Appendices

Appendix I – Different Types of Green Roof Systems

[Adapted from Forbes (2006) and Loh (2009)]

A green roof is a roof with vegetation integrated into its design. The term 'green roof ' usually refers to an engineered system, thus many people would exclude lichen growing on roofs unintentionally. Since the advent of green roofs, a green roofs industry has developed and many other variations of green roofs now exist.

1. Extensive green roof systems are typically characterised by shallower system profiles of 60-200 mm depth, with a weight of 60-150 kg/m², with lower capital cost, no added irrigation and lower maintenance.

2. Intensive green roof systems are those characterised by system profiles ranging from 150 to 1000 mm in depth, with a weight of 180-500 kg/m² and able to support a wider range of plants, though demanding more maintenance.

3. Semi-intensive or semi-extensive green roof systems include features of both intensive and extensive green roofs. They are of slightly greater depth than extensive systems (100-200 mm), allowing for a greater diversity of plants to be grown and local habitats recreated. Based on the same principles as extensive roofs they are light weight and generally low maintenance.

There are also some variations of the above.

a) Built-in or integrated green roofs: the green roof components are installed as a series of layers

b) Modular green roofs: they are partially assembled off-site and installed in units. Some modular systems feature plastic or metal trays that are filled with growing medium and placed on the rooftop. Plants can be grown in these trays before or after installation. Other systems feature plants pre-grown in mats that are laid onto the roof surface.

c) Sedum roofs: these are usually pregrown sedum mats based on 20 mm of substrate or systems of greater substrate depth (standard depth = 70 mm) in which sedums can be seeded or planted.

d) Meadow roofs: these roofs are based on 70-100 mm substrate depth. They involve the use of seeded or planted low, droughttolerant grasses, perennials and alpines. These can be native or ornamental species.

e) Brown or biodiversity roofs: are a low maintenance roof made of gravel or recycled material such as crushed brick or concrete with small amount of soil providing habitat for certain types of plant and insect life, and some moss covered roofs. Such roofs are designed to recreate natural and often local habitats rich in birds, plants and insects. This is often done by using the by-products of the development process such as rubble and subsoil which are left to colonise naturally overtime or seeded with wildflowers.

f) Wetland green roofs: are roofs that function as a wetland ecosystem usually in conjunction with grey water recycling of the building they cover.

g) Rooftop gardens: are where planting is not integrated into the roof system, and thus are technically not classified as green roofs. However, sometimes there is no clear distinction as some rooftop gardens have an amount of intensive or extensive planting together with container planting and permeable surfaces. Green roofs are not just confined to rooftops but include gardens built on building podia, ‘sky gardens’ (a Singaporean term) which can occur at mid-levels of building and also apartment balcony gardens.

h) Urban agriculture: includes examples of rooftops being used for aquaponic or hydroponic food production using either intensive green roof systems or equipment situated on rooftops. When cultivation uses containers, then the term ‘green roofs’ is used loosely.

Appendix II – Summary of Key Findings from Literature Review

Table A2.1 Summary of key findings from literature in Europe

Study	**Location**	**Key findings**
Alcazar and Bass (2005)	Spain (Madrid)	The energy performance of three roofing systems is compared. Thermal and optical characteristics are monitored. ESP-r energy simulation software is used to compare annual energy consumption. The study show that the green roof resulted in a total annual energy consumption reduction of 1% with a 0.5 % reduction in the heating season and a 6 % reduction in the cooling season.
Alexandri and Jones (2008)	Greece (Athens)	Thermal effect of green roofs and green walls is studied in both inside the canyon and at roof level. The climatic characteristics of 9 cities, 3 canyon geometries, 2 orientations and 2 wind directions are examined using a two-dimensional, prognostic, micro scale model. Green roofs and walls can cool local temperatures by between 3.6°C and 11.3°C, depending on the city.
Alexandri and Jones (2007)	Greece (Athens); UK (Cardiff)	A one-dimensional heat and mass transfer model is developed to study the effect of green roofs on mitigating raised urban temperatures. The model is validated with an experiment, conducted in Cardiff in summer 2004.
Del Barrio, (1998)	France (Mediterra. region)	A mathematical model was developed to represent the dynamic thermal behaviour of green roofs. Green roofs do not act as cooling devices but as insulation, reducing the heat flux through the roof.
Eumorfopoulou & Aravantinos, (1998)	Greece	Thermal calculations using a stationary method. Green roof contributes to the thermal protection of buildings, but does not replace the thermal insulation layer.
Köhler (2006); Köhler, *et al.*, (2002)	Germany (Berlin)	Surface temperatures of a green roof were monitored as early as 1984. Green roof reduced surface temperature but also more importantly reduced the maximum temperature amplitude by half.
Lazzarin, Castellotti and Busato (2005)	Italy (Vicenza)	Experimental measurements were done at the Vicenza Hospital. A numerical model was developed in TRNSYS to calculate thermal and energy performance.
Niachou, *et al.* (2001)	Greece (Athens)	Analysis of the green roof thermal properties and investigation of its energy performance. Extended surface and air temperature measurements were taken at the indoor and outdoor environment of the buildings. Thermal properties and energy saving were examined through a mathematical approach.
Santamouris, *et al.* (2007)	Greece (Athens)	Experimental investigation of the energy and environmental performance of a green roof in a nursery school building in Athens. Reduction of the building's cooling load during summer was 6-49%. But the influence of green roof in heating load was insignificant.
Spala, *et al.* (2008)	Greece (Athens)	Energy and environmental investigation data of the green roof system performance in an office building in Athens. A 40% reduction of building's cooling load during the summer period was found. But the influence of green roof in heating load was insignificant.
Theodosiou (2003)	Greece	A green roof model for building energy simulation is presented. It is validated using real data in the Mediterranean area. A parametric study is performed to evaluate green roof as a passive cooling technique.

Table A2.2 Summary of key findings from literature in North America

Study	**Location**	**Key findings**
Bass and Baskaran (2003)	Canada (Ottawa)	Evaluate rooftop and vertical gardens as an adaptation strategy for urban areas in a Canadian context.
Connelly and Liu (2005); Liu (2003); Liu, (2002)	Canada (Ottawa)	A green roof and a reference roof were monitored to allow direct comparison of thermal performance. The green roof was more effective at reducing heat gain than heat loss. The green roof reduced temperature fluctuations and also modified heat flow through the roofing system by more than 75%.
Martens, Bass and Alcazar (2008)	Canada (Toronto)	Studied the impact of roof-to-envelope ratio on green roof energy performance using a modified version of EPS-r for the month of July in a Toronto climate.
O'Keeffe, *et al.* (2008)	USA	Design of an instrumented model green roof experiment.
Sailor (2008)	USA	A green roof energy balance model was developed and integrated into the building energy simulation program EnergyPlus.
Sailor, Hutchinson, and Bokovoy (2008)	USA (Portland, Oregon)	Measured the thermal properties of ecoroof soils. The results indicate significant variability as a function both of soil composition and soil wetness. Thermal conductivity: 0.25-0.34 W/m.K for dry samples and 0.31-0.62 W/m.K for wet samples. Specific heat capacity: 830-1123 J/kg.K for dry samples and 1085-1602 J/kg.K for wet samples. Albedo was consistently higher for dry samples (0.17-0.40) decreasing substantially (0.04-0.20) as moisture was added. Thermal emissivities were relatively constant at 0.96 regardless of soil type or moisture status.
Sonne and Parker (2008); Sonne (2006a); Sonne (2006b)	USA (Florida)	Measurement and testing of energy performance in a Florida green roof. Maximum temperature reduction was 22 °C (54 °C – 33 °C). Heat flux reduction of 18.3% to 49.5%.
Spolek (2008)	USA (Portland, Oregon)	Performance monitoring of three ecoroofs (280-500 m^2) for 3 years. The ecoroof heat flux was reduced by 13% in winter and 72% in summer. Overall reductions of rainwater discharge: 12% and 17%.

