SIMULATION MODELLING OF DYNAMIC INSULATION AS A MEANS FOR ENERGY SAVING AND HUMAN COMFORT

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In the loving memory of my mother …

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ABSTRACT

Dynamic Insulation is a novel method of recovering conduction heat loss through a building envelope. The recovery is an active process that allows air to move through the fabric against the temperature gradient. It also promises better indoor air quality for the occupants primarily due to the filtration properties of the construction material. This study is concerned with quantifying the energy savings and enhancement of human comfort if this technology is integrated into a building. A suitable building and plant simulation computer tool (ESP-r) was employed to do this. Due to the fact that such a modelling study has not been undertaken until now, the thesis is firstly concerned with finding a method suitable to simulate this technology using facilities already available within the simulation tool. After development of a simulation approach, validation of the approach was attempted in the light of known analytical solutions and experimental studies. From there on an exercise in the simulation of a proposed building was conducted and relevant results drawn from the performance predictions. The results from the simulation exercise confirmed the benefits associated with such a ventilation technique and additionally yielded results that were representative of the amount of energy savings (up to 9%) and improvement in human comfort that might be expected. Finally, the results have been translated into suggestions for best practice whilst using Dynamic Insulation.

LIST OF SYMBOLS

Unless otherwise specified the following symbols and subscripts have the stated meaning and are used in the text without formal definition. All other symbols used have been defined forthwith.

Symbols

ë	Thermal Conductivity W/m K
x	Distance of element under consideration from outside wall surface m
L, L_j	Total thickness of element m
T_0, T_L, T_j, T_x	Temperatures at various distances from outside wall surface ^{0}C
$T_{¥i}$, $T_{¥e}$	Temperatures at a very large distance from internal and external wall surfaces respectively ^{0}C
u	Air velocity m/s
ñ	Density of air kg/m^3
c	Specific heat capacity of air J/kg K
R, R_e, R_i, R_s	Thermal resistance m^2 K/W
R_{dyn}	Dynamic Thermal Resistance m^2 K/W
U	Coefficient of overall heat transfer W/m^2 K
q_c	Conduction heat flux W/m^2
q_{c0}, q_{cx}, q_{cL}	Conduction heat fluxes at different distances from outside wall surface W/m^2
q_u	Convection heat flux due to Dynamic Insulation W/m^2
G	Dimensionless number, representative of total thermal resistance of the envelope
h_s, U_s	Heat transfer coefficients for static case W/m^2 K
h_{dyn}, U_{dyn}	Heat transfer coefficients for dynamic case W/m^2 K
q_s	Convection heat flux for the static case W/m^2

Subscripts

e	Exterior
i	Interior
s	Static
dyn	Dynamic

CHAPTER 1

Introduction

1.1 Dynamic Insulation

The concept of Dynamic Insulation emerges from a need to capture conduction energy loss from the fabric of a building. In a very simplistic sense air is drawn in through the building fabric and on its way in it gains heat from the fabric that was originally going to be lost to the exterior Miscellaneous other benefits have also been attributed to it e.g. better indoor air quality, control of moisture within the building fabric etc. It has effectively been adopted and has shown substantial energy savings in the Scandinavian countries. In the UK this concept has been adopted in a few novel buildings especially in Scotland. This area of study is still quite nebulous both in theoretical depth and in practical issues like erection and dynamic construction design.

1.2 Importance of Research

Energy saving is important from a sustainability point of view in that there has been an almost exponential increase in the use of natural resources over the last fifty years (the post World War II period) and it can be argued that such promotion of energy use has led to unsustainable overuse of much of the Earth's resources [13] Energy saving also has the obvious advantage of lowering the running cost of a building.

Human comfort is very important for the occupants of a building to live and work. Aside from ergonomic health issues it is of utmost importance if one is concerned about productivity. Productivity is directly related to comfort. The major corporations have come to realise that comfortable working environments pay off in big dividends. [14] There are many important reasons to provide an environment that has stable thermal comfort. Careful control of temperature and humidity not only makes occupants more comfortable, but also achieves significant operating and maintenance savings over the life of a building. Furthermore, thermally comfortable buildings are more likely to retain employees and occupants, raising property values and income [10]

1.3 Computer Simulation

IT has become very important in the analysis of buildings. Initially computer models were simply computer versions of hand calculators. Computer based design has come a long way from there and now computer simulation has come to be relied upon more and more with the knowledge that traditional design approaches were simply not capable of giving an indication as to how a building will perform in reality. Simulation is currently used for a multiplicity of functions in the building design process e.g. overheating analysis, plant sizing, plant and control performance analysis, ventilation/contamination analysis, lighting design, day lighting design, renewable energy resources integration etc.

The simulation tool used for the requisite simulations is ESP-r.

ESP-r allows an in-depth appraisal of the factors that influence the energy and environmental performance of buildings. The ESP-r system has been the subject of sustained developments since 1974 with the objective of simulating building performance in a manner that:

a) Is realistic and adheres closely to actual physical systems,
b) Supports early-through-detailed design stage appraisals, and
c) Enables integrated performance assessments in which no single issue is unduly prominent.

ESP-r attempts to simulate the real world as rigorously as possible and to a level that is consistent with current best practice in the international simulation community. This is because it addresses all aspects simultaneously. It is based on a finite volume, conservation approach in which a problem (specified in terms of geometry, construction, operation, leakage distribution, etc.) is transformed into a set of conservation equations (for energy, mass, momentum, etc.) that are then integrated at successive time-steps in response to climate, occupant and control system influences. [12]

1.4 The Project

The objective of the thesis is to develop and apply a modelling approach to Dynamic Insulation and to quantify the associated energy saving and human comfort. This thesis is primarily concerned with identifying a suitable simulation technique for modelling of Dynamic Insulation, validation of the same against known analytical solutions and simulation of a real building to identify the energy savings that may be expected and to look at human comfort for the occupants. An obvious prerequisite to doing this is to become familiarised with whatever literature is available on the subject, a review of any modelling work that has been done on Dynamic Insulation. The probable approach from there on is the development and validation of models using analytical and empirical validation methods and then the application of findings to a case study to evaluate the performance of Dynamic Insulation in terms of energy consumption and human comfort.

Robust and time tested as ESP-r is, it so far unfortunately does not support building fabric through which fluid can pass and exchange heat. A search was carried out for such a simulation tool but none was found. The first problem then was to adapt ESP-r to emulate fluid permeable walls. After that validation was carried out this being done against the one-dimensional steady state theory of Dynamic Insulation. After a reasonable level of confidence was achieved in the simulation technique the actual simulation of the test house was done.

CHAPTER 2

Dynamic Insulation & Simulation Modelling

2.1 Dynamic Insulation

2.1.1 Historical Perspective

Dynamic Insulation was first studied in the middle of the 19th century at the University of Munich by Professor Max von Pettenkoffer [6], but it was only in 1965 that D R Pattie, Professor of Engineering Science at the Ontario Agricultural College, Canada, developed the basic thermal theory and a mathematical representation for its calculation [6]. Also during this time Dynamic Insulation was starting to be employed in barns and other air permeable structures in the Scandinavian countries notably Norway and Sweden where the natural stack effect was being used [17]. A significant contributor during the 60s was the Norwegian University of Agriculture and such constructions were used as barn roofs primarily due to the efforts of Trygve Graee [6]. The application of Dynamic Insulation was by now being considered for buildings requiring large air change rates e.g. sports halls, and for buildings requiring efficient moisture control e.g. swimming pools. The Swedish and Norwegian Building Research Institutes have been and still are quite active.

The first application of this technology to residential buildings was due to the work of Helmut Bartussek of Austria [11] and it was shown that a U value of zero was, at least theoretically possible. Arvid Dalehaug [16] indicated that Dynamic Insulation reclaimed 50% of conductive heat losses from a building. A lot of work has been done in this field at the University of Lund, Sweden and lately at the University of Aberdeen, Scotland. Mathematical analysis of both heat transfer and filtration properties has been extended by Taylor and Imbabi (University of Aberdeen).

The first building in the UK employing this concept was the Camphill Trust in Aberdeen in 1995-96 and it is generally considered that the thermal performance of the building was worse than expected [6], this was probably due to leakage of air into the indoors through cracks and vents despite the fact that the building was constructed to a higher-than-normal standard. Of the still relatively few dynamically insulated buildings in the UK the notable ones are McLaren Community Leisure Centre, Callander and the Drumchapel Ecological, Sports and Environment Centre, Glasgow.

2.1.2 What is Dynamic Insulation?

Dynamic insulation is the name given to that type of insulation in which all or part of the conductive heat loss is recaptured by the active flow of fluid (air for building constructions) against the temperature gradient. This scheme of flow is called contra-flux mode of Dynamic Insulation. Such a construction may also be used in the pro-flux mode in which the fluid flows in the same direction as heat but then its insulation properties are not realised. All building fabric is permeable to air to some degree but for dynamically insulating materials (such as cellulose) the permeability is quite high (0.25~0.3m^2/hPa) and for a pressure difference of up to 50Pa between the external and internal environments a significant amount of air can be drawn in at low air velocities (of the order of a few m/h). A pressure difference of the order mentioned is to be considered an upper limit because otherwise it would become difficult to open windows and doors. Air drawn in should not be high velocity, as it would then constitute draught conditions.

2.1.3 Selection of materials

The main criteria for the selection of materials are achieving airtight-ness and airflow at a suitable pressure difference across the dynamically insulated construction.

With the use of blown cellulose fibre, excellent fill can be achieved particularly in ceilings. In walls there may be a tendency of slumping of the cellulose fibre, but evidence for this is little. However, BRE's experience with a prototype wall suggests that quality control of the application of the blown cellulose fibre into the wall space is essential to achieve a complete fill [6]. In wall systems, the use of a rigid air permeable board, e.g. low density wood fibre, is recommended to contain the insulation [16] to achieve a suitable pressure drop.

In a ceiling construction a suitable air permeable membrane should be used as the control layer to ensure a suitable pressure drop across the construction. Note that vapour permeable membranes such as Tyvek® are not necessarily air permeable. Air permeability testing to select the control layer material is strongly recommended.

2.1.4 Benefits of Dynamic Insulation

2.1.4.1 Better indoor air quality

Quality of indoor air is of prime importance to humankind because the majority of people living in urban areas spend around 90% of their time indoors. The same is applicable to a lesser but not insignificant extent in rural areas, where a study conducted on children showed that those in the Scottish Highlands experience the same increase in asthma as children in urban areas [17]. Using air permeable construction can ensure better indoor air quality by three mechanisms. Firstly it reduces the need for air intake ducts where dirt particles can accumulate and from where they spread indoors. Mechanical ventilation systems are prime contributors to indoor air pollution (up to 45%) [4]. Ducting, heat exchangers and air filters are almost always a necessity in conventionally built buildings, be they air conditioned or naturally ventilated. Dynamically insulated buildings inherently require less ducting and other mechanical support than conventional buildings. So such type of a building may be quite suitable for heavily polluted city centre sites.

Secondly Dynamic Insulation reduces the amount of particles in the air. Recent research in the U.S. shows that fine air particles (less than 2.5μm in diameter) increase mortality rate. [20] It has been suggested that it is a large number of ultra fine particles (diameters less than 0.1μm) rather than larger ones (diameter less than 10μm) that cause an increase in mortality and asthma. Studies on rats show that non-toxic particles in the micron range may prove to be toxic in the sub-micron range [20]. These are able to settle in lung alveoli and cause inflammation. Not only this, but adsorbed chemical air pollution on their surfaces can damage sensitive tissue. Such small particles also have longer residence time in the atmosphere.

Dynamic Insulation with its very low air velocities is extremely efficient at filtering particles less than 0.5μm in diameter. Furthermore because of its thickness being more than conventional filters it is better than these even though it has lower single fibre collection efficiency. The filtration of a Dynamic Insulation wall can be made to approach the performance of a high efficiency particulate arrestor (HEPA) air filter [20]. The clogging up of a Dynamic Insulation wall, and the transition from depth filtration to surface or filter cake filtration, has been studied [5&20]. There is the possibility of formation of a filter cake at the surface. This would require the presence of a greater pressure difference for the insulation to perform at the same level as before, this would be quite undesirable. The dust settling and consequent filter cake formation is quite low for a Dynamic Insulation wall because of low flow rates and larger surface area. Satisfactory performance life of a typical wall under such conditions has been put at more than 100 years [5], which is considerably greater than the service life of the insulation material.

Thirdly Dynamic Insulation construction allows moisture and air pollution to diffuse out of the structure through the pores of the construction. Monitoring at Rykkinnhallen Sports Hall, Baerum, Norway identified lower carbon monoxide levels (115ppm inside to 200ppm outside) but this remains unsupported by any report on the monitoring strategy [5]. Whilst there is evidence of the above in the pro-flux mode it is quite unlikely in the contra-flux mode[1], but remains the likely outcome whenever air is not drawn in through

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1 Mass transfer of pollutants in a porous medium is governed by diffusion. The direction of flow can be changed by forced fluid flow in the direction opposite that of net diffusion (this can conveniently be done by causation of a pressure difference across the medium). Diffusion will stop if the velocity of fluid (air) flowing against the concentration gradient is greater than or equal to the critical velocity V_c where

$$v_c = \frac{\ln(c_i/c_o)}{R_d}$$

c_i and c_o being the inner and outer concentrations respectively and R_d is the total diffusive resistance.

the walls (for example outwith working hours at an office). No conclusive study into the diffusive properties of Dynamic Insulation could be found.

The quality of the indoor environment can significantly impact building occupants. Quality indoor environments can result in:

- Increased occupant satisfaction
- Enhanced performance/productivity
- Reduced absenteeism at workplaces
- Marketing advantage
- Reduced liability

Lower operations and maintenance costs

2.1.4.2 Health Considerations

Recent Swedish research [17] has shown that most modern buildings experience a range of relative humidity between 30 and 70%. The growth of bacteria, fungi and other health hazards as a function of the RH is shown in fig 1.1. Vapour open and ventilated constructions tend to suppress such health hazards because it is possible to keep the relative humidity within the optimal zone by the use of Dynamic Insulation. There is a further appeal in terms of environmental friendliness, recyclability and sustainability, which may be important to some consumers.

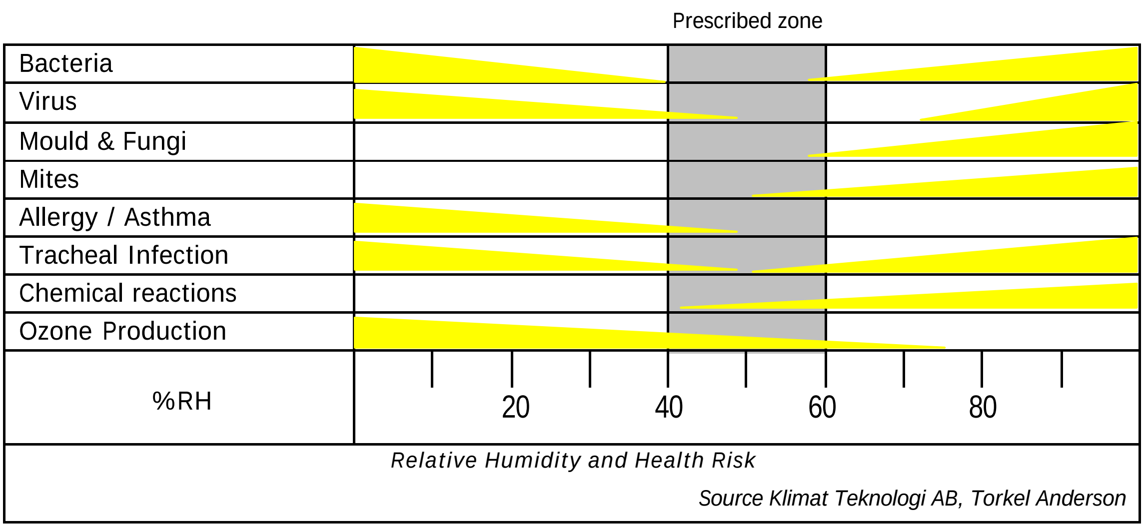

Figure 1.1 Favourable RH ranges for health hazards.

