Underground Passenger Comfort
Rethinking the current thermal and lighting standards

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ABSTRACT: This paper examines existing energy-intensive and unsatisfactory methods of cooling and lighting London Underground stations and explores passive and low-energy strategies to improve human comfort. Problematic comfort conditions commonly found in these underground stations include excess heat accumulation, insufficient ventilation, occupancy overcrowding, and disconnection from the outside environment. By making the stations comfortable for passengers, the excess consumption of energy for air-conditioning and artificial lighting can be minimized. Dynamic design solutions can introduce subterranean sunlight at the platform level and modulate the thermal interaction between the indoor and outdoor environments to achieve a comfortable equilibrium. Accompanying the research, analysis of several strategies for improvements to passenger comfort were performed using environmental modelling software. The improved design reveals that daylighting, which can increase human comfort, is feasible during daytime in the underground space year-round. The addition of skylights can illuminate the station, but the horizontal glazing must be balanced with adequate protection from thermal transfer with the external environment. Thermal analysis shows that increasing ventilation can help to cool the thermal mass of the station construction and surrounding soil, help to dissipate internal heat gains, improve passenger comfort, and may replace the need for mechanical systems.

Keywords: comfort, daylighting, passive cooling, underground, passenger

INTRODUCTION

This paper investigates sustainable solutions that can be applied to London Underground stations to improve passenger comfort since mass public transport is vital to the city's ability to support economic activity and tourism. In Central London, passenger surveys and thermal measuring have revealed that underground train stations are thermally uncomfortable, especially in older and deeper tunnels. New air-conditioning (scheduled for installation in 2009) coupled with increasing station occupancies could lead to an increase in the excessive internal heat gains and the degradation of the soil capacity around the tunnels to absorb heat.

HUMAN COMFORT

Environmental factors that effect perception of thermal comfort are: clothing level (varies), metabolic heat production, air movement (0.03-0.05 m/s), relative humidity (40-70%), surface temperature (2-3°C maximum higher than the air temperature), air temperature (18-21°C relaxed, 15-18°C walking), occupancy level, psychological influences, air compression, air pressure. High radiant temperatures can cause discomfort in parts of the body that are close to the surface even when the air conditions are comfortable due to rapidly increasing skin temperatures [4]. Increasing air velocity can improve thermal comfort because it helps to increase the convective heat loss from the body through evaporation of perspiration. In the middle of the summer season, the London outdoor climate conditions are uncomfortably warm (according to the Predicted Mean Vote or PMV of comfort satisfaction of people in their surrounding conditions), which contributes to uncomfortable temperatures in the underground stations. Train generated air movement creates rapid changes in pressure and temperature and can cause discomfort. Dramatic changes in temperature may make a person uncomfortable by disrupting the heat balance and causing the body to make an effort to re-balance it.

THERMAL CONDITIONS

Average outdoor air temperatures in London range from 0°C (December/January) to 32°C (July). The lowest temperatures in the diurnal cycle occur in the early morning when sky cloud cover is generally lowest. Daytime temperature peaks are in the afternoon due to solar radiation. During the winter months, the sunshine hours are much less than summer so the solar radiation has less time to warm the earth and the diurnal temperature differences are smallest. Months that daytime coupling with the outdoor climate could be useful for thermal comfort are April through October, with the exception of July which is too warm. The urban heat island effect adds 5 to 6°C to London's outdoor temperatures [7]. Average wind speeds in Central London are 7 to 15 m/s [9]. Lessening the urban heat island around a building can minimize the effects on the indoor environment. High internal heat gains and low levels of thermal exchange between indoor and outdoor environments result in excessive underground station temperatures. Internal gains can be attributed to metabolic processes of the people inside station, train operation, heat re-radiated from the ground, and station electrical equipment. The lag in the seasonal variation of station temperatures indicates a relationship with the outdoor climate that is modulated by the ground mass. Cut-cover underground train stations (approximately 30 meters below grade) can benefit from more contact with the outdoor environment. At shallower depths, soil is least dense and contains less water than greater depths, thus provides less heat absorption. In the case of a station this may be beneficial because heat can dissipate more quickly during the short time frame that the station is closed. The roof plane is an important element in regulating the thermal gains and losses between the station and the outdoor climate, because in most cases it is the only barrier between the two. It also can create a connection with outdoor natural daylight.