Table A2.3 Summary of key findings from literature in Asian countries

Study	**Location**	**Key findings**
Fang (2008)	Taiwan	Controlled experiments to study coverage ratio (CR) and total leaf thickness (TLT), against thermal reduction ratio (TRR). A TRR map was drawn to provides guidance on thermal reduction planting arrangements for green roofs.
Kumar and Kaushik (2005)	India	Energy balance model for green roof using a control volume approach based on finite difference methods. Experimental measurements were done in Yamuna Nagar (India).
Ondimu and Murase (2006)	Japan (Osaka)	Inverse modeling of thermal properties of a Sunagoke moss mat for roof greening. The thermal resistance of the material was 14.15 and 5.08 K/W, respectively, at volumetric water contents of 0 and 100%. The universal heat transfer coefficient was 6.42 and 17.9 W/m^2.K, respectively, for the same conditions.
Onmura, Matsumoto and Hokoi (2001)	Japan (Osaka)	Field measurements; wind tunnel experiment; numerical calculations. The evaporative cooling effect of a roof lawn garden showed a 50% reduction in heat flux. A reduction in surface temperature from 60 to 30 °C during day time led to the conclusion that evaporative component is an important role in reducing the heat flux.
Takakura, Kitade and Goto (2000)	Japan (Tokyo)	The cooling effect of various kinds of greenery cover was investigated by experimental model and computer simulation. Different coverings included: bare concrete, soil layer, soil layer with turf, and soil layer with ivy.
Wong and Chen (2009); Wong, Tan and Chen (2007); Wong, *et al.* (2002)	Singapore	Experimental measurements were done at green roofs installed on multi-storey carparks in housing estates. A maximum temperature difference of 18 °C was observed and maximum 60% of heat gain was stopped. High relative humidity was also observed due to the presence of plants.
Wong, *et al.*, (2003a)	Singapore	Field measurement was carried out on a rooftop of a low-rise commercial building. Maximum reduction in roof surface temperature was 19.4 °C and maximum reduction of reflected global radiation at 500 mm heights was 247 W/m^2. Ambient temperature at 300 mm height can be reduced by 5.9 °C.
Wong, *et al.*, (2003b)	Singapore	DOE-2 simulation study of a green roof on a 5-story Singapore office building showed annual energy consumption savings of 0.6% to 14.5% depending on characteristics of the green roof.
Yokoyama, *et al.* (2007); Yokoyama, Yamaguchi and Ishii (2004)	Japan (Tokyo)	Experimental studies and calculations on rooftop greenery system with container tank of rain water, and light and thin rooftop greening.
Zhang, *et al.* (2006)	China (Hebei)	Effect of a green roof on the thermal load of a commercial building was studied using a pair of comparative testing rooms (one with an ordinary roof and the other with a green roof).

Appendix III – Methodology Plan and Instrumentation Plan

1. Methodology Plan

1.1 Literature study on overseas and local experience

- Search for and review research papers and reports (see *References List*)
- Evaluate study methods and identify suitable approach for this study
- Prepare information for numerical & simulation models

1.2 Development of research methods and instrumentation

- Assess site conditions and constraints
- Prepare instrumentation plan and tools
- Collect information for thermal analysis

1.3 Field studies and measurements

- Take infra-red and digital photos of the green roof sites
- Determine measurement points and periods
- Set up and arrange measurements

1.4 Theoretical numerical models and simulation

- Identify suitable data and information for numerical models
- Calculate thermal performance and compare different situations
- Estimate energy impacts through building simulation

2. Instrumentation Plan

Measuring Parameters	Instruments	Remarks
Temperature of roof surfaces	• Infra-red thermometer (Fluke 561 HVACPro) • Thermocouple and digital thermometers	On-site inspection
Temperature of green roof layers	• Temperature sensors (soil type) • Data logger (multi-channel or HOBO)	Data-logging
Temperature and relative humidity of air	• Temperature sensors and data logger (HOBO) • Software and accessories	Data-logging
Infra-red photos and data	• Infra-red cameras (Fluke Ti40 and FLIR S-40)	On-site inspection
Heat flux at green roof	• Heat flux sensors • Data logger (multi-channel or HOBO)	Data-logging
Soil moisture content	• Soil moisture sensors • Data loggers (HOBO)	On-site inspection & data logging
Weather conditions (* or make use of HK Observatory data)	• Wireless weather station (Davis Instruments Vantage Pro2)	HK Observatory: www.weather.gov.hk

Since the thermal studies will involve some expensive equipment such as infra-red thermal imaging camera, the principal investigator has borrowed such equipment from the University of Hong Kong. This will reduce the costs for arranging or renting such equipment just for this study. Moreover, the basic measuring instruments and dataloggers acquired for this study will be reused in the University for other academic and research purposes.

Appendix IV – Basic Information of the Green Roof Sites

Table A4.1 Basic information of the green roof sites

Site	Green roof area (m^2)	Type of plants	Soil thickness (mm)
Ngau Tau Kok Municipal Office Building (above a public library)	112	Arachis pintoi (野花生), Meiastoma dodecandrum (地菍), Zephyranthes grandiffera (風花雨)	150 and 200
APB Centre, 4/F (above carpark)	147	Sedum lineare (佛甲草), sedum lineare - golden teardrops (金葉佛甲草), portulaca gilliesii (宿根太陽花)	100
APB Centre, 10/F (above office)	206	Sedum lineare (佛甲草), sedum lineare - golden teardrops (金葉佛甲草), portulaca gilliesii (宿根太陽花)	100
Yuen Long Government Primary School (above some classrooms)	280	Axonapus compressus (大葉草), cyndom dactylon (比毯草), sediam linerse (佛里草), parthenocissus himalayana, codiaeum variegatum 'mixed', schefflera arboricola, Ixora chinensis, allamanda nerilfolla, rhapis excelsa, alpinia speciosa, duranta repens, ophiopogon japonicus, cuphea ignea, rhododendron 'simsii', rhododendron pulchrum, hibiscus rosa-sinensis 'cooprel', aglaia odorata, canellia japonica, buxus hartandii, rhoco discolor 'dwarl'	Extensive: 100; semi-Intensive: 350
St. Bonaventure Catholic Primary School (top of an assembly hall)	240	Sedum from China, small amount of ported plants	50

Appendix V – Ngau Tau Kok Municipal Office Building

Figure A5.1 Location map and aerial photo of NTK Building (source: www.centamap.com)


Overview 15 Jul 2009 (dry condition)


Overview 30 Jul 2009


Overview 30 Jul 2009


Plant type 1: Arachis pintoi (野花生)


Plant type 2: Meiastoma dodecandrum （地菍） (right hand side)


Plant type 3: Zephyranthes grandiffera (風花雨) (right hand side)