2.1.4.3 Interstitial Condensation

The greater part of humidity damage to construction material is due to air leakage or more appropriately moisture flow from the inside to the outside. Condensation occurs in the material wherever the temperature is lower than the dew point temperature. Moisture may leak outwards because of a general overpressure inside conventionally built and operated buildings. A moisture transfusive wall when operated in the contra-flux mode encourages moisture flow inwards and dispenses with the need for a vapour barrier (see fig 1.2).

This is because Dynamic Insulation provides its own vapour barrier provided that the air velocity is greater than the critical value defined previously. Critical velocity can show greater variation than the optimal velocity for energy conservation and the two may not correlate well under diverse external weather conditions, but nevertheless chances for interstitial condensation are minimal except e.g. very hot sun shining on recently rain saturated cladding in which case RH can rise quickly and cause condensation in the still relatively cool insulation.

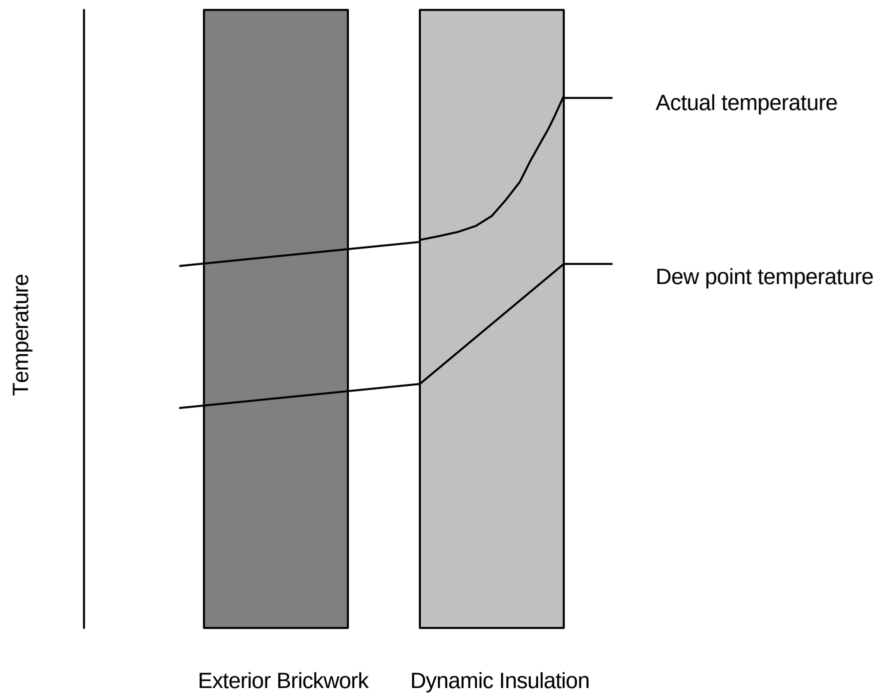

Figure 1.2 Variation of Temperature within the fabric of a construction employing Dynamic Insulation

2.1.4.4 Energy Saving

Cambridge Architectural Research has carried out a parametric modelling study on typical UK house and office configurations. The model assumes that the entire wall area of the buildings was available for Dynamic Insulation and a heat exchanger was also used to recover energy from outgoing air [7]. The results of the study indicated that the following design and operational characteristics had first order effects on reducing energy consumption using contra-flux Dynamic Insulation:

1. Ventilation rate
2. Air leakage
3. Volume / Surface area ratio
4. Thermal conductivity of the building envelope
5. External air temperature

For houses, the modelling indicated that around 25% of the total energy saving could be achieved using Dynamic Insulation, the rest (75%) using the heat exchanger. However, the study does not report the saving as a proportion of the energy use of the building without these measures.

2.1.5 Effect of Solar Radiation

Although the influence of solar radiation on the performance of Dynamic Insulation has been noted, its effect has not been quantified, except by Baker [18]. The latter determined the solar heat gain factor[2] of a prototype wall at BRE as 0.02, from measurements of incident solar radiation, temperature and heat flux through the wall. This value depends on the

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2. Solar heat gain factor is a measure of how much energy in a particular heat transfer event is supplied by solar heat.

$$g = \frac{U\Delta T - H}{G_v}$$

where g is the solar heat gain factor, U is the fabric U value, ÄT is the temperature difference between the outside and inside surface temperatures, H is the total heat flux and G_v is the incident solar radiation.

properties of the outer skin of the wall. The BRE prototype wall is constructed with an outer skin of profiled metal sheets, the surface of which can heat up to 40^{o}C+.

Provided the material properties of the outer skin are known, it is possible to estimate or model the influence of the solar radiation on heat transfer by both radiation and convection to the external surface of the Dynamic Insulation. Similarly, the effect of under-cooling at night can be determined.

Practical experience has shown that solar gains can dominate performance. At the McLaren Community Leisure Centre overheating of the sports hall due to high roof void temperatures (>40^{o}C) was noted over the summer period [4]. The supply air fans in the roof were consequently switched off and opening windows provided ventilation. On a sunny day the ventilation heat loss can be considerably reduced by the solar gains.

2.1.6 Under-pressure production and factors disturbing it

The most important factor in making Dynamic Insulation work is the production and maintenance of an under-pressure in the building. Under-pressure can be achieved passively by means of the natural stack effect; this pressure difference in terms of density difference and temperature difference is given by the two equations below

$$\Delta P = (\boldsymbol{r}_e - \boldsymbol{r}_i)gh$$

$$\Delta P = ah\left(\frac{1}{T_e} - \frac{1}{T_i}\right)$$

ΔP = Stack effect pressure [Pa]

ρ = Density [kg/m^3]

G = Gravitational field strength [9.81 N/kg]

h = Height from neutral pressure level NPL [14]

a = 3414 N K/m^3

T = Absolute temperature [9]

Subscript e is exterior and i is interior [16]

The stack effect has been used in practice in the Dynamic Insulation of barns in the Scandinavian countries. Attractive as it may seem, the stack effect has its down sides. Firstly it is strongly temperature dependent and increases with greater temperature difference. The pressure variation is a uniform one as shown in fig 1.3. Even when assuming that the temperature of the interior is strictly controlled it has to be taken into account to design a dynamic wall. [16]

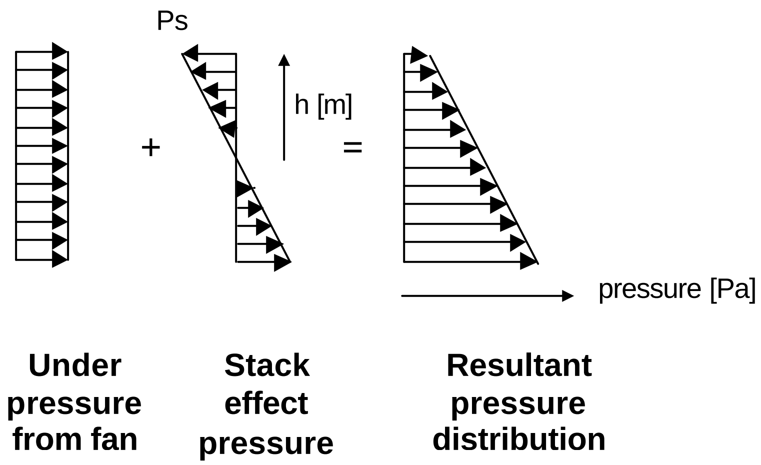


Figure 1.3 Resultant pressure distribution on inside wall surface due to the stack effect pressure and under-pressure from fan.

A more reliable scheme to produce and maintain an under-pressure is by means of mechanical ventilation systems. The two most popular configurations are shown in fig 1.4.

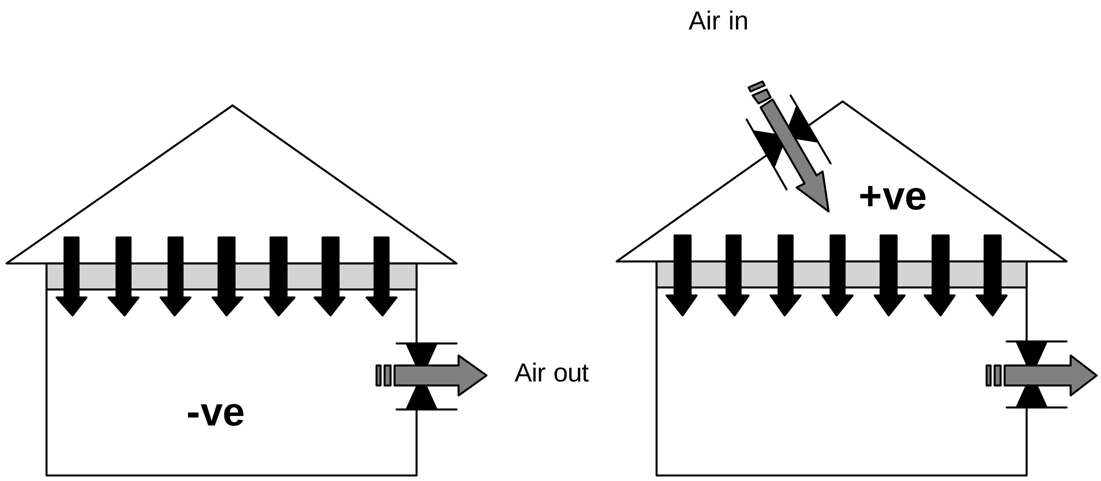


Figure 1.4 Two most common configurations for under-pressure maintenance for the purpose of Dynamic Insulation.

The air speeds when such a system is in operation have an upper limit of around 10m/h, which is significantly below draught conditions (0.2m/s) [17]. Such a system also allows excess moisture to be removed from the interior. It should be noted that the dynamic wall only acts as a vapour barrier and does not provide for any means of moisture removal. There may be some outward diffusion of moisture through the dynamic wall though (See section 2.1.4.1)

An important consideration when designing houses with dynamic walls is to make the construction exceptionally airtight because otherwise a greater amount of energy would have to be expended to produce the required pressure difference. The air must flow in through the air permeable walls rather than through construction joints, penetrations through walls, around doors and windows, etc. This adventitious air infiltration must be kept to a minimum, and requires careful design of construction details and close supervision during construction [8]

Opening and closing door and windows would disturb the pressure difference. This has been shown not to have a long-term adverse effect on the pressure difference provided that the doors and windows are opened for a short time [16&19] For example opening a standard sized door for 30 seconds in a room where the air velocity in the dynamic wall is 6m/h would cause the air to move pro-flux by something like 5cm assuming complete pressure difference reversal i.e. the same pressure difference now acting in the reverse sense. Normal airflow would resume once the door is closed.

A great amount of pressure disturbance is caused by wind. The pressure difference is given by

$$\Delta P = C_p\left(\frac{rV^2}{2}\right)$$

where

ΔP = Wind Pressure difference [Pa]

ρ = Density of air [kg/m^3]

C_p = Co-efficient of pressure [dimensionless]

V = Air velocity [m/s]

A typical distribution is shown in fig 1.5. [8]

The co-efficient of pressure has to be measured experimentally in a wind tunnel or obtained from computer simulation programs (e.g. FLUENT) or established correlations. As a general observation the wind angle and building aspect ratio significantly affect $C_{p.}$ The pressure on the windward side is about 0.5-0.8 times the dynamic or velocity pressure and the negative pressure on the leeward side is approximately 0.3-0.4 times this pressure. For Dynamic Insulation the effect of wind can be neglected for intermittent gusts but not for more persistent winds. This means the conductive heat loss is recovered most effectively from the windward wall and least effectively from the leeward wall. There may even be the possibility for reversal of contra-flux airflow to pro-flux in the event of a large enough wind speed; this could cause a substantial heat loss from the leeward wall. The problem can be overcome by making the outer cladding of the dynamic wall element reasonably wind proof, for example a sufficiently wide continuous cavity all around the house could greatly reduce the pressure disturbances due to wind. [8]

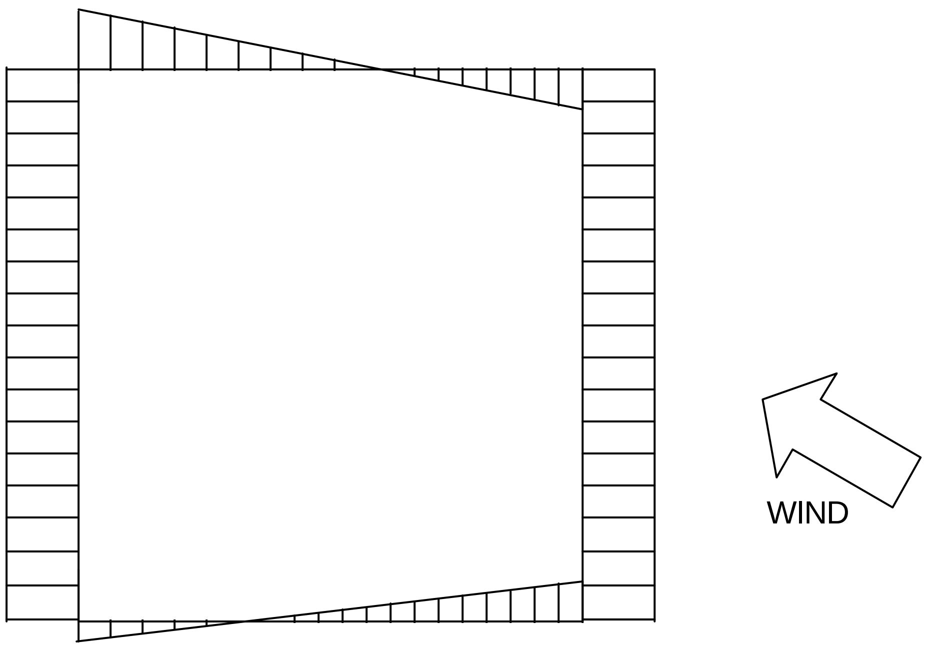


Figure 1.5 Pressure distributions around a building due to wind.

2.1.7 Dynamic Insulation – Some Concerns

2.1.7.1 Surface finishes

For Dynamic Insulation to operate effectively, the ventilation air must be able to flow into the building without restriction. In a ceiling system, such as the one used in the McLaren Community Leisure Centre, air permeable ceiling tiles are used [6]. However, in a wall system, the use of a permeable wall liner is likely to be problematic. The surface cannot be decorated using normal paint or wallpaper. Pictures cannot be hung or furniture placed against the wall. It should also be possible to clean surfaces easily. Solutions to this drawback usually consist of having a normal plasterboard liner (which is impermeable to air). Air is drawn through the Dynamic Insulation into a cavity behind the plasterboard from where it is distributed into the room. In a Norwegian sheltered housing scheme, the air is brought in under the windowsill [17]. In the Japanese test house, 10mm gaps are used at the top and bottom of the plasterboard [16]. A prototype test wall built on a test cell at BRE Scotland uses a 25mm slot at the top of the plasterboard liner, to which plastic ductwork and a fan are attached [6].