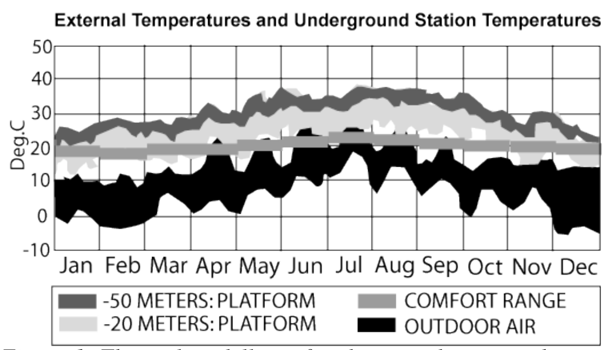

Figure 1: Thermal modelling of underground stations shows a variation in platform temperatures at different depths.

Thermal modelling of underground stations with different depths using TAS shows that the seasonal regression of outdoor climate lessens with an increase in underground depth (Fig.1). Highs of 47°C (32°C outdoors) were reached during the European Heat Wave in 2006 [13], and temperatures regularly top 30°C in the deep tunnels, exceeding the adaptable summer comfort range by 6 to 8°C. Temperatures are typically about 2°C warmer in deeper stations because the soil around them has been absorbing their heat for centuries, so there is a thermal lag of up to three months and a reduced capacity for thermal absorption by the soil. A train arriving on opposite platform creates 2m/s air gusts, and temperature fluctuations upon arrival and departure of trains were up to 5°C. Temperatures average 10°C cooler in corridor than platform. At the beginning of the platform, maximum air velocities of 5.7m/s (6.8m/s at end of platform) are achieved shortly after the train arrives or leaves (suction effect) often also experienced when trains come on the opposite platform [6]. The typical London Underground Station suffers from several negative environmental factors in unison: crowed spaces, low air movement, higher metabolic rates contribute to dissatisfaction with the thermal environment. Evening commuters are faced with higher underground temperatures due to the heat accumulation in the system throughout the day and an increase in passengers. Each of the 18,700 evening passengers emits 90 to 300 watts of heat on average. Higher metabolic rates produce more heat, and in warmer temperatures, more of that heat will be latent whereas in a cooler temperature more of it will be sensible (containing less moisture). The faster the train is moving between stations, the greater the breaking friction and associated heat production. As train velocity doubles, its kinetic energy and braking heat load increase 5-fold, resulting in a tunnel temperature increase of up to 5°C. The platform is very sheltered from the external environment and is insulated by the thermal mass of the surrounding soil. The transition from the exterior climate to the platform climate can be as much as 15°C different. This can be reduced by blocking heat from the trains. The platform has the largest amount of internal heat gains of any zone of the station between the metabolic gains of the people and the heat gains from the train and equipment.

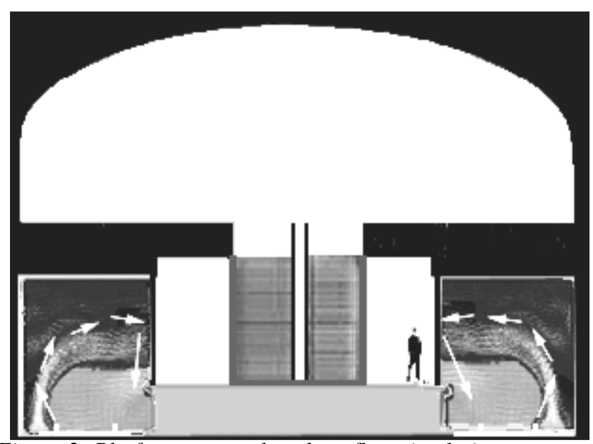

Figure 2: Platform screen door heat flow simulation.