Digital logger thermometer and battery


HOBO data logger with temperature sensors

Figure A5.2 Selected site photos of NTK Building

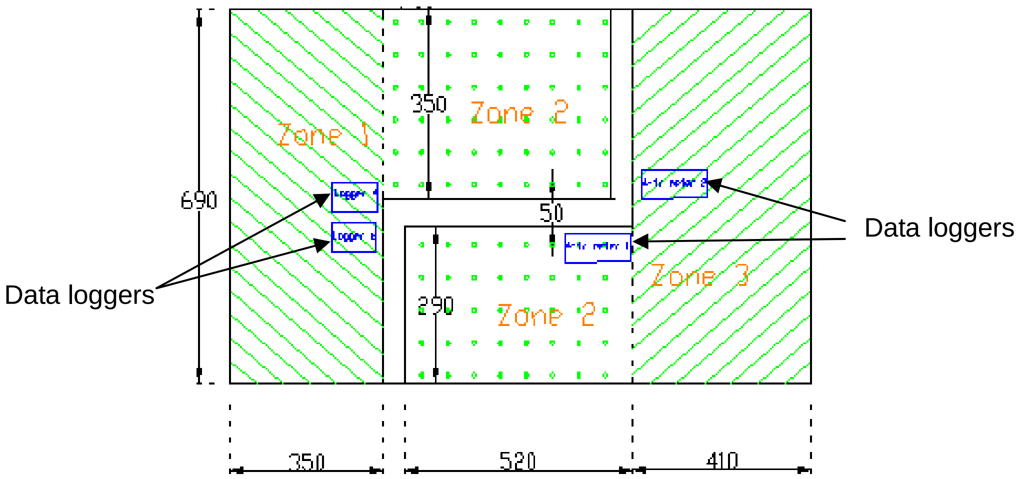


Figure A5.3 Green roof plan of NTK Building

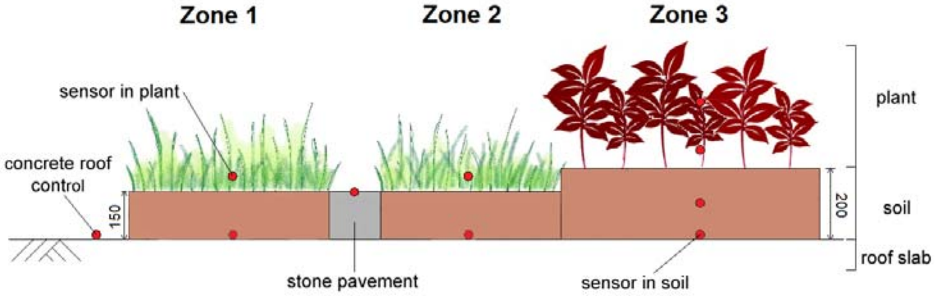


Figure A5.4 Green roof section and sensor positions of NTK Building

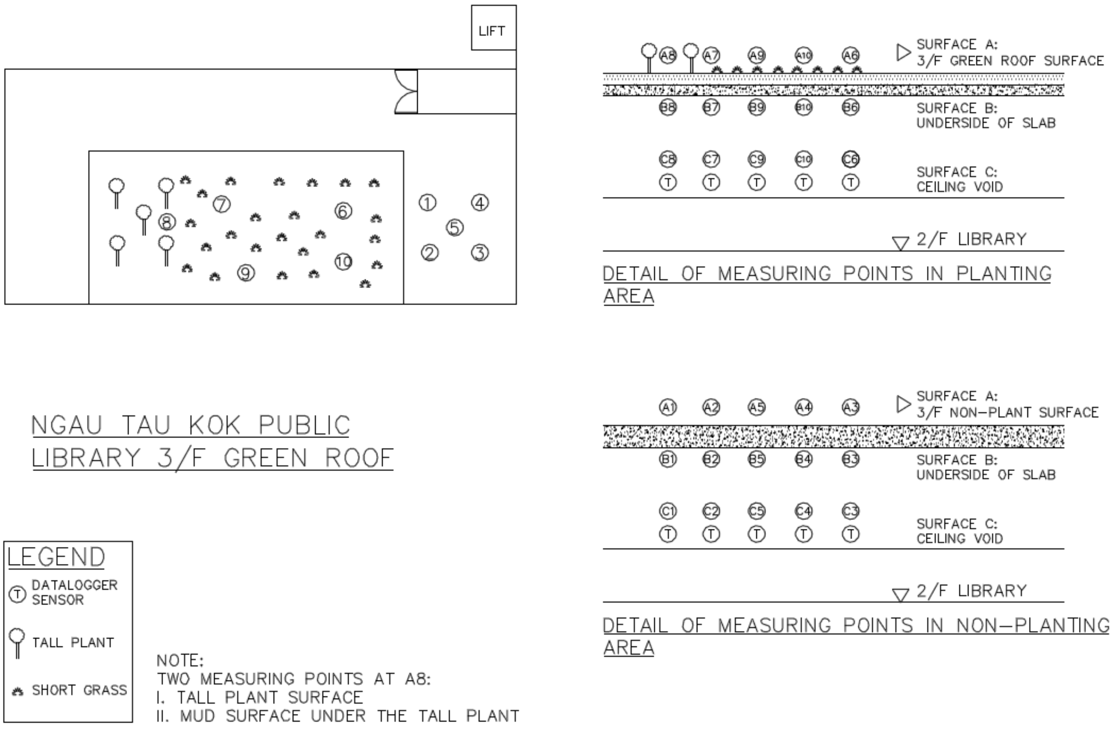
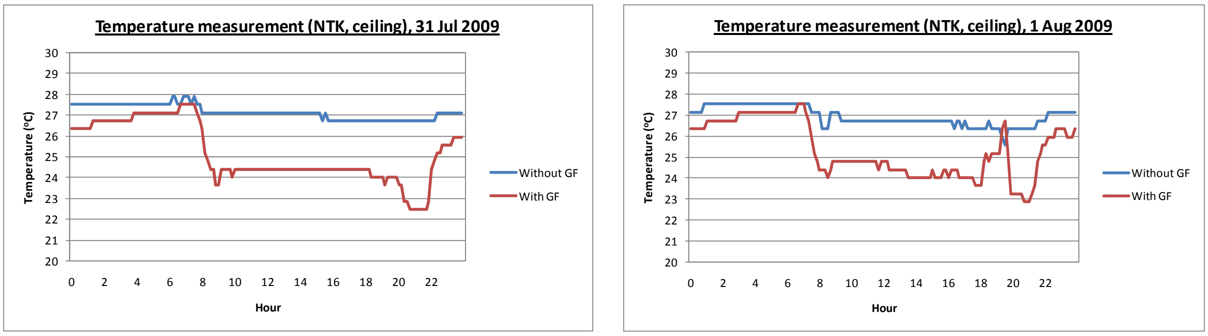


Figure A5.5 Temperature measuring points of NTK Building from EMSD subcontractor



(Note: Only two days were taken here because the sensors dropped from the slab on 2 Aug 2009.)

Figure A5.6 Temperature of NTK Building at ceiling below the roof, 31 Jul-1 Aug 2009