2.1.7.2 Buildability Issues

In order to achieve the required performance, buildings applying Dynamic Insulation must conform to stringent detailing criteria. It is crucial to the building performance that the airflow through the Dynamic Insulation is maintained as designed since it is integral to the heating requirement of the building. The following issues should be considered when planning a Dynamically Insulated structure [6].

- A fully wind-proof outer skin to protect the insulation from pressure fluctuations, which might cause flow reversal and condensation.
- Prevention of air leakage along ceiling joists to avoid condensation.
- An airtight loft construction carried out to an identified and testable standard.

- A generally airtight building: air leakage paths would undermine the airflow through the Dynamic Insulation by allowing cold air to be drawn directly from outside.
- The airflow is dependent on the pressure differential across the building envelope: in practical terms this is restricted to around 50Pa, the highest acceptable pressure difference which would not give rise to problems with doors opening and shutting.
- Good ventilation of the unheated roof void, positioning of air inlets, etc. may contribute to energy savings.
- A checklist of items that could be installed incorrectly should be drawn up for pre-commissioning; e.g. installing fans the right way round.
- Extracts should not be near light fittings, as this will deflect the downward flow pattern of air in case of a dynamically insulated roof.

2.1.7.3 Design issues

- The dynamically insulated building should be seen as an entire system, rather than as an assemblage of parts such as dynamically insulated walling components.
- Architects are not enthusiastic about building elements that advertise their technical properties in a visual way, or constrain designers' freedom to determine the aesthetics of the building envelope.
- The responsibility for correct performance of the building must be clearly defined, perhaps by a manufacturer's warranty.
- Architects or construction supervisors must be able to check that design tolerances are being achieved on site and have effective remedies available.
- Designers need access to simply presented but authoritative guidance on technical issues, including relevant performance data for material and assemblages; design checklists; and specialist advice.

2.1.7.4 Construction issues

- The extent to which building properties assumed in modelling can be realised in actuality is a key question. Building professionals will want to see examples of Dynamic Insulation in practice, with thorough documentation of detailed design and correct procedures. They are also concerned over the maintainability of components and installations over the lifetime of the building (related to liability of building designer and construction supervisor).
- Modular construction may provide cost savings for builders. The use of specialist teams, possibly trained and licensed by product manufacturers, could be a way of ensuring a high-quality result in terms of site construction.
- Designers would like to see a single supplier take responsibility for manufacture and installation of all elements of the dynamic envelope and associated systems. This "one stop shop" approach would certainly simplify liability issues.

2.1.7.5 Cost

- Cost considerations are vitally important to building users, particularly in the commercial sector: to justify extra investment in novel technologies, potential users need to be able to refer to financial cost benefit modelling exercises to give detailed information on likely payback.
- However, the over cost in larger non-domestic buildings will tend to be less than in smaller ones. This is because many of the mechanical systems will already be in place, or specified as part of a new development. This may be an important factor in payback analysis.
- In the domestic sector, interesting financial mechanisms are being developed by housing associations to charge more for low energy

houses, which users recoup over their occupancy period in the building through lowered running costs.

2.1.7.6 Maintenance

- Building owners and occupants are also concerned about long-term maintenance issues, both in the case of building fabric and accompanying mechanical systems. A case can be made for a 'fit and forget' system, particularly in the domestic sector, embodied in existing extract systems like cooker hoods or bathroom extract, to reduce maintenance problems.

2.1.7.7 Further Technical issues

- Radon and Methane - Under some conditions, potential problems should be considered of methane and radon induction due to the under-pressure inside the building. This is a particular concern for dwellings, and applies especially to buildings with basements.
- Regulation - The status of Dynamic Insulation systems in relation to building regulations must be made clear in order for the concept to be widely taken up.

2.2 Simulation Modelling

2.2.1 Development and Overview of ESP-r

Over the last 25 years new fields of computer analysis for buildings have emerged

(a) Dynamic energy simulation e.g. ESP-r. It involves the calculation of the performance of the building (temperatures, fluid flows, energy fluxes) with time, using time varying climatic variables occupant and control strategies as boundary conditions.

(b) Computational Fluid Dynamics (CFD e.g., FLUENT) CFD involves the solution of the basic equations of conservation of energy, mass, concentration and momentum for one or more species of fluid. This gives the temperature, velocity and concentration fields for a particular fluid flow situation. CFD is used in building design for detailed airflow analysis.

(c) Lighting analysis (e.g. RADIANCE) Detailed lighting tools use a backwards ray tracing technique to produce photo realistic images. The path of each light ray in the image is calculated and the simulation process is computationally intensive.

(d) Systems simulation (e.g. TRNSYS) these programs are used to calculate the dynamic performance of HVAC and other component related systems.

Computer simulation tools are particularly suitable for appraising different design options while considering a large number of design parameters. This is particularly true when considering many low energy design issues such as influence of thermal mass, solar shading, infiltration, ventilation, and active solar systems. The analysis of these issues requires a model that represents the building in a global manner, able to deal with all the different building subsystems and related energy flows. The field of building simulation is expanding to enable the integration of models of all the disparate domains of a building. One example of such an integrated simulation system is ESP-r. Within ESP-r the building and all its energy domains and their interlinkages can now be modelled, each energy subsystem being described within the context of the complete building model. These domains are combined in an integrated building model and simulated with a representative climate, occupant interaction and control strategies to give an indication of the dynamic performance of the entire building over a period of time. The integration on these fields allows the complexity of the building to be analysed in full, taking into account the couplings between the various energy subsystems that comprise the building. Simple hand calculations do not account for the complexity and couplings found between the various domains.

2.2.2 Purpose and Usage of ESP-r

ESP-r is a transient energy simulation system that is capable of modelling the energy and fluid flows within combined building and plant systems when constrained to perform to control action.

One or more zones within a building are defined in terms of geometry, construction and usage profiles. These zones are then inter-locked to form a building, in whole or in part, and, optionally, the leakage distribution is defined to enable airflow simulation. The plant network is then defined by connecting individual components. As required, component networks can be defined to represent a model for airflow according the actual Dynamic Insulation regime. And finally, the multi-zone building and multi-component plant are connected and subjected to simulation processing against user-defined control.

The entire data preparation exercise is achieved interactively, and with the aid of pre-existing databases that contain standard (or user defined) constructions, event profiles and plant components. Results analysis modules are used to view the simulation results, undertake a variety of performance appraisals and explore the interactions between assessment domains. Changes to the model parameters can then follow depending on these appraisals.

The system offers sophisticated input/output facilities that enable the user to answer such design questions as

- What, and when, are the peak building or plant loads and what are the rank-ordered causal energy flows?
- What will be the effect of some design change, such as increasing wall insulation, altering the window shape and size, changing the glazing type or distribution or changing the heating/ cooling control regime?
- How will comfort levels vary throughout the building?
- What are the relative merits of different heating and cooling systems and their associated controls?
- How will temperature stratification, in terms of zone sensor and terminal unit location, affect energy consumption and comfort control?
- What contribution does building infiltration and zone-coupled airflow make to the total boiler or chiller load and how can this be minimised?

- How do suggested design alterations affect airflow and fresh air distribution (i.e. indoor air quality) within the building?
- Which are the benefits from architectural building features such as atria, sunspaces, courtyards, etc?
- What is the optimum arrangement of constructional elements to encourage good load levelling and hence efficient plant operation?
- Which heat recovery system performs best under a range of typical operating conditions?

And so on. This allows the user to understand better the interrelation between design and performance parameters, to then identify potential problem areas, and so implement and test appropriate building, plant and/or control modifications. The design to result is more energy conscious with better comfort levels attained throughout [22].

CHAPTER 3

One Dimensional Steady State Theory of Dynamic Insulation

3.1 Fundamental Analysis

Consider a porous wall of thickness L, through which heat is being conducted to the outside as shown in fig 3.1

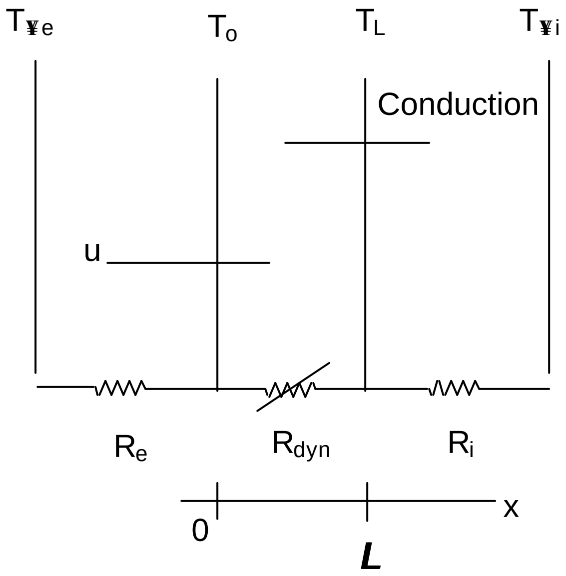


Figure 3.1 Dynamic wall with internal and external surface resistances.

The heat lost due to conduction is given by

$$q_{cx} = -\lambda \frac{dT}{dx}$$

The heat recovered due to airflow from the outside to the inside (contra-flux) assuming that heat transfer occurs instantaneously as the air passes through the fabric is given by

$$q_u = u\rho cT$$

The net heat flux at any place in the wall is the sum of these

$$q_{net} = -l \frac{dT}{dx} + urcT \qquad (1)$$

For the steady state case

$$\frac{dq_{net}}{dx} = 0$$

Hence the above equation reduces to

$$\frac{d^2T}{dx^2} - \frac{urc}{l}\frac{dT}{dx} = 0$$

This equation can be solved to give the result

$$T = C + Be^{Ax} \qquad (2)$$

Where $A = \frac{urc}{l}$ (3)

Applying the boundary conditions

$$T_0 = C + B\Big|_{x=0}$$

$$T_L = C + Be^{AL}\Big|_{x=L}$$

These simultaneous equations can be solved for B and C

$$B = \frac{T_L - T_0}{e^{AL} - 1} \qquad (4)$$

$$C = \frac{T_0 e^{AL} - T_L}{e^{AL} - 1}$$

Fig 3.2 shows the variation of T with constant external and internal surface temperatures of 0 and 20^0C using different values of u (m/s as shown in legend). The dynamic wall is assumed to be 0.6m thick and having a thermal resistance of $0.6m^2$ K/W. The variation of T with x, with changing thermal resistance (1.2 to 6 m^2 K/W in steps of 0.6) at constant value of $u=8.333\times10^{-4}$m/s can be seen in fig 3.3 the other parameters being fixed at the above values.

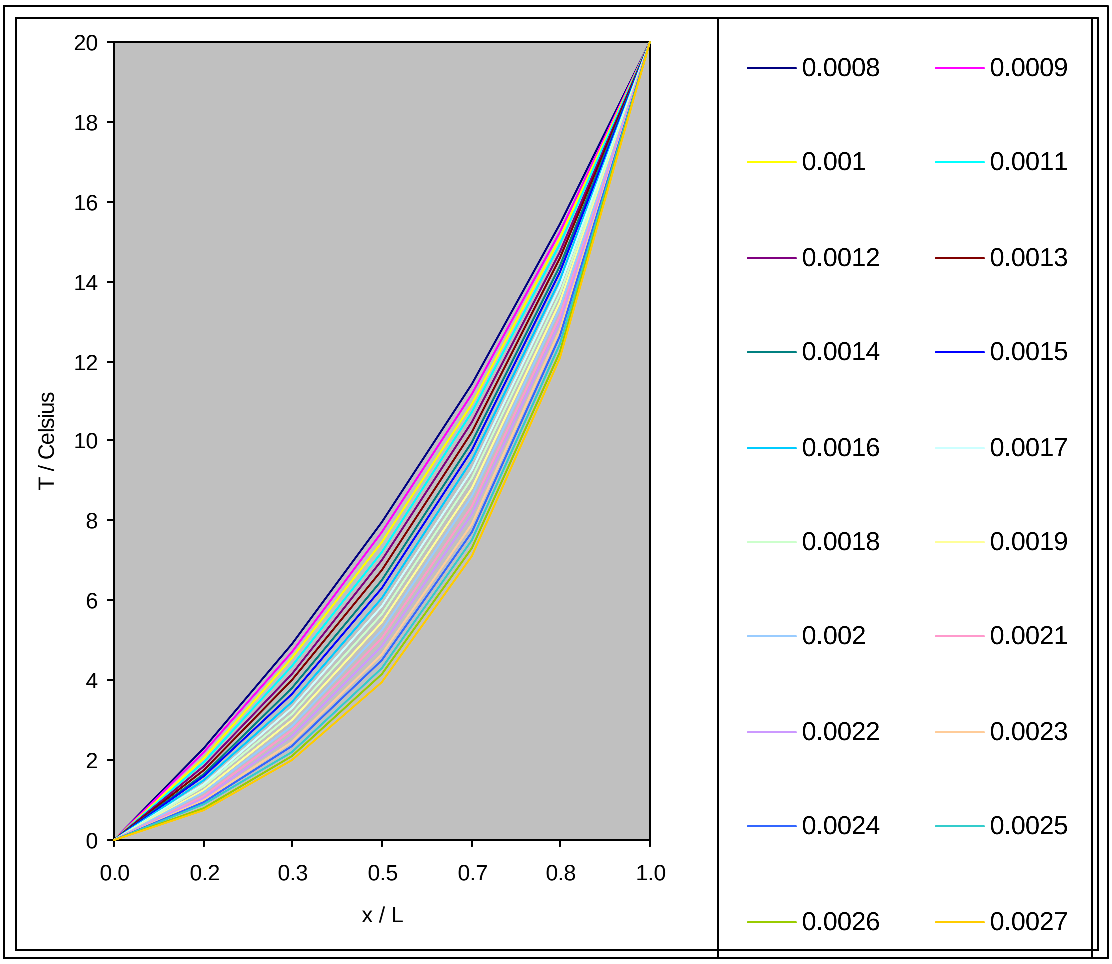


Figure 3.2 Variation of temperature within wall fabric at different air velocities.

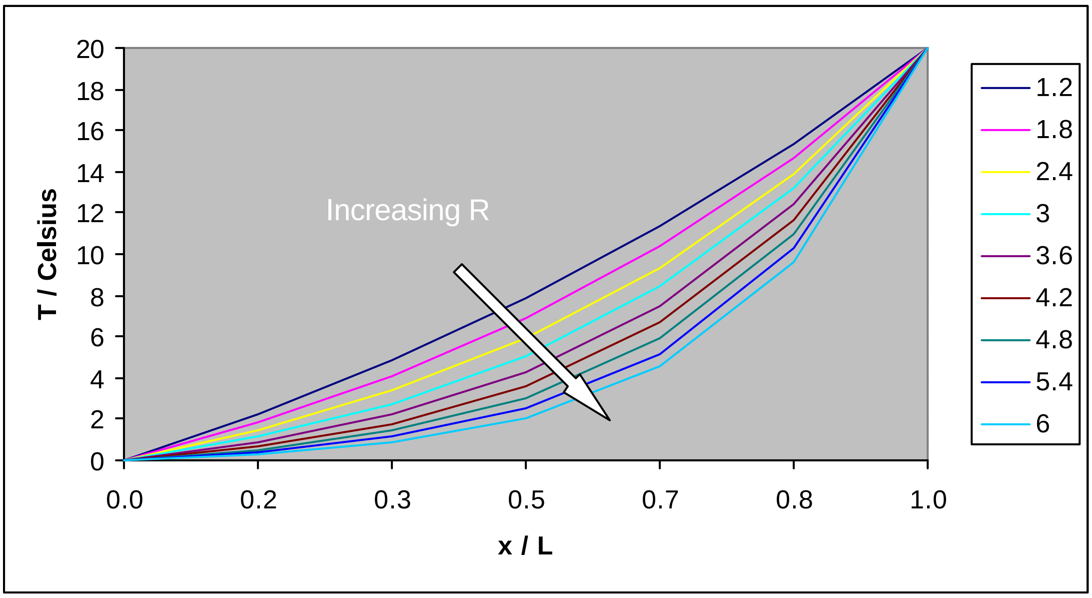


Figure 3.3 Variation of temperature within wall fabric, at different air velocities, upon increasing thermal resistance.