Platform edge doors (Fig. 2) and regenerative breaking are valuable techniques for preventing train associated heat gains from moving from the tunnel to the platform. Combined, these strategies can help to minimize the need for cooling in an underground station. The relationship of the underground station air temperatures to the outdoor climate is similar to a heavily insulated building. The thermal conditions also respond to the fluctuations in the ground temperatures of the surrounding ground mass. The ground composition can affect its thermal storage characteristics. The ground can act as a direct heat sink because the building can be in contact with the effective temperature of the ground [10]. The ground has conductivity of 1.4 to 2.1 W/K*m by appropriate varying density, which is higher than air: 0.025 W/K*m. An increase in conductivity of surfaces in the station can cause a decrease in the internal temperatures. The average ground temperature at 10-20 meters below the surface is 10°C, London's mean annual temperature, which can be useful for passive cooling of the underground stations. The earth surrounding the tunnel is able to absorb up to 30% of the excess heat produced in the tunnels, but the other 70% of the excess heat contributes to passenger discomfort [11]. The ground temperature remains very constant and does not experience diurnal or seasonal temperature swings as the outdoor air does. Temperature changes that do occur as a result of exterior fluctuations are much slighter and experience a lag of up to a month. This slow fluctuation of temperatures can also mean that dissipation of stored heat is a slow process. Accretion of heat stored in the ground around the existing underground tunnels and stations over time has reduced the specific heat of the soil by raising its average temperature. High internal heat gains resulted in exhaustion of the geological capacity around deep level tunnels to "soak up" heat [8]. A study conducted by Ampofo et al. [3] found that the average temperature six meters from tube tunnels is 19°C due absorption of the heat in the tunnels and lack of ventilation to dissipate the high level of gains. ARUP [1] found that a graded track can provide an average of 3°C of cooling over a flat track while extracting high-grade heat at tracks reduced overall station temperatures by about 10°C [1]. Increased surface areas of thermal mass to absorb more internal gains coupled with ventilation of the mass to dissipate gains and prevent accretion of heat can prevent this from occurring in a new station. The use of building materials with a high thermal capacity can help reduce heat transfer into the building by absorbing radiated heat from the sun or other sources of heat.

The existing ventilation equipment is inadequate for removal of internal heat gains from the stations and tunnels. There are currently, 160 ventilation shafts throughout the underground system [13]. With over 220 stations and only 94 ventilation shafts in stations, this means the only 34% of stations are ventilated. There are some common difficulties with natural ventilation strategies. Natural ventilation can either assist or retard airflows depending on the time of year and the difference between outdoor and indoor temperatures. To balance the ventilation entering and exiting the station, air that is close to the outdoor temperature can be supplied in an insulated cool stack and exhausted through a warm stack [10]. This would help to excrete the indoor heat. Ventilation stacks may bring fresh air into the underground space through natural air buoyancy flows. Buoyancy driven stack ventilation through openings in the roof is driven when there is a temperature difference in the tall internal space, which results in different air densities. As cool air falls, it pushes hot air up (and out of the building). As wind falls down the ventilation stacks, can loose heat to the exposed thermal mass and drop in temperature (Peter Schamet Lecture on the Malta Brewery, AA 2007). An increase in platform exits from one to three could improve the cooling of the space, resulting in cooling of over 5°C, and similarly doubling the size of the ventilation shaft from 15m2 diameter to 30m^2 diameter could yield 1°C temperature cooling (ARUP.com). Current strategies of using the movement of the trains for air circulation is also ineffective because it fails if the train were stalled or stopped at a station, and it produces unpredictable wind speeds and directions when the train is moving that can disrupt the natural flow of air for ventilation. Ventilation helps reduce the increase in air pressure caused by trains acting like pistons in the tunnels. With proper exchange of air through ventilation, the interior mass of the underground building could loose heat at night that had been absorbed throughout the day when internal gains were high because the heat stored in the building mass will flow to the cooler indoor air which will become warm and can be convectively ventilated. During the night time, the sky temperature drops below the air temperate (creating a sky temperature depression), allowing daytime heat gains to flow from surfaces through the process of radiation; the atmospheric window near the zenith in clear skies acts as a heat sink, absorbing longwave radiation so it is important that the thermal mass has a good, unobstructed 'view' to the sky. During summer mornings, reducing the rate at which the building warms up can help to preserve the thermal inertia of the cool night sky; this can be done with insulation and limited air exchanges.

SOLAR AVAILABILITY

During the summer months, the average diffused solar radiation in London is greater the direct solar radiation. An overcast sky is brightest in the zenith. Top-lighting will thus give much more (2 to 3 times) daylight than windows in other orientations [5]. A London station can make use of sunlight for less than 50% of their summer hours and less than 10% of their winter hours. Measurements in existing stations have shown that the ticket level achieves illumination levels of 91-311 lux, and the artificially lit platform receives 60-70 lux (Outside: 998-12,900 lux) [2]. In a typical transportation building, reception and circulation areas require an average daylight factor of 2% (low 0.6%).

This requires a minimum illumination of 200 lux, it can be achieved when the outdoor illuminance is 200/.02 = 10 klux. According to the daylight availability curve from the European Daylight Atlas, this can be achieved about 52% of the daily sunlight hours.