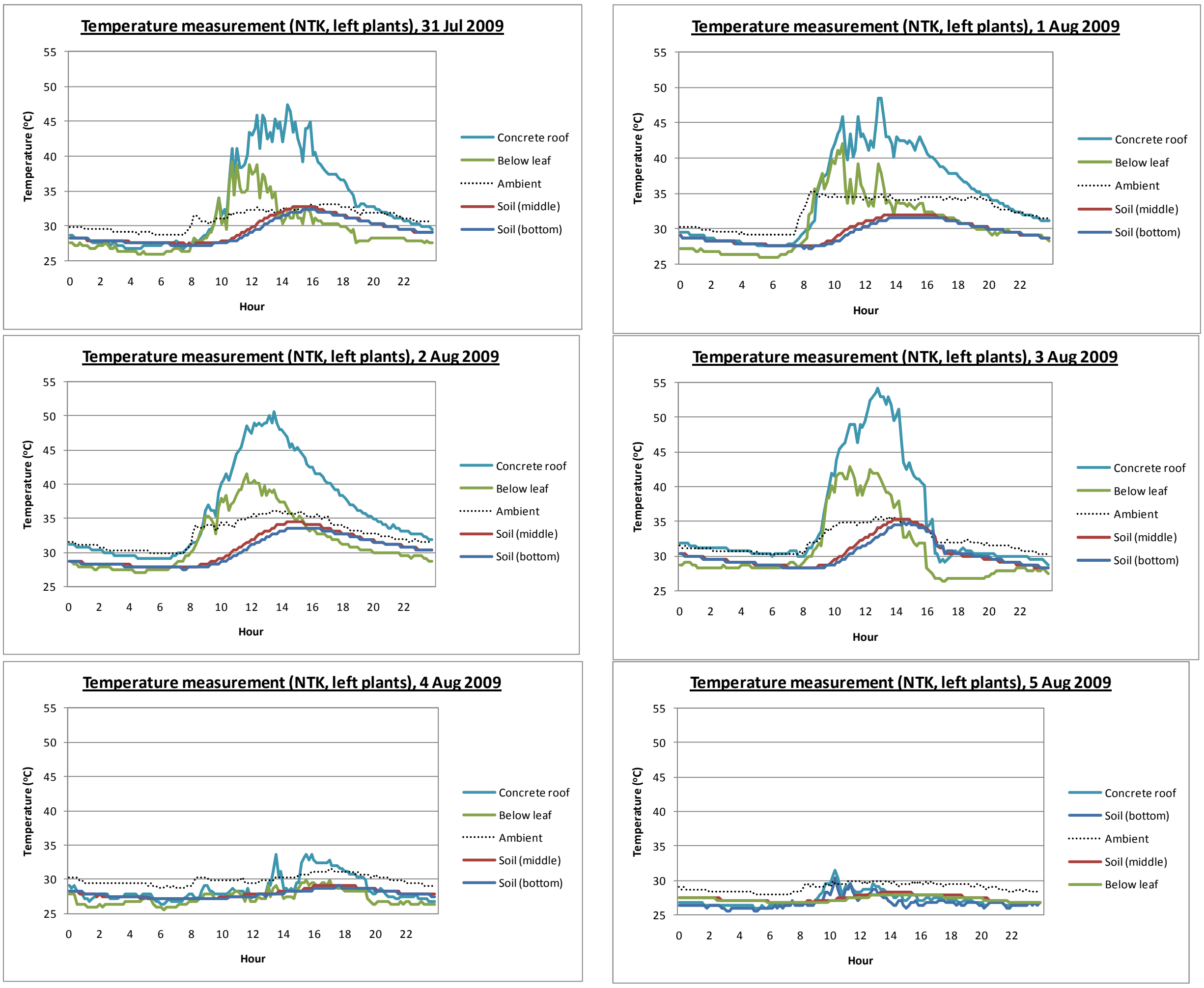
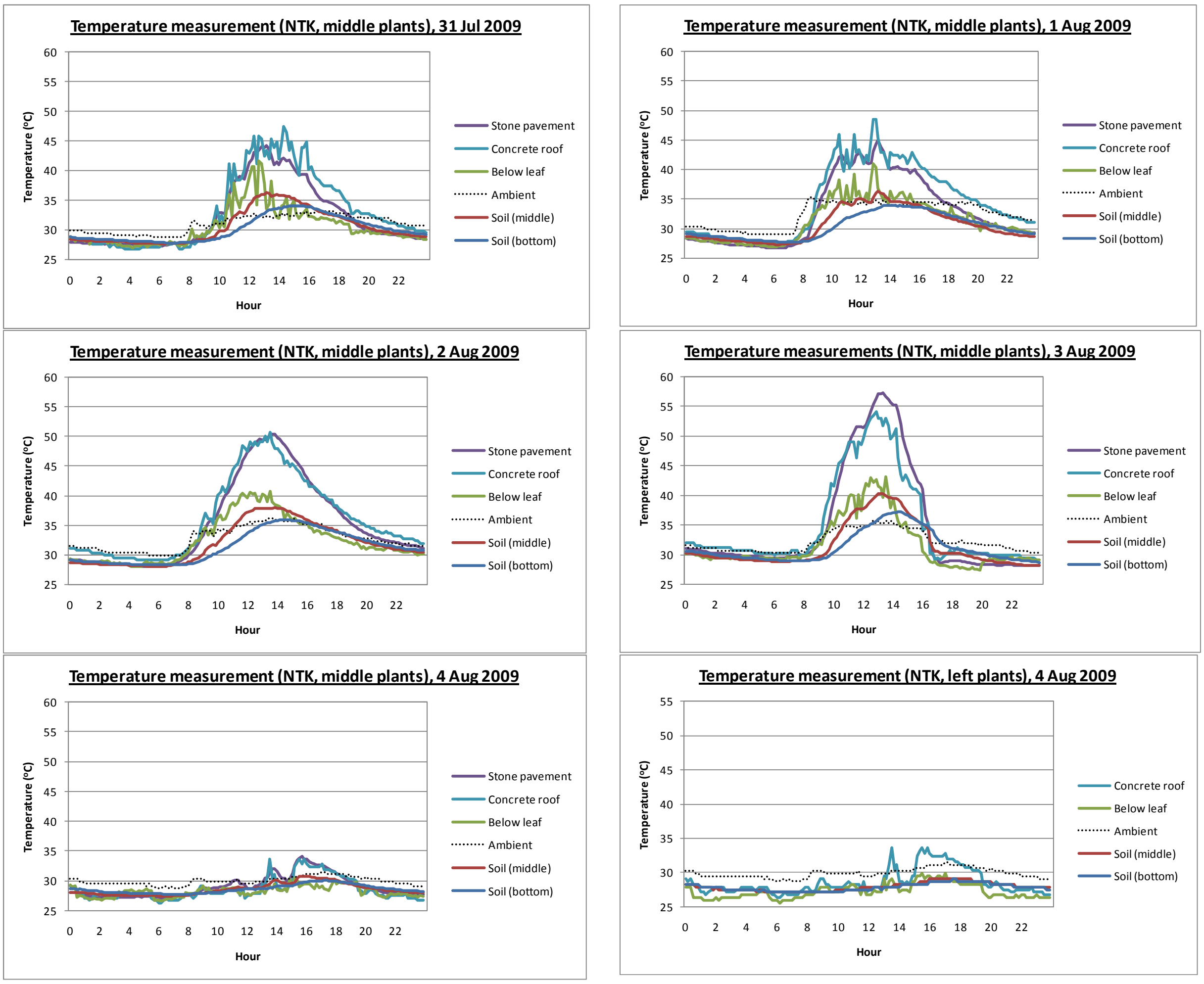