A further very useful result can be obtained

$$\frac{T_x - T_0}{T_L - T_0} = \frac{e^{Ax} - 1}{e^{AL} - 1}$$

The variation of the factor on the left hand side of the above equation when plotted against the ratio x/L yields graphs similar to and more general than the ones shown above.

An alternative expression may be derived for q_{cx} from (2) and q_{c0} from (4)

$$T = C + Be^{Ax}$$

$$\frac{dT}{dx} = ABe^{Ax}$$

$$q_{cx} = -\lambda \frac{dT}{dx} = \lambda ABe^{Ax}$$

$$q_{c0} = q_{cx}\big|_{x=0} = \lambda AB$$

$$q_{cx} = q_{c0}e^{Ax} \qquad (5)$$

The variation of q_{c0} may be plotted for a range of values of u as in fig 3.4. The value of internal and external ambient temperatures are at 20 and 0^0C respectively, the thickness of the dynamic wall is 0.6m and its thermal resistance varies from 1.2 to 6 m^2 K/W in steps of 0.6. Values of air velocity from 1 to 10 m/h have been investigated.

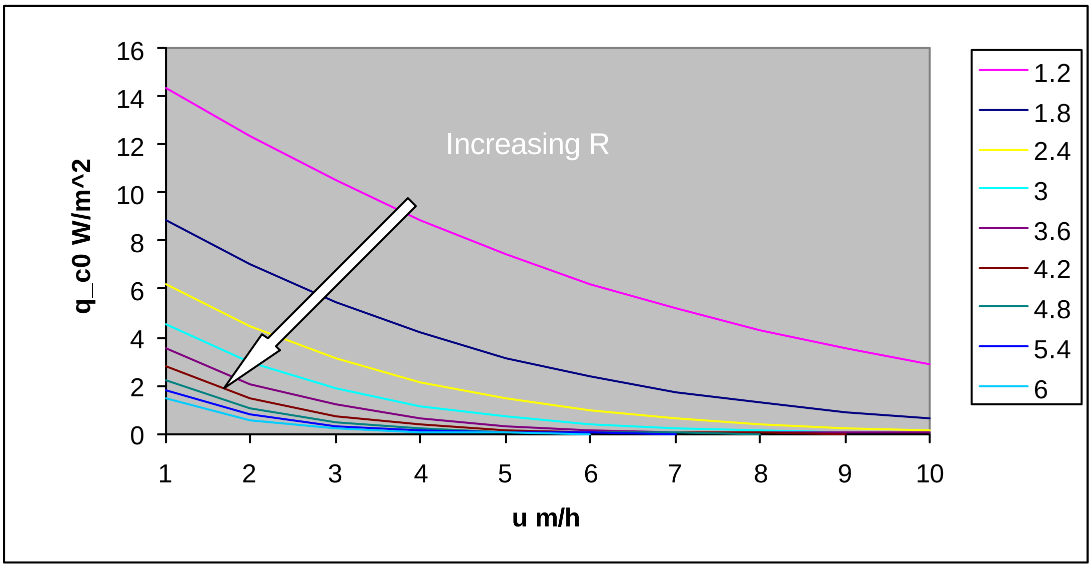


Figure 3.4 Variation of external conduction heat flux, at different air velocities, upon increasing thermal resistance.

The above equations show that the conductive heat flux at the external wall is minimum but increases further ‘into’ the structure from the outside surface. A graph of q_{cx} against x/L for values of u from 1 to 10m/h has been plotted in fig 3.5. Figure 3.6 shows that conductive heat flux at the internal surface increases with air velocity.

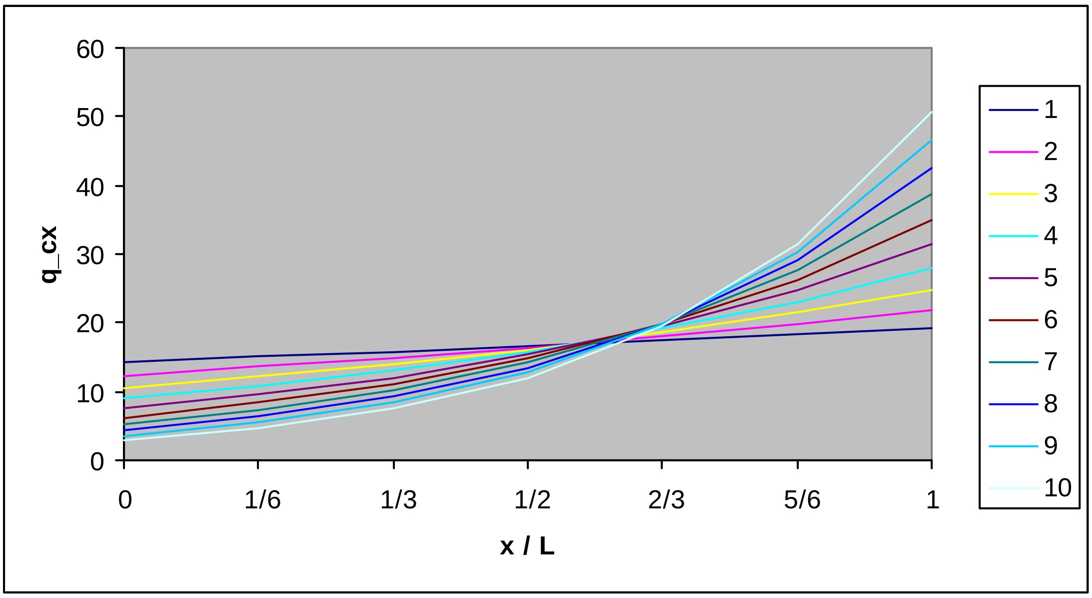


Figure 3.5 Variation of conduction heat flux within wall fabric at different air velocities

Figure 3.6 Variation of conduction heat flux at the internal surface with changing air velocity.

3.2 U Value for wall element only

Deriving for the external conduction heat flux q_{c0}

$$q_{c0} = \lambda \frac{u\rho c}{\lambda} \frac{T_L - T_0}{e^{AL} - 1}$$

$$q_{c0} = \frac{\lambda A}{e^{AL} - 1} T_L - T_0 \qquad (6)$$

$$q_{c0} = \frac{AL}{e^{AL} - 1} \frac{T_L - T_0}{R} \qquad (7) \qquad \left[R = \frac{L}{\lambda}\right]$$

From (7) the coefficient of overall heat transfer for the dynamic wall can be calculated.

$$\frac{q_{c0}}{T_L - T_0} = \frac{AL}{(e^{AL} - 1)R}$$

$$U_{dyn} = \frac{AL}{(e^{AL} - 1)R}$$

$$U_s = \frac{1}{R}$$

$$\frac{U_{dyn}}{U_s} = \frac{AL}{(e^{AL} - 1)} \qquad (8)$$

$$q_s = \frac{T_L - T_0}{R}$$

$$\frac{q_{dyn}}{q_s} = \frac{AL}{(e^{AL} - 1)} \qquad (9)$$

Here U_{dyn}, the dynamic U value, is the U value of the fabric when air is made to flow through it and picks up the conduction heat loss. It may be compared with U_s that is the normal U value of the fabric i.e. without any airflow through it. Similarly q_{dyn} and q_s are the corresponding heat fluxes with and without airflow through the fabric respectively. Equations (8) and (9) present very good contrast between the static and dynamic cases as may be appreciated by the following graphs (fig 3.7 through 3.9). For each of these the external and internal temperatures were the same as before. For fig 3.7, L was kept at 0.6m and λ at 0.5W/m K. For fig 3.8, λ was varied from 0.5 to 0.1W/m K in order that R was incremented stepwise from 1.2 to 6m^2 K/W and for fig 3.9, λ was kept fixed at 0.5W/m K and L was varied from 0.2 to 1.0m in steps of 0.2m. The air velocity u for both the latter cases was kept constant at 1m/h.

It can be seen that increasing either u, R or L has the same effect of decreasing the dynamic U value of the building fabric. The most pronounced effect is obtained by increasing the incoming air velocity. It must be emphasised though that with increasing the incoming air velocity there is the added overhead of raising the temperature of this air to ambient conditions and as will be shown later this may cause energy efficiency to decrease after a critical value for a given case. The variation of q_{dyn} / q_s will also show the same form as the graphs below because equations (8) & (9) are equivalent.

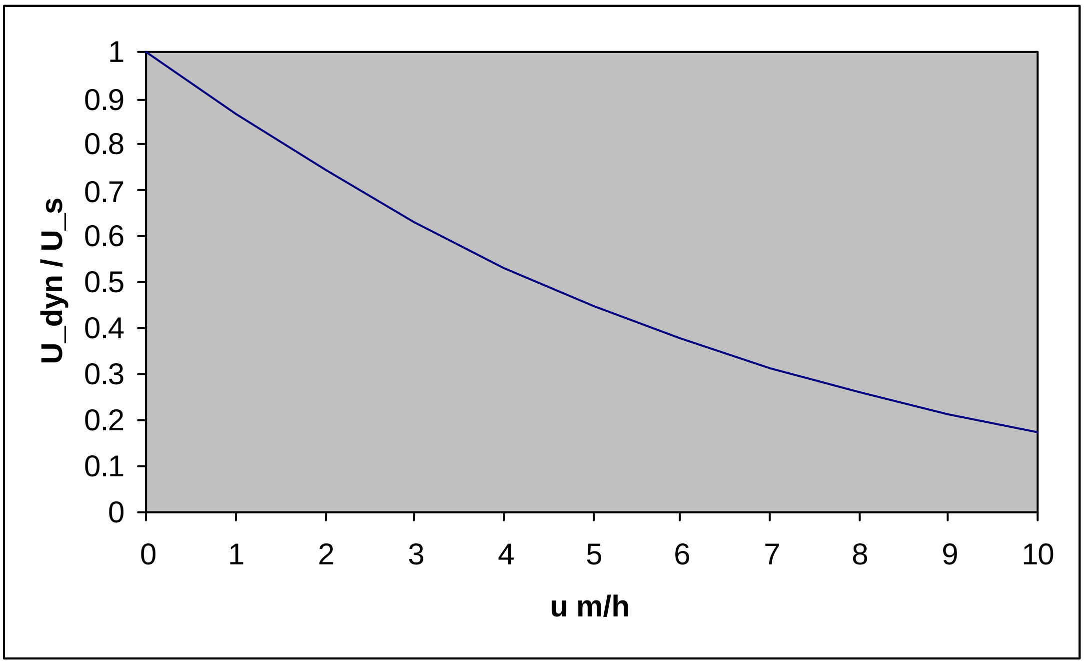


Figure 3.7 Ratio of dynamic and static U values as a function of air velocity.

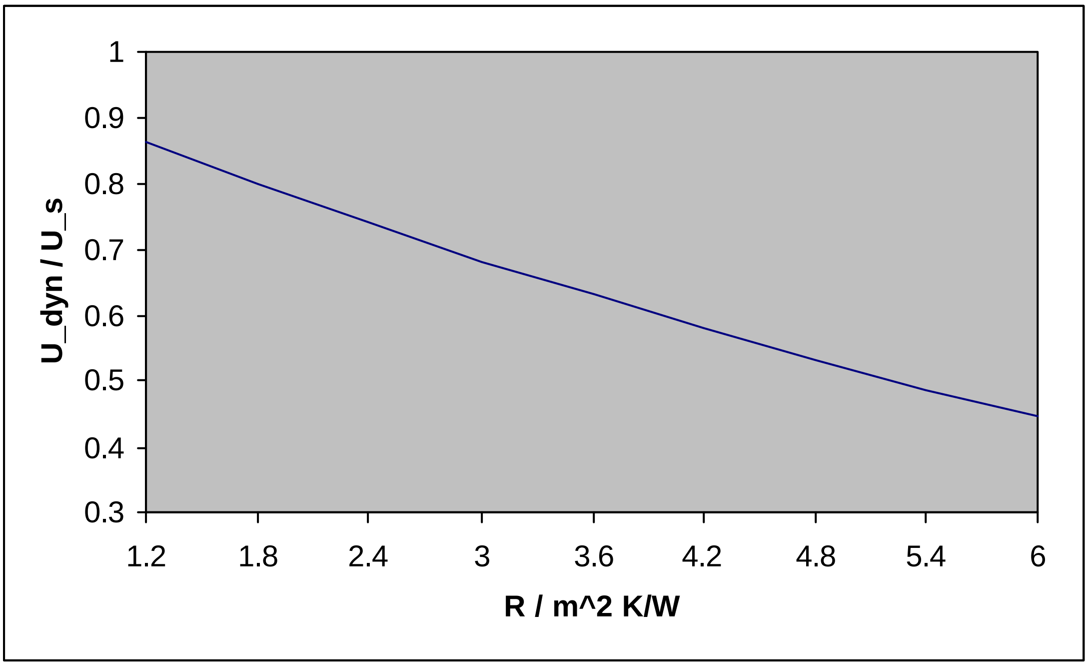


Figure 3.8 Ratio of dynamic and static U values as a function of thermal resistance.

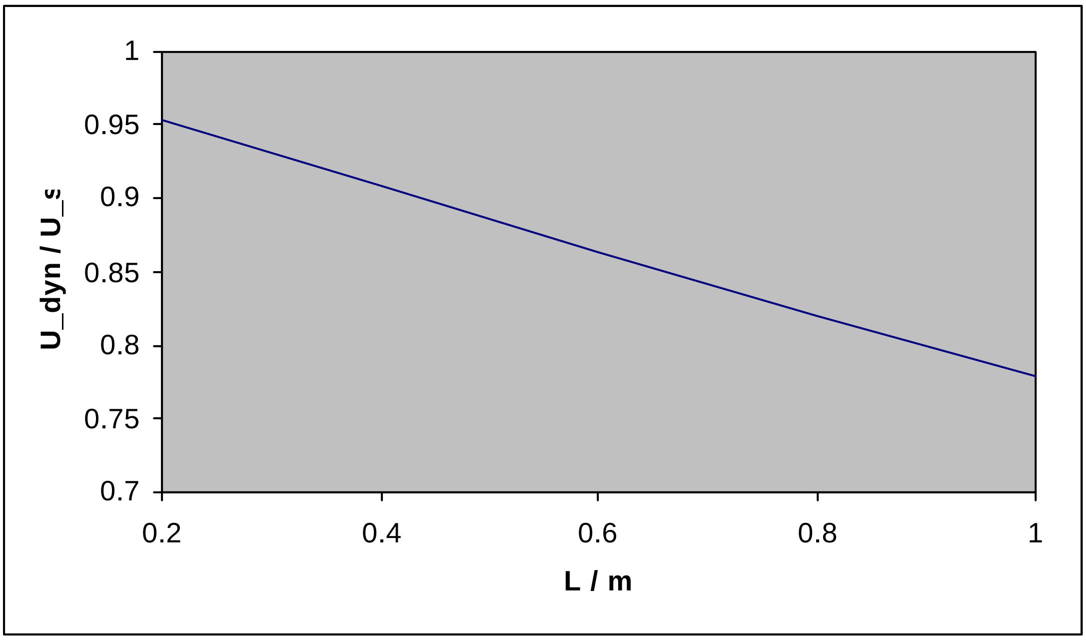


Figure 3.9 Ratio of dynamic and static U values as a function of wall thickness.

