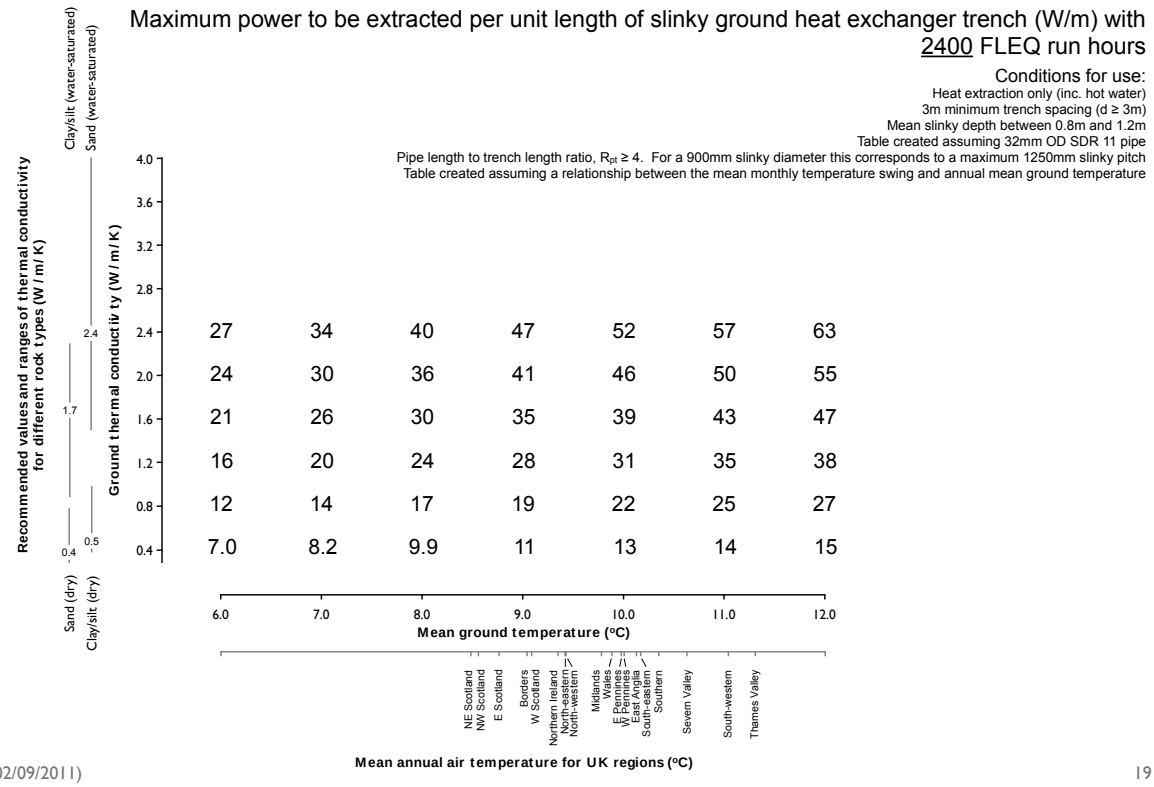


Figure A6: Example of Pipe pressure loss chart for header elements.