Figure A5.7 Temperature of NTK Building: left short plants 31 Jul-5 Aug 2009



Temperature measurement (NTK, middle plants), 31 Jul 2009

Temperature measurement (NTK, middle plants), 1 Aug 2009

Temperature measurement (NTK, middle plants), 2 Aug 2009

Temperature measurements (NTK, middle plants), 3 Aug 2009

Temperature measurement (NTK, middle plants), 4 Aug 2009

Temperature measurement (NTK, left plants), 4 Aug 2009

Figure A5.8 Temperature of NTK Building: middle short plants 31 Jul-5 Aug 2009

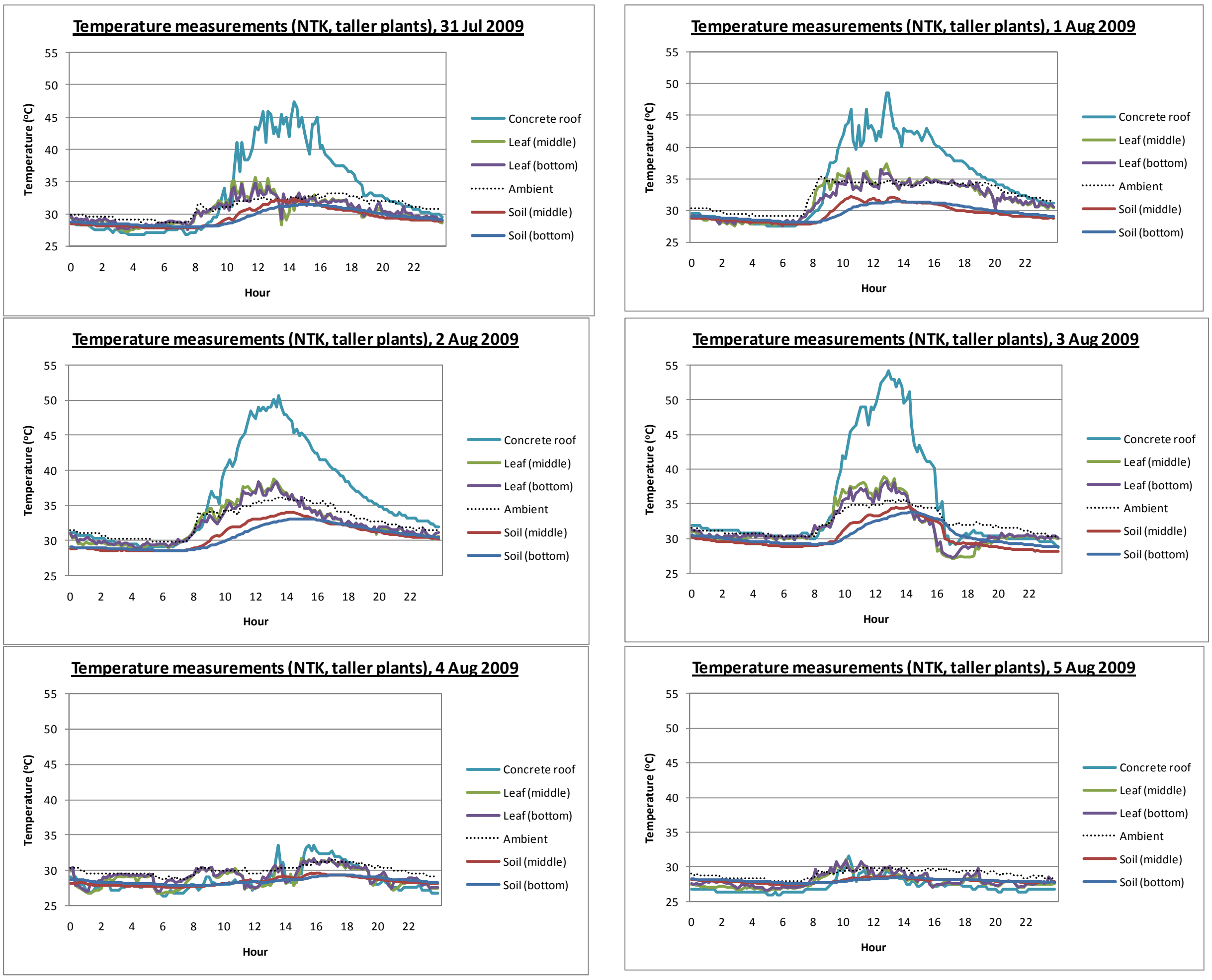


Figure A5.9 Temperature of NTK Building: right taller plants 31 Jul-5 Aug 2009

Appendix VI – APB Centre at To Kwa Wan

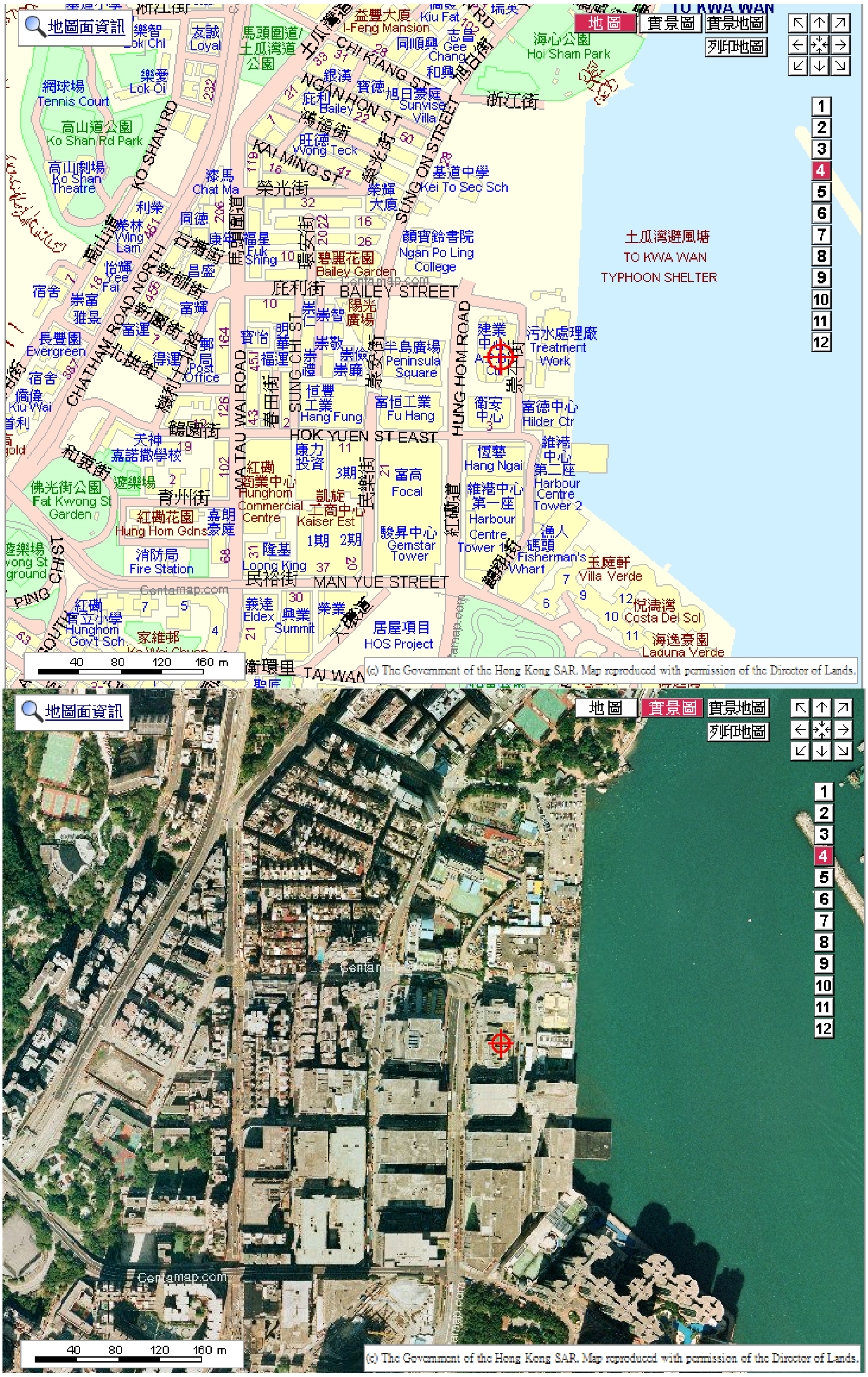


Figure A6.1 Location map and aerial photo of APB Centre (source: www.centamap.com)

Figure A6.2 Locations of the green roofs in APB Centre (source: www.centamap.com)

4/F green roof (15 Jul 2009)

4/F green roof plant types (15 Jul 2009)

10/F solar PV system (15 Jul 2009)

10/F green roof (15 Jul 2009)

4/F green roof (6 Aug 2009) (rainy day)

1/F green roof (13 Aug 2009)