Fig 3.10 shows the variation of U_{dyn} with u and it can be seen that the U value for a dynamic wall approaches zero for large enough air velocity.

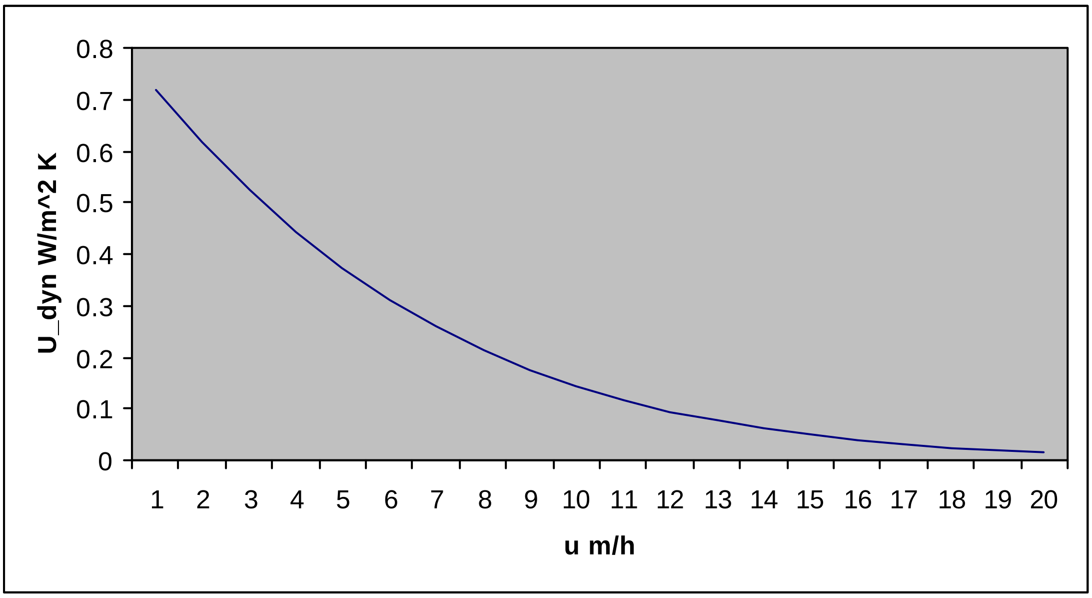


Figure 3.10 The dynamic U value as a function of air velocity.

3.3 U Value of wall element and air films

At the outer surface of the wall, the convective heat flux due to air movement into the wall is negligible at this point therefore the total heat flux will be purely conductive hence

$$q_{c0} = q_e = \frac{T_0 - T_{\infty e}}{R_e} = -\lambda \left.\frac{dT}{dx}\right|_{x=0} \qquad (10)$$

Taylor and Imbabi [21] have postulated that the conduction flux is also equal to the incident heat flux on the inside surface of the wall. This follows from the physically impossible implications if the net heat flux q_i is considered to be both conductive and convective. The heat flux then would vary inversely as the air velocity and as the air velocity gets higher q_i would tend to zero and the internal wall surface temperature T_L would tend to the internal air temperature $T_{\infty i}$, which is contrary to experiment. On the other hand if q_i is set to the conduction heat flux, then q_i increases with increasing air velocity driving down the surface temperature T_L. Hence

$$q_{cL} = q_i = \frac{T_{\infty i} - T_L}{R_i} = -\lambda \left.\frac{dT}{dx}\right|_{x=L} \qquad (11)$$

Incorporating the global environment temperatures we now can refine upon the dynamic U value.

$$T_{\infty i} - T_{\infty e} = (T_{\infty i} - T_L) + (T_L - T_0) + (T_0 - T_{\infty e})$$

$$T_{\infty i} - T_{\infty e} = q_{cL} R_i + (T_L - T_0) + q_{c0} R_e$$

Using (10) and (11)

$$T_{\infty i} - T_{\infty e} = q_{c0} e^{AL} R_i + q_{c0} \frac{(e^{AL} - 1)}{A\lambda} + q_{c0} R_e$$

$$\frac{q_{c0}}{T_{\infty i} - T_{\infty e}} = U'_{dyn} = \frac{1}{R_i e^{AL} + \frac{(e^{AL} - 1)}{A\lambda} + R_e} \qquad (12)$$

$$\frac{U'_{dyn}}{U'_s} = \frac{R_i + R_s + R_e}{R_i e^{AL} + \frac{(e^{AL} - 1)}{A\lambda} + R_e} \qquad (13)$$

In (12) and (13) U'_{dyn} and U'_s represent dynamic and static values as before but with the incorporation of surface resistances. The graph of fig 3.7 is reproduced in fig 3.11 along with a line corresponding to (13)

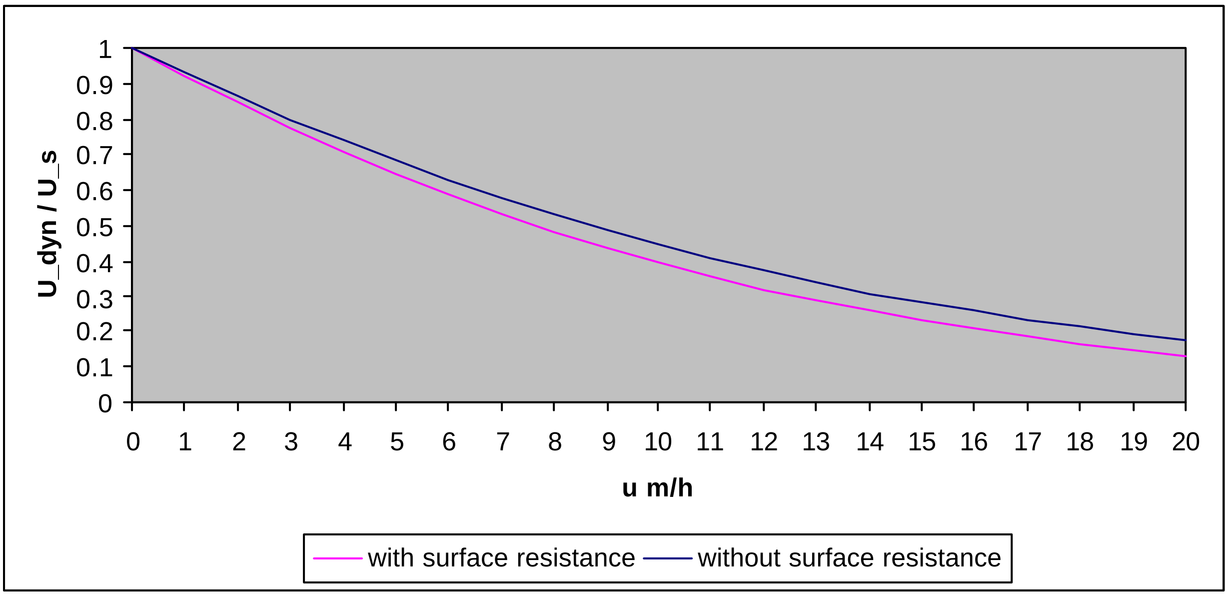


Figure 3.11 Effect of air film on the ratio of dynamic and static U values.

By comparison of equations (8) and (13) and using typical values of the various input parameters, it may be seen that when considering the static and dynamic cases for assessment of heat flux, inner and outer air films may be neglected for walls with different U values. But the same is not true when assessing the wall temperatures [21].

3.4 Overall energy recovered

Dynamic Insulation is capable of reducing the fabric conduction losses (to zero). It should be noted that the ventilation heat requirement for both static and dynamic cases is the same in that the temperature of the incoming air has to be raised to the temperature of the ambient interior air. As is evident from fig 3.4 for the dynamic case, as the velocity increases the heat recovery reaches a maximum value equivalent to the fabric conduction loss, (which is lost in the static case). Upon increasing the air velocity further there is no more conduction energy saving but it actually constitutes an overhead in the form of the heat that has to be given to this air to raise its temperature to the indoor air temperature. The amount of heat that has to be provided to the air in both the cases is the same and may be represented by $u\rho c$ When considering the total heat loss (conduction and ventilation) for both the dynamic and static cases the following equations may be used

$$\frac{q_{total\_dyn}}{q_{total\_s}} = \frac{\dfrac{1}{R_i e^{AL} + \dfrac{(e^{AL}-1)}{A\lambda} + R_e} + u\rho c}{\dfrac{1}{R_i + R_s + R_e} + u\rho c} \qquad (14)$$

$$\frac{q_{total\_dyn}}{q_{total\_s}} = \frac{U'_{dyn} + u\rho c}{U'_s + u\rho c}$$

The variation of q_{total_dyn} / q_{total_s} with u is shown below (fig 3.12). Typical value of R_i=0.14m^2 K/W and R_e=0.04m^2 K/W have been taken.

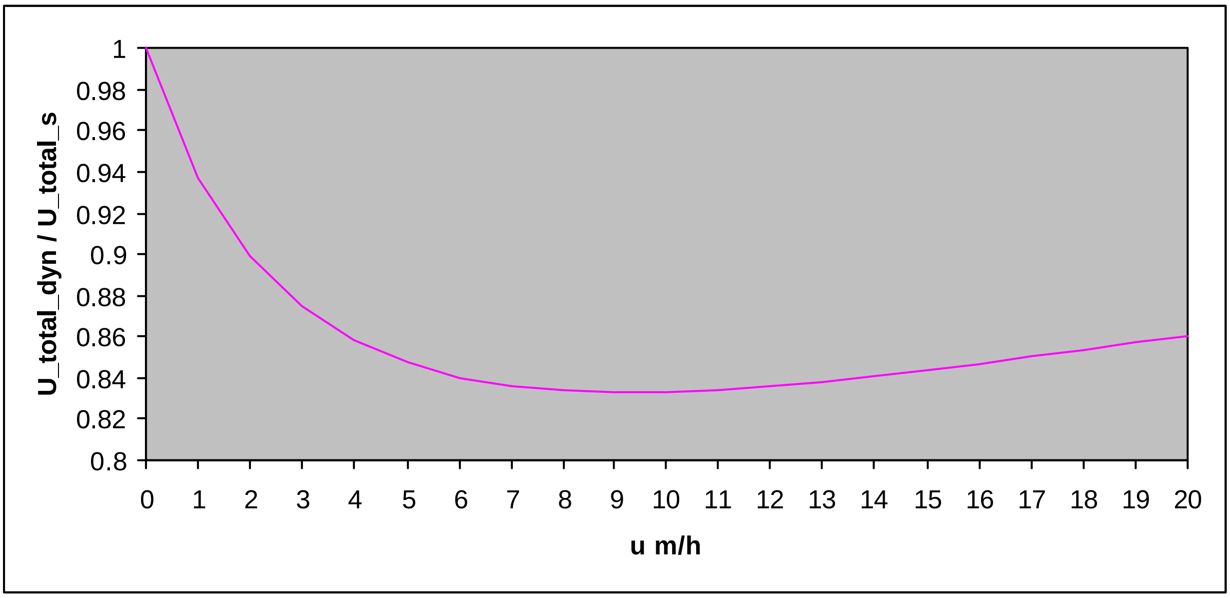


Figure 3.12 Ratio of total dynamic and static U values as a function of air velocity.

The reduction in heat requirement may be expressed as

$$\%reduction = \frac{q_{total\_s} - q_{total\_dyn}}{q_{total\_s}} \times 100$$

$$\%reduction = \frac{U_s - U_{dyn}}{U_s + u\rho c} \times 100 \qquad (15)$$

Percentage reduction in heat requirement is plotted as a function of air velocity in fig 3.13 and for the case investigated the maximum reduction is obtained at an air velocity of about 8m/h and the percentage reduction theoretically achieved is little under 17%.

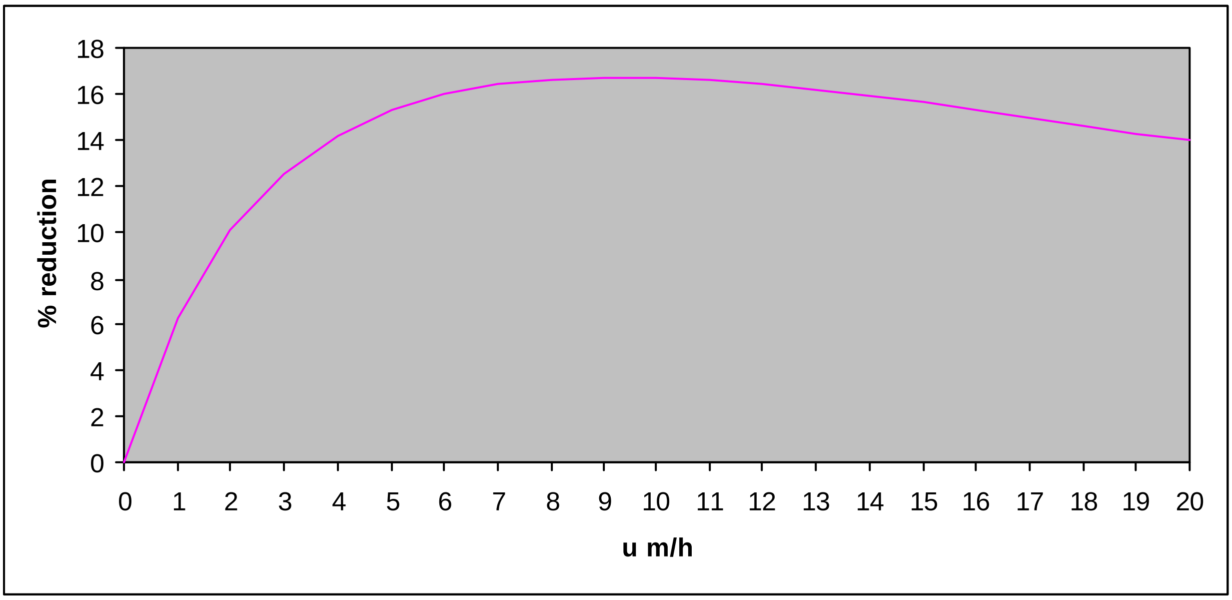


Figure 3.13 Reduction in heating energy requirement as a function of air velocity.

As can be seen the total energy saved in the dynamic case increases with u reaches a maximum and then decreases. Hence it is obvious that for any given configuration of a dynamic wall there must be some optimal air velocity. For example Baker recommends u=1.2m/h for the design configuration he has taken [19].