VICTORIA STATION PRECEDENT

A low-energy groundwater cooling system like the one trailed at Victoria Underground Station can handle excessive internal gains in the tunnel using a heat exchange with the London aquifer, normally at 12°C, can help to reduce station temperatures. The study, by Thompson, et al. [11,12], found that a heat pipe trial system for the Victoria Underground Station provided 5°C of cooling in the tunnel. The system works on the principle that the temperature of the air is less stable and either below or above the temperature of the ground. The greater the difference between the two, the faster the rate of thermal heat transfer to the cooler environment. When the tunnel is above the ground temperature, it will transfer heat into the ground. These low-energy measures help to prevent the accretion of heat in the soil around the tunnels.

STRATEGIES

By implementing a hybrid of techniques, the indoor temperatures can naturally adapt to changing conditions and provide thermal neutrality to its passengers. By increasing the naturally available resources for comfort cooling, underground stations can improve upon existing thermal problems and minimize their dependence on fossil fuels. The adaptive comfort zone for London ranges from an upper limit of 21°C in July to a low of 12°C in January. Ideally, the station temperatures will continue to have less diurnal variation from the outdoors, but will be much closer to the comfort range.

STRATEGIES: TUNNEL FEATURES

The majority of the internal gains can be confined to the tunnel when platform screen doors are in place. The addition of tunnel vents helps to reduce air temperatures in the tunnels and minimize convective heat transfer to the train carriages. Modifying the thermal conductivity of the tunnel surface can greatly increase the capacity of the ground surrounding the tunnel to absorb the heat in the tunnel. In cut-and-cover type stations, highly insulated, operable glazing is ideal for balancing underground solar exposure and thermal exchanges. This protects from winter low temperatures and can allow for the release of high internal air temperatures to the external environment through natural conduction of air.

STRATEGIES: SKYLIGHTS

Skylights provide light, ventilation, and heat exchange. Air leaving the station through can absorb heat from interior concrete surfaces, cooling the thermal mass of the structure. The design of the underground building relies heavily on the external envelope for modulation of the external climate. Coupling and decoupling of the building with the outdoor environment can increase the comfort level of indoor temperatures throughout the year. Since a London Underground Station platform is on average, twenty meters below grade, the ample thermal resistance provided by the ground and structure make double-glazing unnecessary.

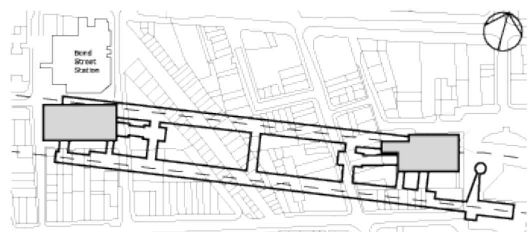

Figure 3: Simulation Base Case: outlined platform is at 20 meters below street level. The grey areas are the station entrances modelled as operable skylights.

A thermal model (TAS) simulation of this condition shows that too much insulation can result in overheating of the internal platform. Instead, single glazing can be used with controls of the apertures to regulate airflows between the exterior and interior environments. Ample sized operable skylights avoid high amounts of air friction that is created with smaller apertures. Tall, atrium-like spaces are ideal for inducing buoyancy driven stack ventilation because of the available height and the natural difference in temperatures between indoors and outdoors (lower station levels being consistently higher than outdoors). The warmer indoor air will be forced out of the high apertures. By increasing the aperture of the skylights from 0 to .5, the rate of heat loss from the interior by conduction is increased and the indoor air temperatures are lowered. Night purge ventilation takes place when the external air and sky temperatures drop below the internal temperatures. This system works because the thermal transfer of heat moves in the direction of the cooler environment which is the outdoors, and the flow rate can further be increased by the stack effect in the 20 meter high interior space (the hot air rises to the top due to air stratification). Air flow in the opposite direction (downward) is undesirable at these locations due to poor air quality created by the cars passing overhead, so they should only be opened when the indoor temperatures exceed the outdoor temperatures to encourage an outlet air flow from the station.

Figure 4: New open platform station used for simulations. Outlined platform is at 20 meters below street level. The grey areas are the station entrances modelled as operable skylights.

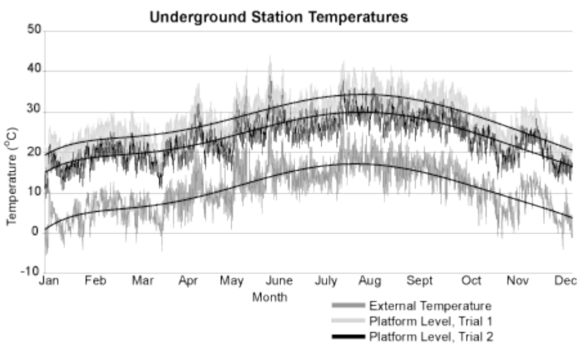

Figure 5: TAS simulation. Base Case, trail 1 and modified station, trial 2. Platform is at 20 meters below street level for the analysis.