HOBO data logger with temperature sensors

Temperature sensor at carpark ceiling

Figure A6.3 Selected site photos of APB Centre

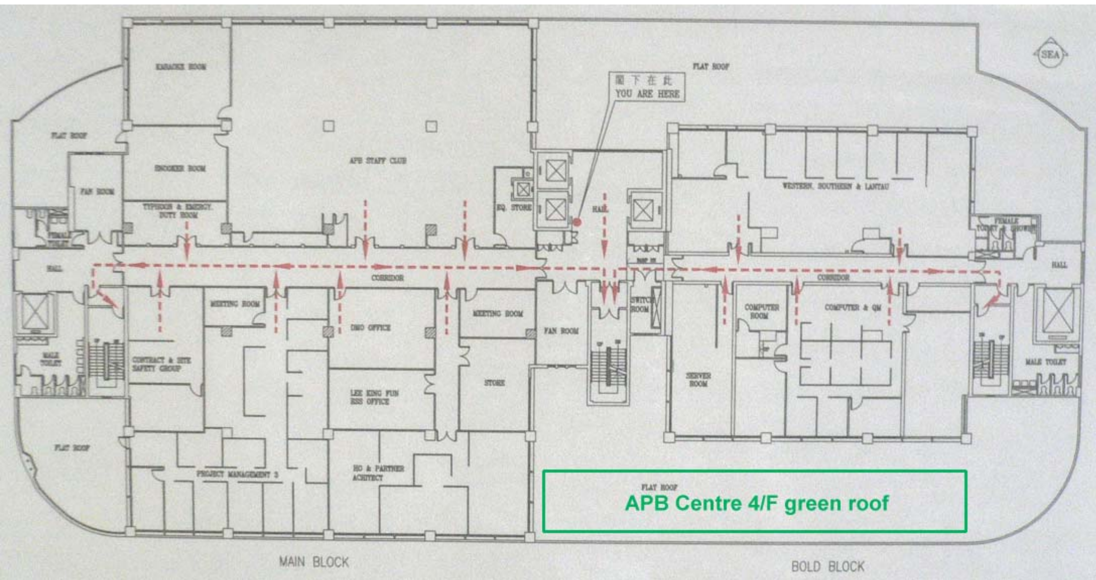


Figure A6.4 Floor plan of APB Centre 4/F

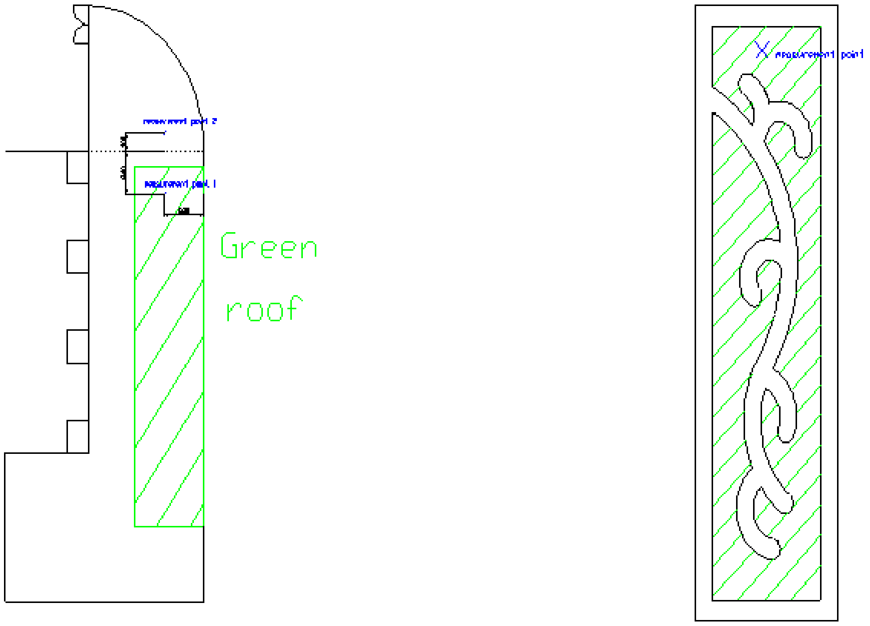


Figure A6.5 Green roof of APB Centre 4/F

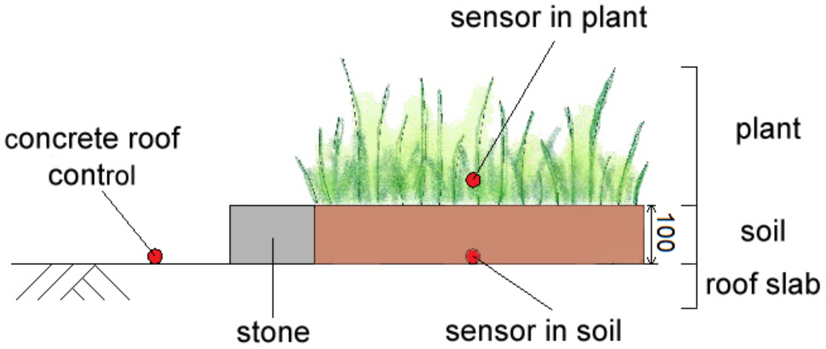


Figure A6.6 Section and sensor positions of APB Centre 4/F