CHAPTER 4

Validation of ESP-r against Analytical Results and Experimental Studies

4.1 Why ESP-r?

The simulation software of choice had to be robust enough to handle the complex interaction of heat and mass flow and at the same time accurate enough to correlate well with reality. Simulation software that supported fluid permeable walls was searched for but unfortunately none was found. ESP-r was found to be quite capable of handling complex networks and was chosen because of the enormous support available locally and because of its good track record in validation studies. The problem then was to either adopt ESP-r to support fluid permeable walls or to simulate with the current model in such a way that Dynamic Insulation might be emulated to a reasonable degree of accuracy. ESP-r itself, as mentioned, has proven to be accurate enough as found in a number of different studies [9]. It has been tested by several organisations external to ESRU and has been found to agree well with known analytical and monitoring data sets. ESP-r was a participant model in the International Energy Agency's Annex 1,4 and 10 projects. It has also been widely tested within the EC's PASSYS project. It has been declared the European Reference Model for passive solar architectural design.

4.2 Approach

Two possible approaches were considered:

1. To address the problem at a fundamental level and construct the source code in such a way that it accepted mass and energy flows through the zone surfaces representative of the building fabric. Such an approach would constitute a finite volume heat balance expression

to represent heat transfer by dynamic means and an additional mass transfer component, as a function of pressure difference, in the current model of the airflow network. This was considered to be more time consuming and intricate than the second.

2. A possible approximation to dynamic behaviour could be obtained by dividing up the dynamic construction into a number of ‘zones’ and heat transfer be maximised at each of the interfaces as air was allowed to enter through relatively large openings (The actual size of the openings does not affect the end result because ESP-r considers a zone to have a homogenous temperature). This was considered to be quite reasonable in that this technically is what happens in a dynamic construction, albeit without a stepwise behaviour.

It was decided that the second approach be followed and results validated against analytical and the same approach be used for simulation of the test house if it gave satisfactory results.

4.3 Need for Validation

There was still felt a need to make sure that the approach developed and implemented was indeed accurate enough because such an approach has never been used before. ESP-r was validated against the one-dimensional steady state theory for Dynamic Insulation.

4.4 Validation against theory

A test cell was constructed in the program as shown in fig 4.1, the internal dimensions of the test cell are 3×4×2.7 metres, and the construction material is a standard external wall (100mm outer leaf brick, 75mm glass wool insulation, 50mm air gap and 100mm breeze block); the roof was 12mm felt, 50mm light mix concrete, 50mm air gap and 8mm ceiling plaster and the floor was 100mm common earth, 100mm granite, 50mm heavy mix concrete and 50mm cement screed. The dynamic wall was made up of a fictitious material called DI element with thermal conductivity 1W/mK, density 1000kg/m^3, and specific heat capacity 650J/kg K. Emissivity and absorptivity were set to 1. The overall thickness of this wall was 280mm. It might be worth noting that the actual construction material, dimensions and other physical details had little consequence on the resulting heat transfer. The only parameter of importance is the heat conductivity and emissivity of the dynamic wall.

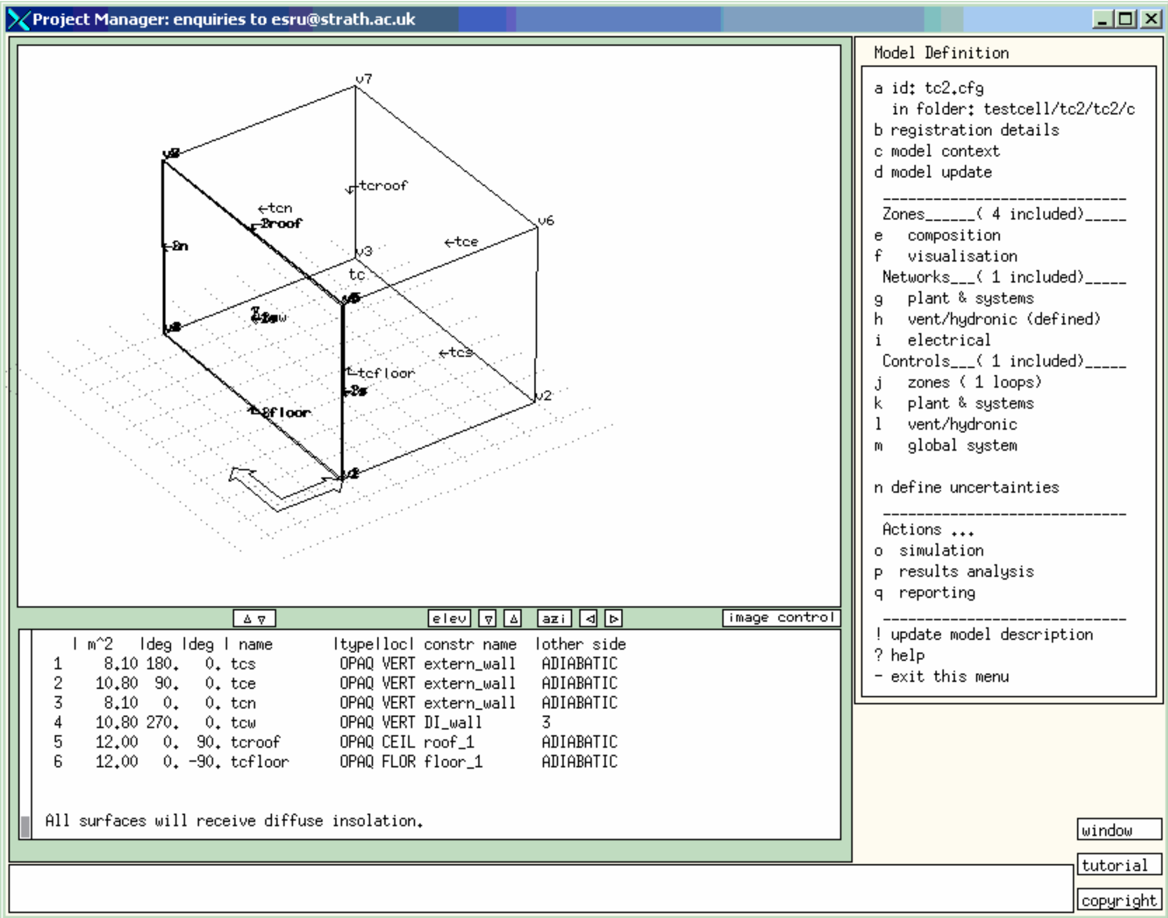


Figure 4.1 Test cell for validation of ESP-r against analytical results.

A heater with capacity 100,000W was set up inside the test cell and the inside temperature controlled to 20^{0}C. Such a large capacity heater was used to ensure that the inside temperature was strictly controlled. The test cell was designed with no casual gains (lights, equipment, occupants etc.) and infiltration. The only air allowed in was through the Dynamic Wall. In order to control the external conditions a steady state climate database was made – although in retrospect a plant with high enough capacity to maintain a constant temperature external to the test cell would have been easier to set up and equally effective.

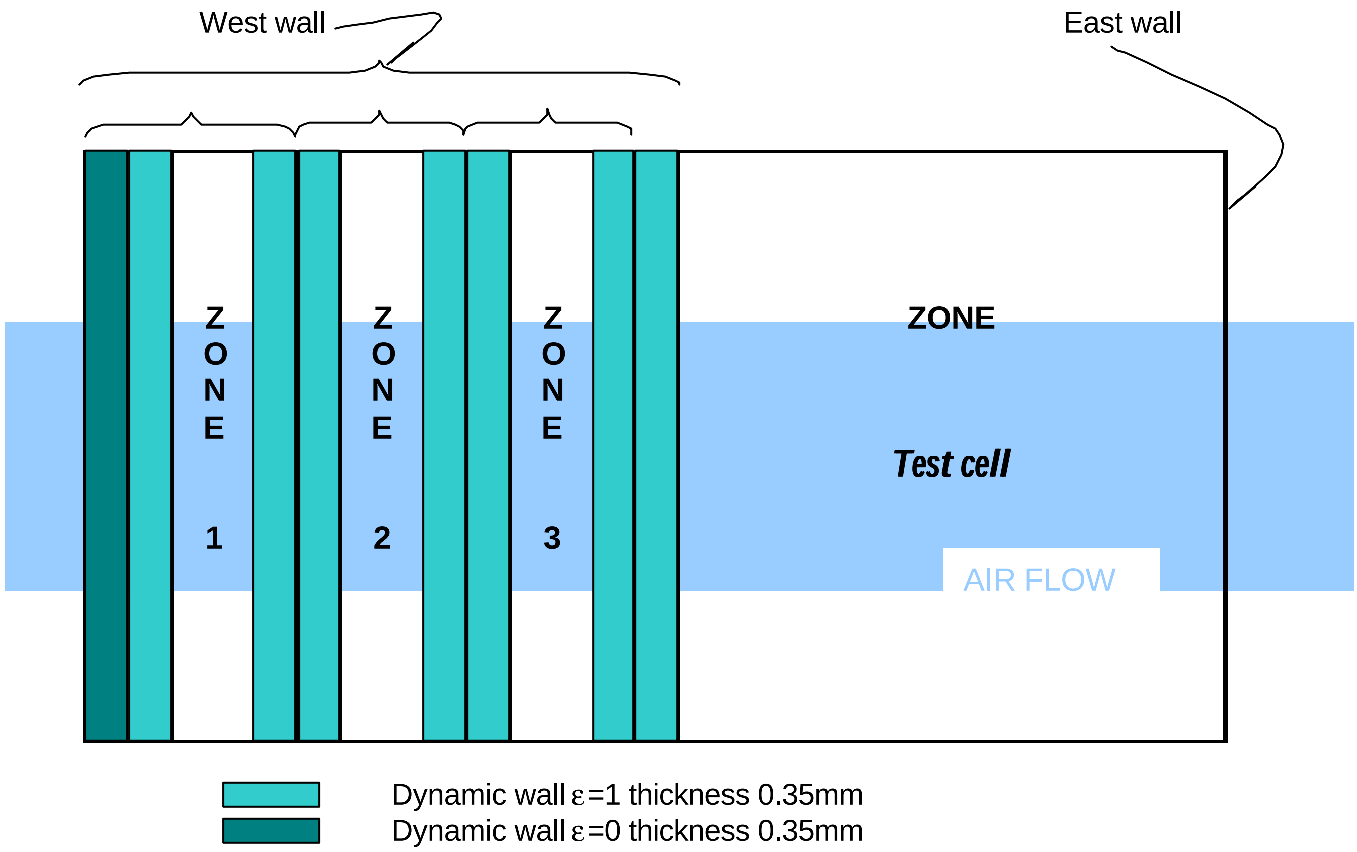


Figure 4.2 Simulation technique using fictitious zones within the dynamic wall.

The climate was set at a fixed temperature of 0^0C, 70% RH, zero wind velocity and solar radiation.

The test cell was designed such that air was drawn in through the West wall. All other walls were defined to be adiabatic so that any disturbance due to these could be eliminated. In order to approximate dynamic behaviour the West wall was divided up into three zones each zone being 20mm wide internally. The purpose of these zones was just to facilitate determination of temperature and other parameters inside the wall and it was ensured that these zones did not change the overall thermal resistance or other thermal properties of the wall in any way. The emissivity of the outside surface was set to zero to eliminate long wave radiation exchange with the atmosphere. It was found that in the absence of this precaution the temperature of the external surface was predicted to be below 0^0C because of radiation exchange with the sky. The dimensions of the different dynamic wall elements are shown in fig 4.2. The convection heat transfer coefficients of the internal surfaces were set to the maximum allowed in ESP-r i.e. 999W/m^{2}K.

Air was let into these wall zones not through the fabric itself but through a $0.5m^2$ opening in each wall. Emissivity and convection heat transfer coefficient of the walls was set such, in order that the heat transfer between these was maximised at each interval in the wall. This strategy was expected to work because as the air entered each of zones 1, 2 and 3 it experienced maximum heat transfer because of the large emissivity and convection heat transfer coefficient, hence it picked up heat at each of these interfaces and its temperature increased at the cost of a decrease in temperature of the fabric. The size of the opening was irrelevant because ESP-r considers a zone to have the same thermo-physical properties throughout.

After this an airflow network was defined, this being from the 0^0C exterior to the 20^0C interior. Air was allowed to flow across each of the wall zones into the test cell and then out the East wall through a constant volume flow rate fan. The test cell was then simulated for one week using the aforementioned 'steady state' climate database. The airflow through the test cell was varied from 2 to 10 m/h corresponding to an air change rate of 1.5 to 7.5ach. The results from the simulations were analysed to yield the zone temperatures. These were characteristic of the wall inside temperatures at x/L of ¼, ½, and ¾. The results from simulation and analytical solution of the relevant equations as set out in chapter 2 are shown in fig 4.3, 4.4 and 4.5. Percentage error was then calculated and is shown in fig 4.6 and 4.7. Heat fluxes at the inside wall surface were also determined and graphs similar to the ones for temperature are drawn in fig 4.8 to 4.10.

The simulation and analytical results correlate remarkably well, with predicted temperature keeping to within 1% of the analytical and predicted heat flux to within 8% up to 8m/h.

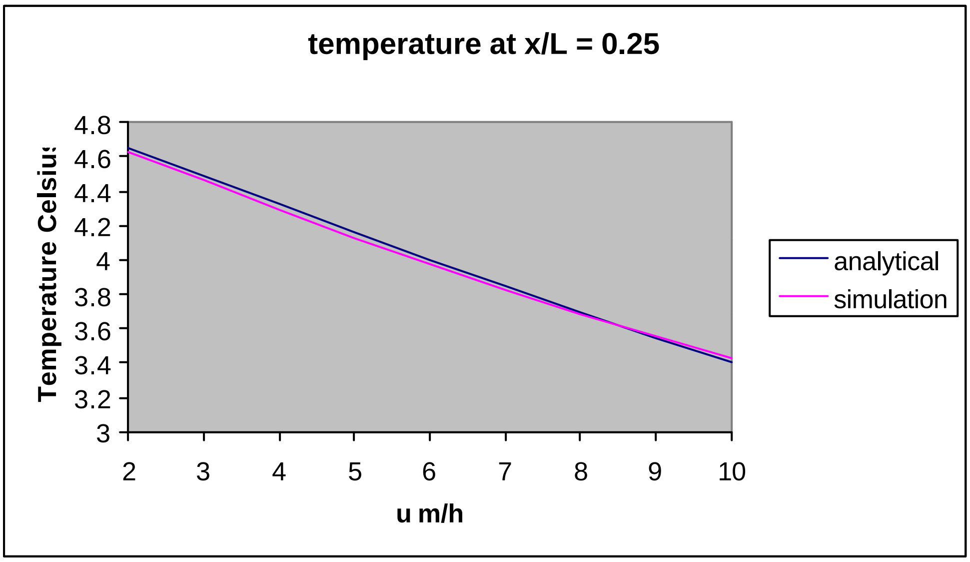


Figure 4.3 Variation of analytical and simulation temperature at different air velocities.