To determine the number and scale of the ideal openings situation for the typical London Underground Station, TAS models were simulated. Winter temperatures in trial 3, shown in Figures 4 and 5, which had the most openings were too cool, but during the summer, the added contact with the external temperatures was useful and greatly improved the comfort on the platform over the first two trials which had less roof openings. Comfortable temperatures could be achieved by with the additional openings in winter by reducing the percentage that the roof windows are open and decoupling from the external climate. This is the best option for attaining comfort throughout the year because the first two trials were unable to adapt to provide comfort in the summer season and more roof glazing can be beneficial for introducing natural daylighting into the station. Figures 6-8 display the results of TAS simulations of the platforms for the progression of a new station design strategies. The objective of these simulations is to establish trends and isolate factors that change the thermal characteristics of the space. The base case simulation in TAS of the station design, using 0.3 apertures for the glazed roof surfaces revealed that the restrictive airflow produces station platform temperatures similar to exiting naturally ventilated stations. Without apertures (not shown), there is very little diurnal swing inside the station and the average annual temperature variation is relatively small in the absence of ventilation due to a high thermal mass from the ground and station concrete construction. The simulation in Figure 8 uses 1.0 apertures. While this condition is unlikely in reality because of limitations of roof glazing systems and because of station security, it can highlight the importance of large apertures during the summer season for cooling. The openness of the station simulation in Figure 8 allows for night purge ventilation to cool the large thermal mass and carry that cooling over to the next day, enabling the station to coupe with peak occupancy loads and not over-heat. Compared to the data in Figure 1, summer temperatures appear reduced. In order to provide comfortable temperatures in the winter season as well, the station will need to de-couple for the exterior climate, similar to the base case scenario. Because of the thermal transmittance of glass compared to concrete roofing, the glazing is used strategically. Skylight glazing must allow for the escape of long wave radiation, the emission of daylight and the omission of solar radiation (double pane, low-e glass). The station apertures allow for night-time ventilation to flush out the heat stored in the mass and renew its thermal capacity. The glass transmittance values must enable a balance between issues of daylighting and thermal modulation of the climate. Figure 7 shows the TAS simulation test results of the station with clear double glazing with a low-e coating. The thermal insulation it offers compared to the single glazing tested in the base case proves to be too great. At a greater aperture of 1.0 the temperatures may decrease, but this option offers less control of the thermal environment.

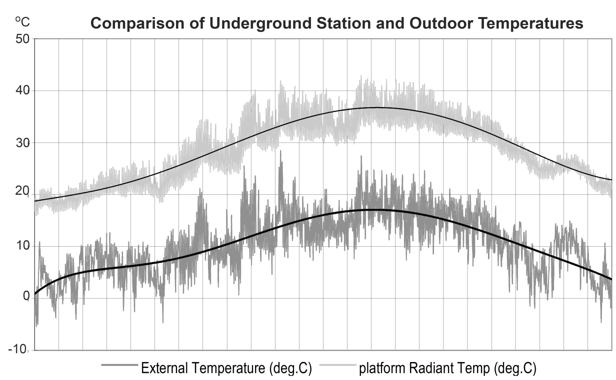

Figure 6: Base case scenario, single glazing. Single glazed windows: last longer, allow more heat to transfer more quickly in the winter months than double glazing. Apertures of .3 were used.

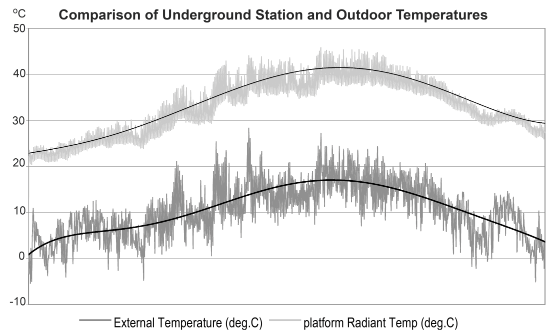

Figure 7: TAS simulation. Same as base case, but with low-e double glazing.