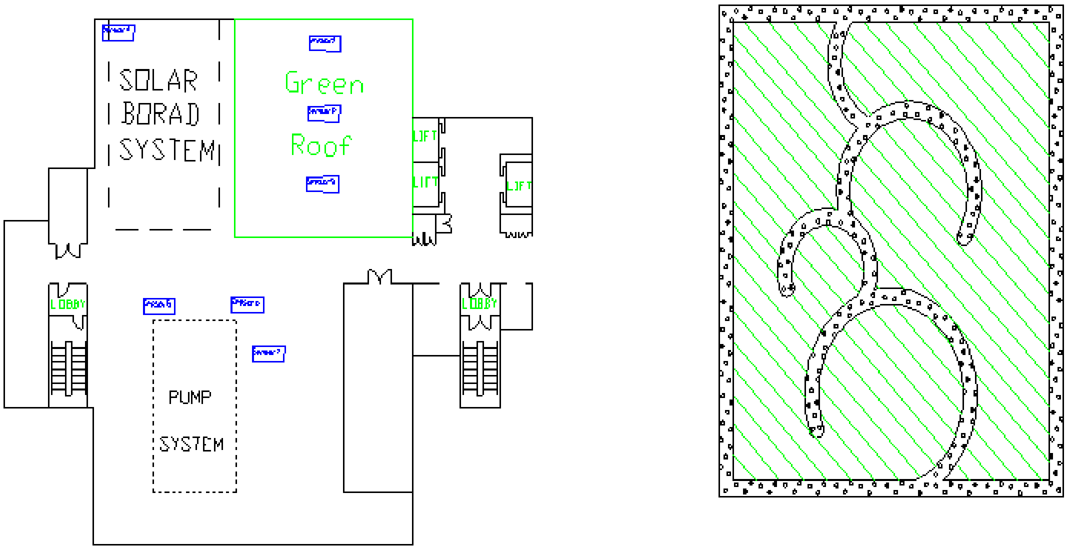


Figure A6.7 Green roof of APB Centre 10/F

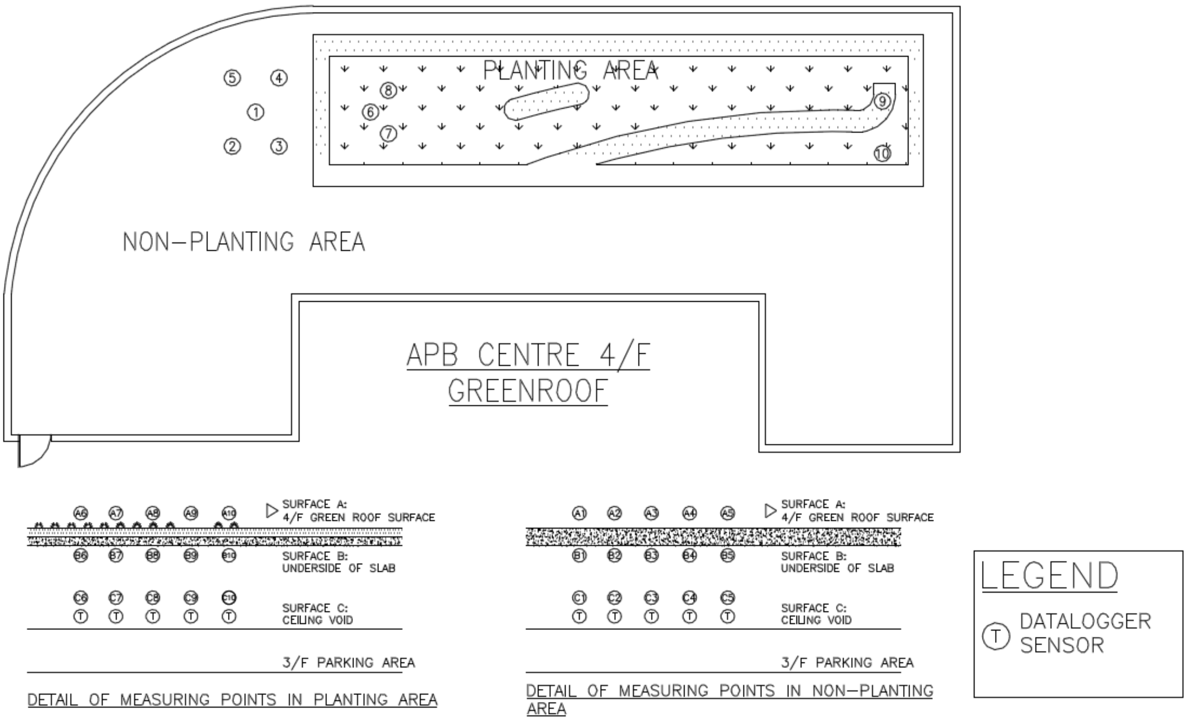
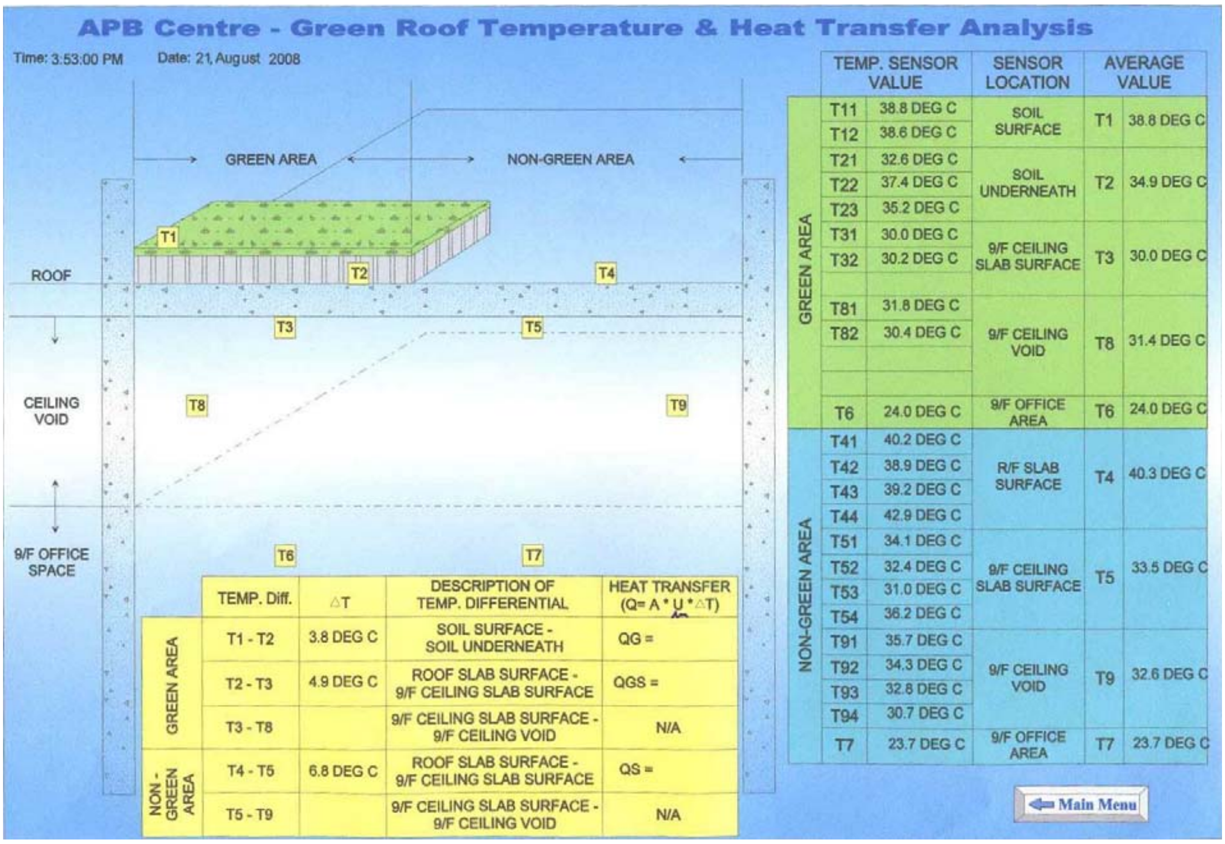


Figure A6.8 Temperature measuring points of APB Centre 4/F from EMSD subcontractor



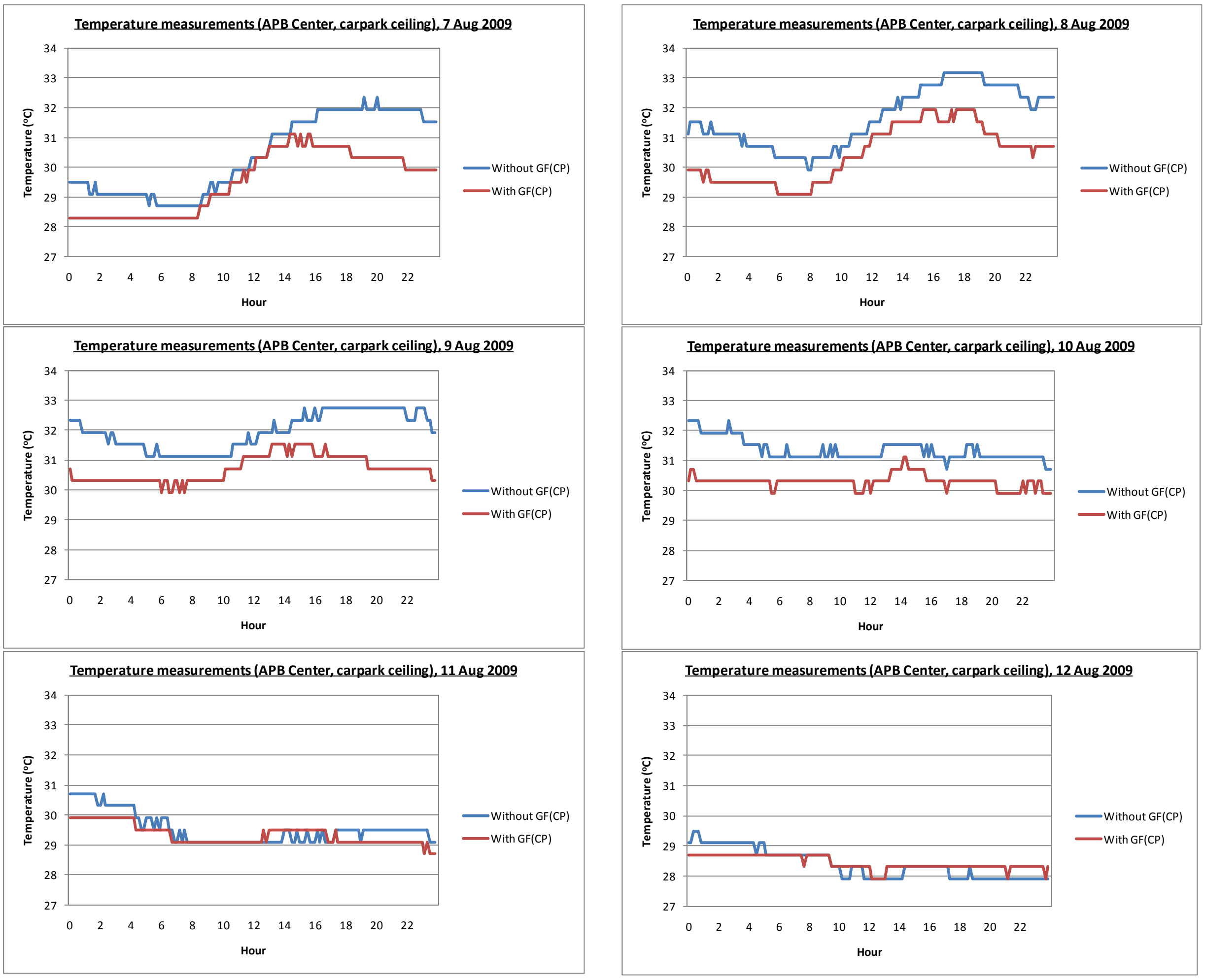
APB Centre - Green Roof Temperature & Heat Transfer Analysis