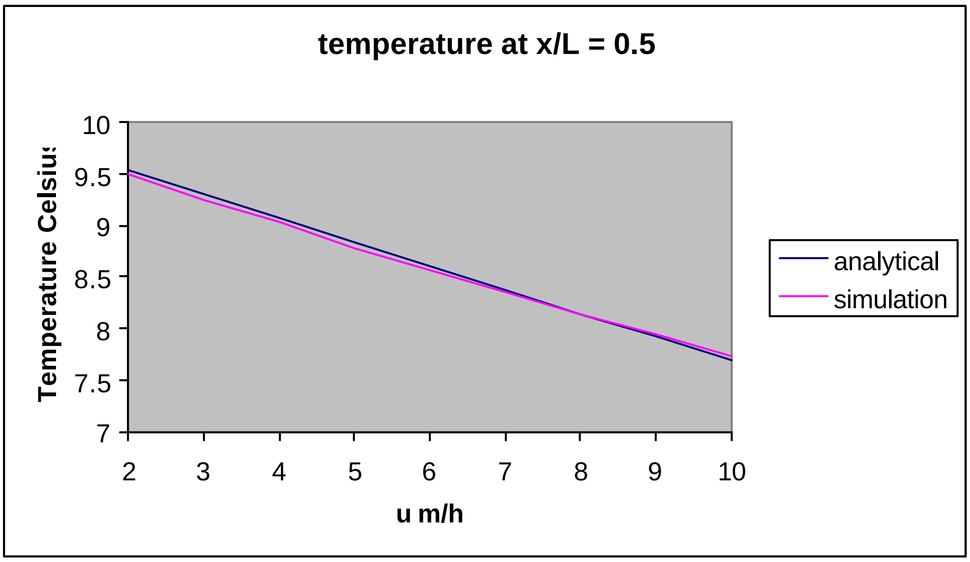


Figure 4.4 Variation of analytical and simulation temperature at different air velocities.

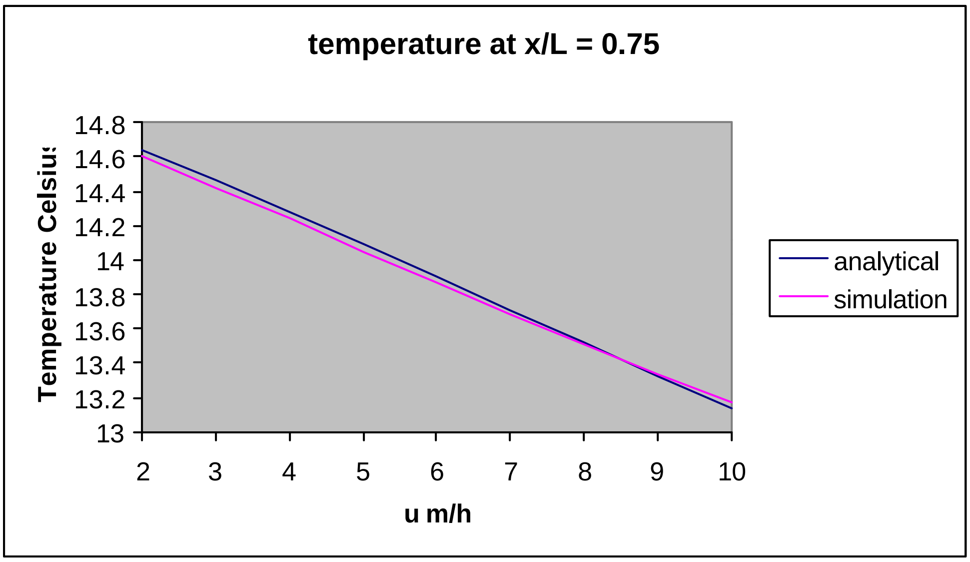


Figure 4.5 Variation of analytical and simulation temperature at different air velocities.

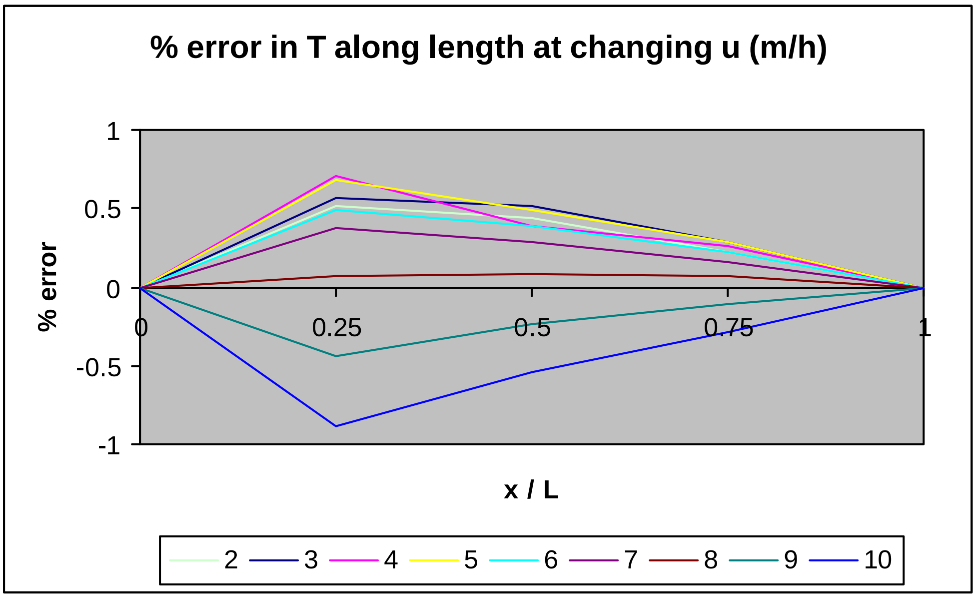


Figure 4.6 % error in temperature inside fabric at changing air velocity.

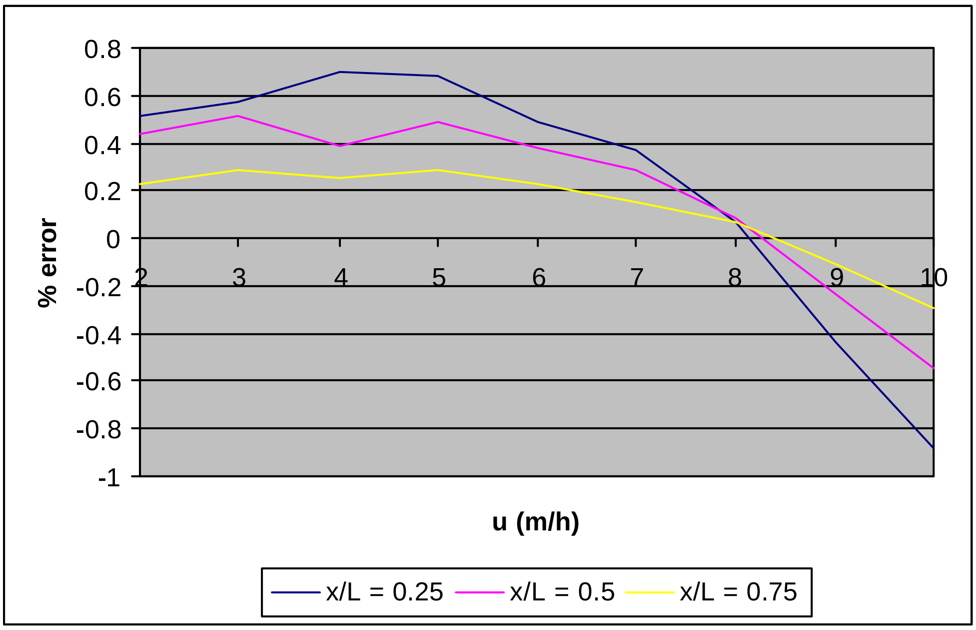


Figure 4.7 % error in temperature at different air velocities at different points within the fabric.

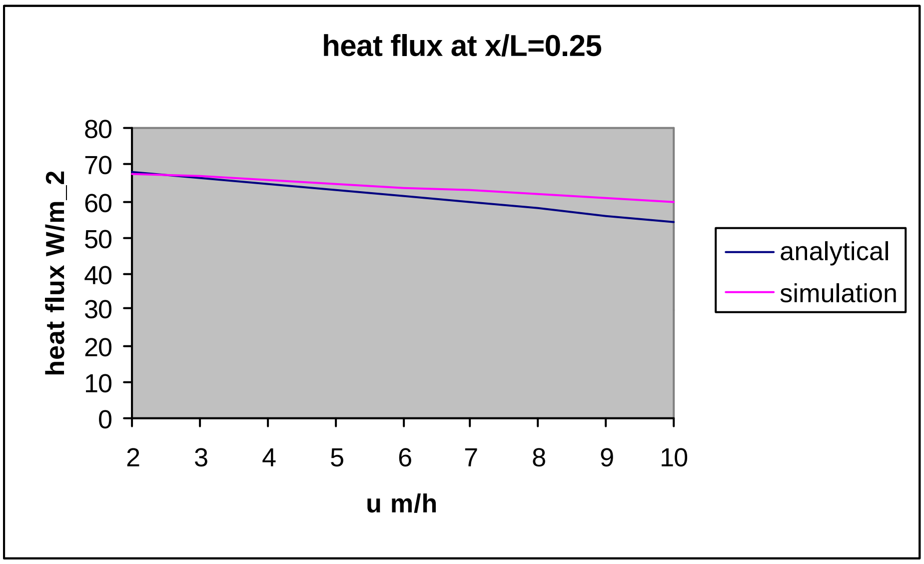


Figure 4.8 Comparison of analytical and simulation heat fluxes at different air velocities.

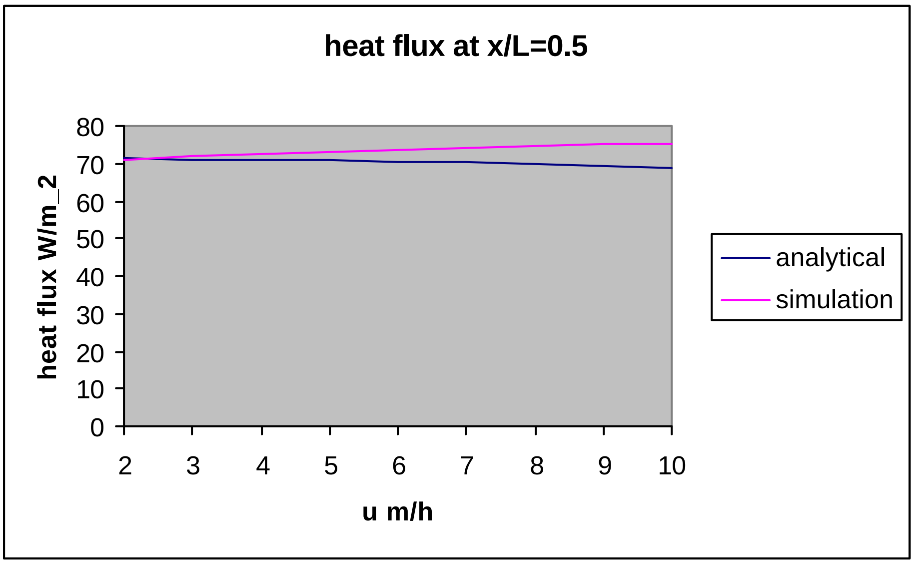
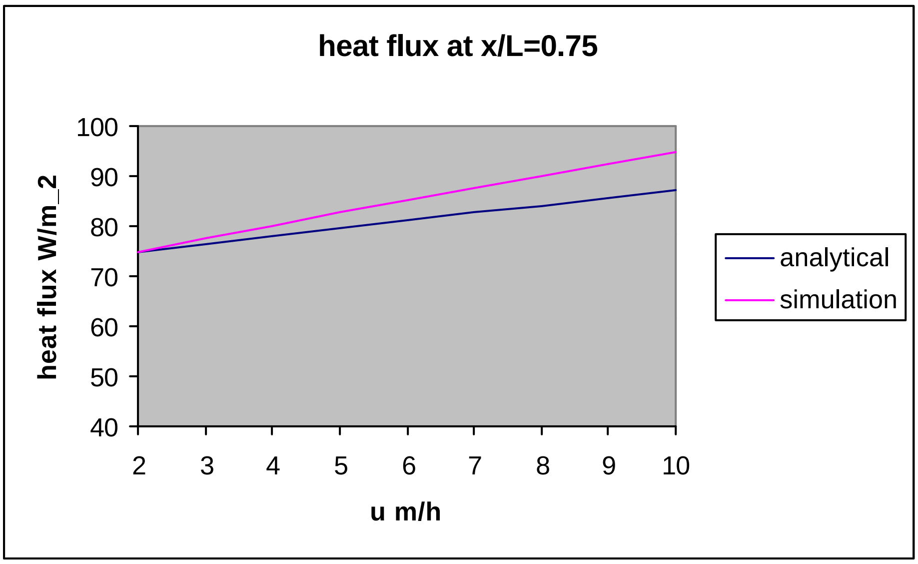


Figure 4.9 Comparison of analytical and simulation heat fluxes at different air velocities.



Fiiure 4.10 Comparison of analytical and simulation heat fluxes at different air velocities.

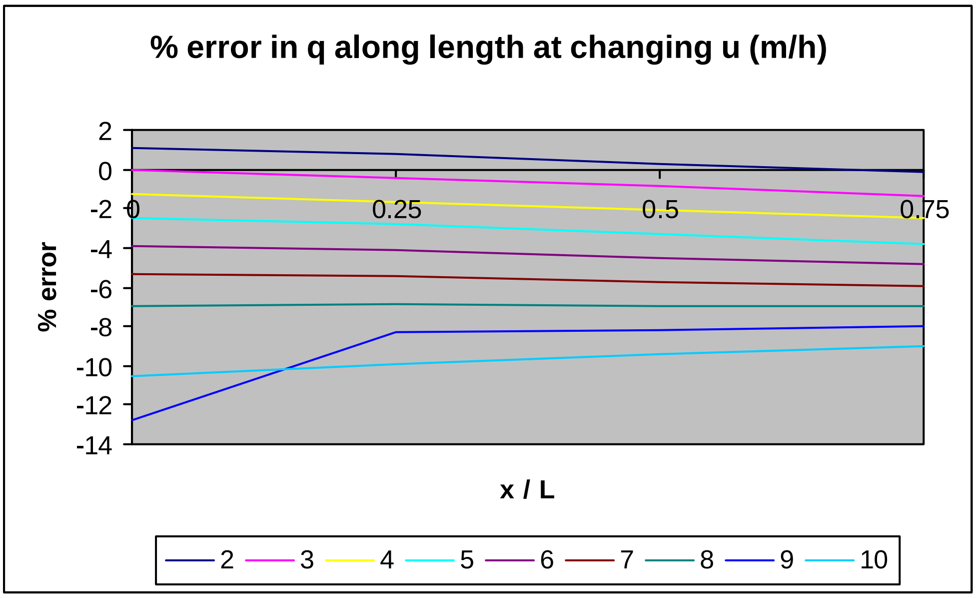


Figure 4.11 % error in heat flux inside fabric at changing air velocity

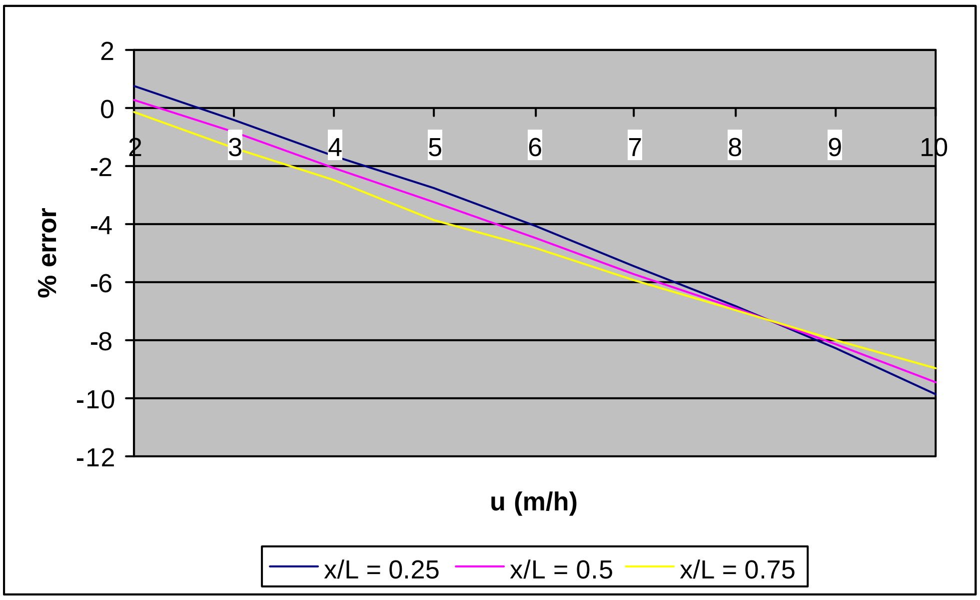


Figure 4.12 % error in heat flux at different air velocities at different points within the fabric.