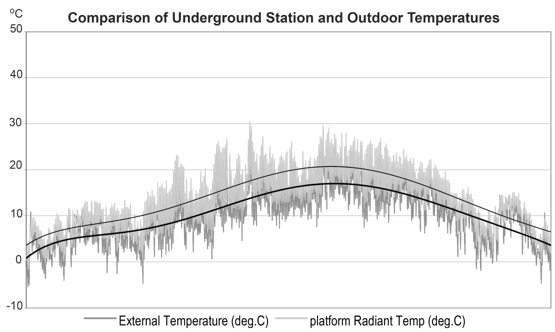

Figure 8: TAS simulation. Same as base case, but with 100% skylight apertures.

STRATEGIES: UNDERGROUND DAYLIGHTING

Using Ecotect and Radiance annual solar access on a typical site condition near Bond Street Station (Central London) was simulated to determine the annual conditions. Radiance software uses ray-tracing to accurately predict the lighting levels that can be achieved in the space. The illumination of underground surfaces relies on reflected daylight values. Analyses at platform level (20 meters below grade) revealed that placing the platform at the north of the site would allow the southern mid-day sun angles the greatest access in clear sky conditions. For natural daylight to reach the platform level, a northern 'light wall' with a high surface reflectance value was tested. With Radiance Daylight simulations, skylight additions to the typical station were trialled. Over 2000 lux was shown to have been available during the key station times in winter nearest the skylights, positively indicating that the goal of exceeding 100 lux should be achievable even in the areas furthest from the skylights.

CONCLUSIONS

New mechanical equipment coupled with higher station occupancies could lead to excessive internal heat gains and the degradation of the soil capacity around the tunnels to absorb heat. The investigations in this paper found that by implementing methods that suit the seasonal conditions, the indoor temperatures can adapt to provide thermal neutrality to its passengers. The use of hybrid systems for ventilation, cooling, and lighting are required to provide year-round comfort. Coupling and decoupling of the building with the outdoor environment can increase the comfort level of indoor temperatures throughout the year. Modifying the thermal conductivity of the tunnel surface can greatly increase the capacity of the ground surrounding the tunnel to absorb the heat in the tunnel.

REFERENCES

1. Abi-Zadeh, D., Sadokierski, S., Tabarra, M., Capability Statement Consultancy Services for Ventilation, and Design of a Modern Subway Ventilation System, Aerodynamics, Fire Smoke Control and MEP Systems in Tunnels, © ARUP, arup.com accessed on 13 July 2007.

2. Alberto E., Filippopoulou, E. Marcondes, MP. Zubia, C. Going Underground, Project 2, Term 2, April 2004, MA Programme, Environment and Energy Studies 2003-04, Architectural Association Graduate School.

3. Ampofo, F., G. Maidment, and J. Missenden. Underground Railway Environment in the UK. 3rd ed. London: Elsevier Ltd., October 30 2003. 13 p.

4. Atmaca, I., O. Kaynakli, and A. Yigit. Effects of radiant temperature on thermal comfort. Bursa, Turkey:Department of Mechanical Engineering, Uludag University. Building and Environment. © 2006 Elsevier Ltd

5. Energy Research Group, Dublin. "Daylighting in Buildings." A Thermie Programme Action. Dublin: The European Commission Directorate-General for Energy (DGXVII), 1994. 1-32.

6. Keller, T. Schirber, A., London Project: The Underground: Extension, Term 1 Project, 15 December 2000, MA Programme, Environment and Energy Studies 2000-01, Architectural Association Graduate School.

7.London Climate Change Partnership, The. http://www.ukcip.org.uk/resources/publications/documents/London_summary.pdf accessed on 20 November 2007.

8. London Underground Environmental Report 2006, Section 5.1 Energy, 5.2 Air Pollution, Transport for London (TFL), http://www.tfl.gov.uk/assets/downloads/environmental-report-2006.pdf accessed on 15 April 2007.

9. Met Office [The], Causes of Weather in the UK. © copyright Crown. http://www.metoffice.gov.uk/education/secondary/students/bi_climate.html accessed on 10, February, 2008.

10. Santamouris, M., Solar Thermal Technologies for Buildings, The State of the Art. James and James Ltd. 2003, London.

11. Thompson, J. A., et al. "Geothermal cooling through enhancement of the natural." Experimental Thermal and Fluid Science. 31 London, U.K. Elsevier Inc., June 07 2006. 551-559. 8 p.

12. Thompson, J. A., et al. "Modelling Low-Energy Cooling Strategies." Applied Energy. 83 London, U.K. Elsevier Inc., 2006. 1152-1163. 11 p.

13. Transport for London, http://www.tfl.gov.uk/corporate/media/newscentre/4770.aspx accessed on 30 December 2007.