Time: 3:53:00 PM Date: 21,August 2008

	TEMP. SENSOR VALUE		SENSOR LOCATION	AVERAGE VALUE	
GREEN AREA	T11	38.8 DEG C	SOIL SURFACE	T1	38.8 DEG C
	T12	38.6 DEG C			
	T21	32.6 DEG C	SOIL UNDERNEATH	T2	34.9 DEG C
	T22	37.4 DEG C			
	T23	35.2 DEG C			
	T31	30.0 DEG C	9/F CEILING SLAB SURFACE	T3	30.0 DEG C
	T32	30.2 DEG C			
	T81	31.8 DEG C	9/F CEILING VOID	T8	31.4 DEG C
	T82	30.4 DEG C			
	T6	24.0 DEG C	9/F OFFICE AREA	T6	24.0 DEG C
NON-GREEN AREA	T41	40.2 DEG C	R/F SLAB SURFACE	T4	40.3 DEG C
	T42	38.9 DEG C			
	T43	39.2 DEG C			
	T44	42.9 DEG C			
	T51	34.1 DEG C	9/F CEILING SLAB SURFACE	T5	33.5 DEG C
	T52	32.4 DEG C			
	T53	31.0 DEG C			
	T54	36.2 DEG C			
	T91	35.7 DEG C	9/F CEILING VOID	T9	32.6 DEG C
	T92	34.3 DEG C			
	T93	32.8 DEG C			
	T94	30.7 DEG C			
	T7	23.7 DEG C	9/F OFFICE AREA	T7	23.7 DEG C

	TEMP. Diff.	△T	DESCRIPTION OF TEMP. DIFFERENTIAL	HEAT TRANSFER (Q= A * U * △T)
GREEN AREA	T1 - T2	3.8 DEG C	SOIL SURFACE - SOIL UNDERNEATH	QG =
	T2 - T3	4.9 DEG C	ROOF SLAB SURFACE - 9/F CEILING SLAB SURFACE	QGS =
	T3 - T8		9/F CEILING SLAB SURFACE - 9/F CEILING VOID	N/A
NON - GREEN AREA	T4 - T5	6.8 DEG C	ROOF SLAB SURFACE - 9/F CEILING SLAB SURFACE	QS =
	T5 - T9		9/F CEILING SLAB SURFACE - 9/F CEILING VOID	N/A

Figure A6.9 Temperature measuring points of APB Centre 10/F from EMSD subcontractor



(Note: Without GF(CP) = under control bare roof (carpark); With GF(CP) = under grass roof (carpark))

Figure A6.10 Temperature of APB Centre 4/F: carpark ceiling below the roof, 7-12 Aug 2009

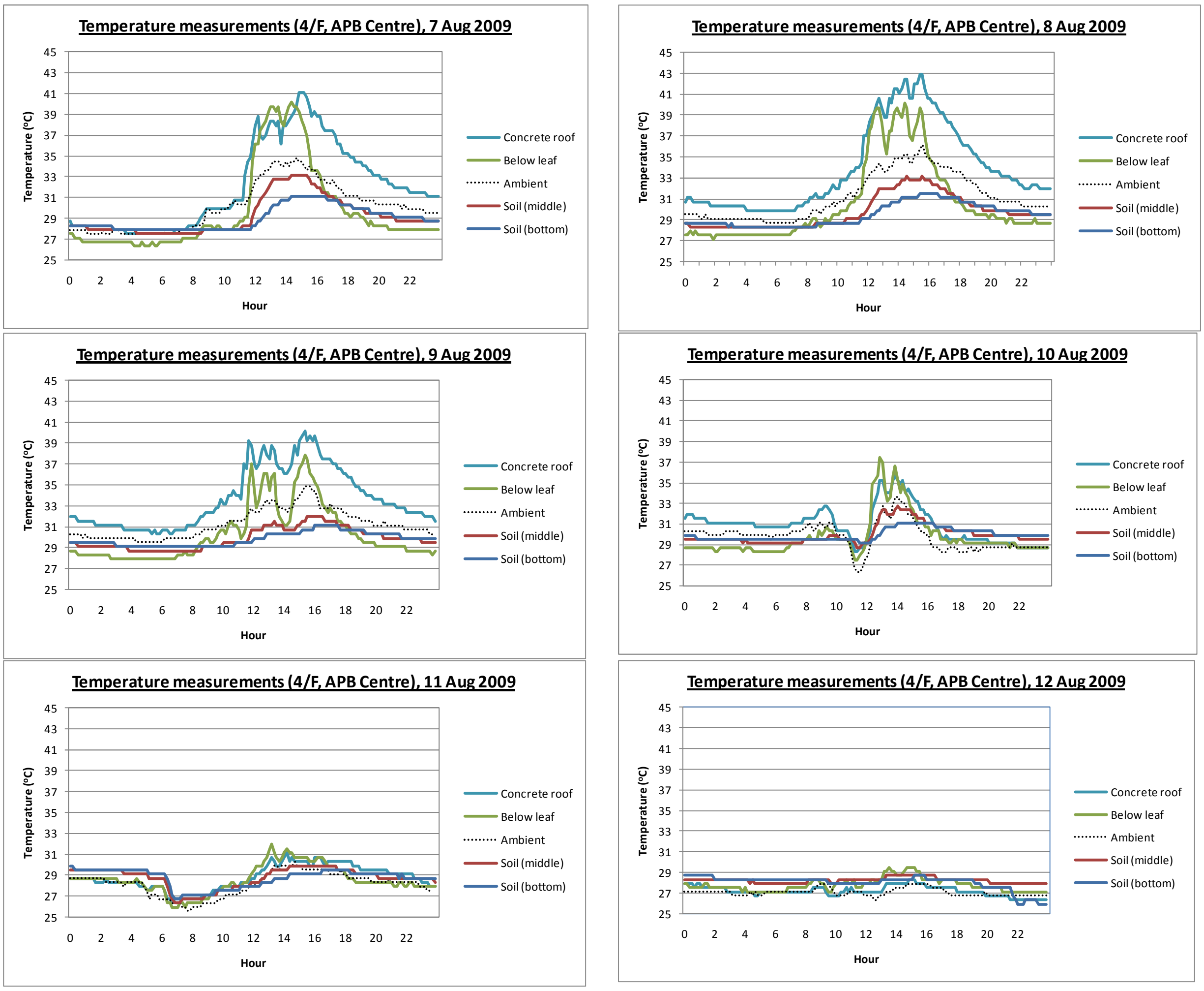


Figure A6.11 Temperature of APB Centre 4/F, 7-12 Aug 2009