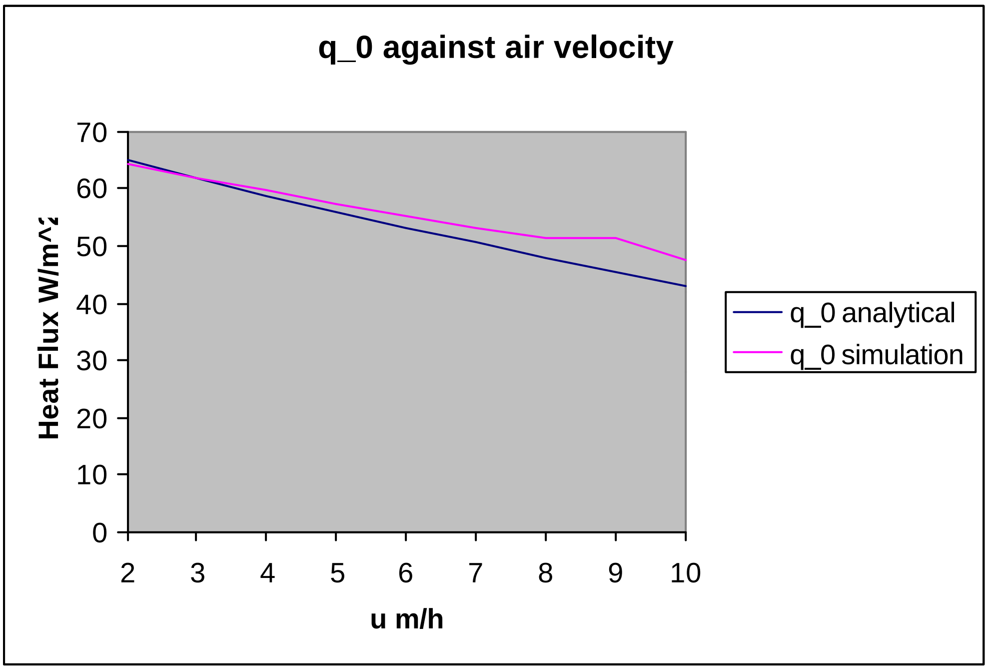


Figure 4.13 Analytical and simulation heat flux at external surface.

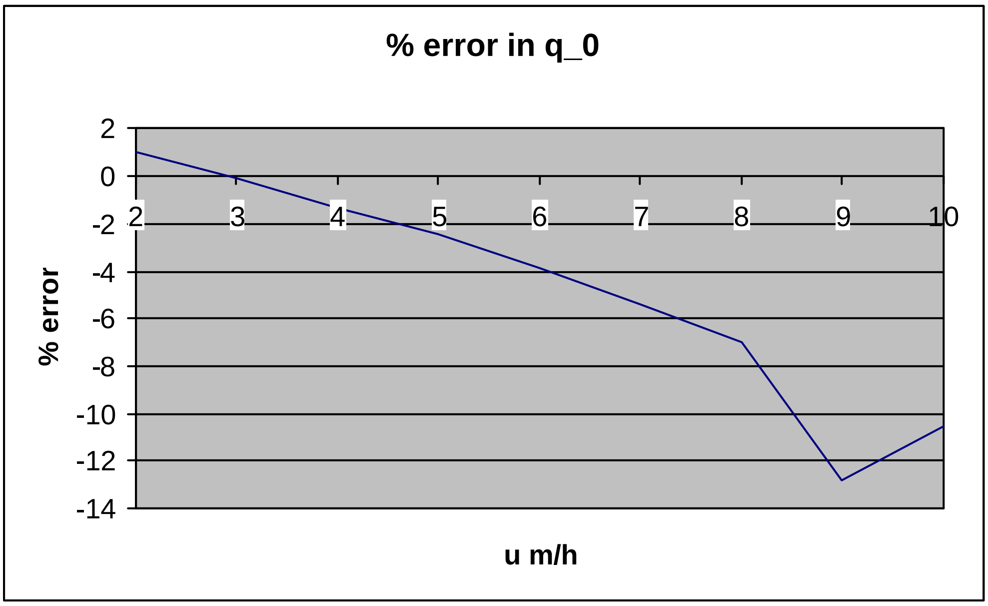


Figure 4.14 % error in external heat flux at different air velocity.

The % error in temperature seems to be a maximum at x/L=0.25 and then decreases back to zero as this ratio approaches unity. The error is overall minimum for an air velocity slightly greater than 8m/h. The heat flux variations from theoretical seem to converge at a higher value of x/L than 1, which of course is not defined. The heat flux itself shows greater variation than temperature. The % error in heat flux is seen to increase linearly with increasing the air velocity through the wall.

It is likely that more accurate results may be obtained if the zones were not equidistant and homogenously placed in space, but if they tended to be concentrated in the region of greatest temperature gradient. Nevertheless the results are considered top be satisfactory for the purpose of this investigation. Due to satisfactory results this method of simulating Dynamic Insulation has been used in validation against experimental studies and in simulation of the actual test house. It is hoped that until the incorporation of a fluid permeable wall module in ESP-r this method will be found to give satisfactory results.

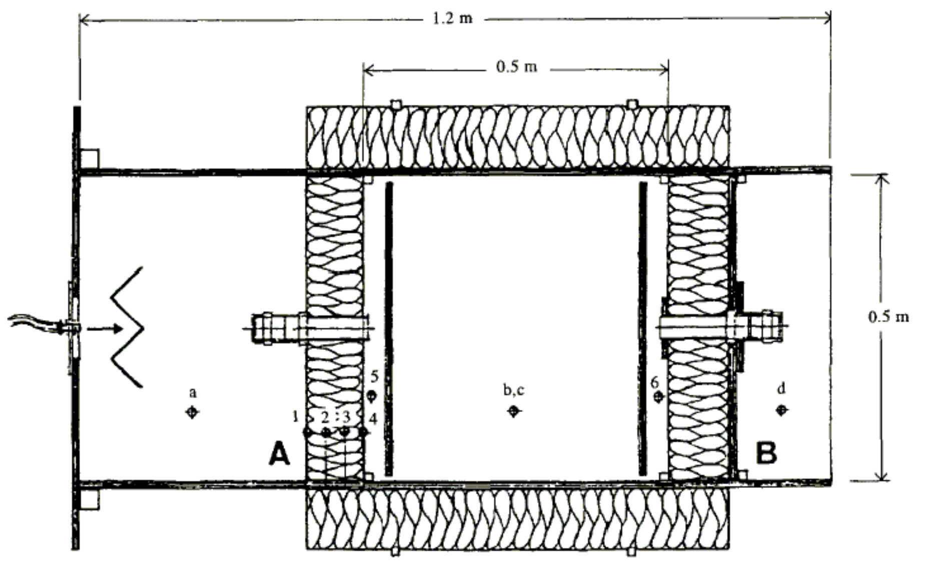
4.5 Validation against experiment

Validation against experimental studies turned out to be more difficult than validation against analytical studies. This was due to unavailability of data especially climate data sets (ESP-r requires values of dry bulb temperature, relative humidity, direct and diffuse solar radiation and wind speed and direction measured at hourly intervals.) Three experimental studies were considered to be good candidates for validation.

1. Crowther (from his PhD Thesis, University of Cambridge) [15]
2. Dalehaug (experimental studies in Japan) [16]
3. Baker (work at Building Research Establishment, East Kilbride, Scotland) [18]

The experimental study by Dalehaug could not be simulated because the climate data was unavailable and Baker's work could not be simulated because of unavailability of internal dimensions. The first one only became possible because Crowther has used a constant inlet air temperature throughout each reading.

Crowther used a hotbox, a plan view of which is shown in fig 4.15. His experiments were designed to measure the temperature profile through the wall as a function of airflow. The hot box was maintained at a temperature of 38.9^{0}C with air flowing through the wall A and out through the vent pipe B. The vent pipe in wall A was capped throughout the experiment. The apparatus is 1.2m and 0.5×0.5m square section box of plywood and covered with 100mm of mineral wool insulation. Wall A is a tight fitting batt of mineral wool and is air permeable. Air is pumped into a plenum on the left of wall A. The mean temperatures measured at the points shown in fig 4.15 are given in table 4.1.



	Mean temperature ^{0}C				
Airflow m/h	Probe a	Probe 1	Probe 4	Probe 5	Probe b & c
0.6	20.08	20.92	36.68	37.88	39.04
1.32	20.37	20.84	36.20	37.84	38.99
2.76	20.88	21.22	35.28	37.38	38.92
4.2	20.98	21.14	34.32	37.04	38.89
5.5	22.02	22.00	33.68	36.80	38.92

Table 4.1 Temperature of different probes at different airflow.

Crowther's hotbox was simulated using the airflow rates of table 4.1 and the corresponding external air temperatures (probe a). The temperatures of probes 4 and 5 have been predicted using ESP-r. Thermo-physical details of the materials used could not be found therefore typical material properties were used. The hotbox as an ESP-r model is shown in fig 4.16 and a comparison of experimental temperature and predicted temperature using simulation is shown in figs 4.17 and 4.18.

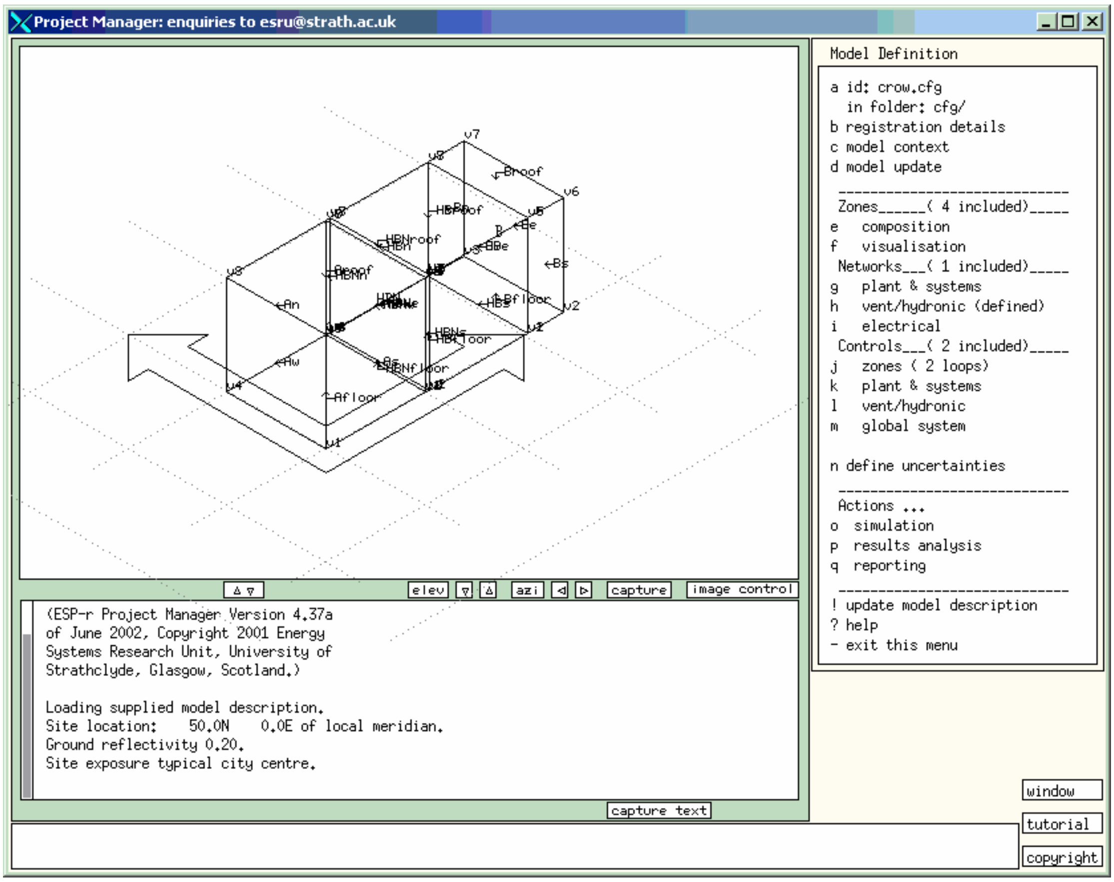


Figure 4.16 Test cell used to validate ESP-r against analytical results.

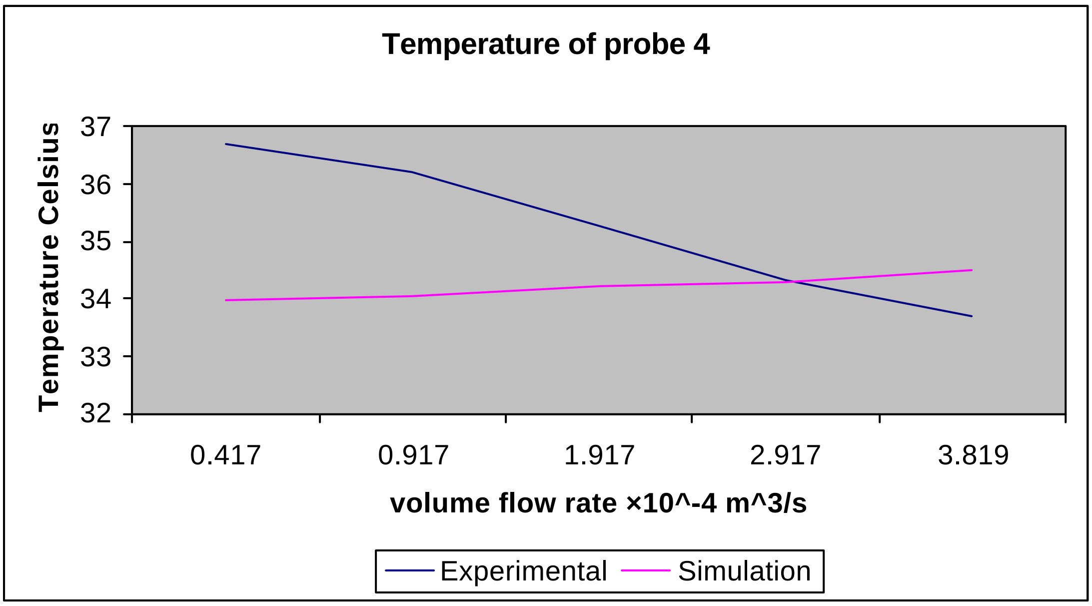


Figure 4.17 Experimental and simulation temperatures at different flowrates.

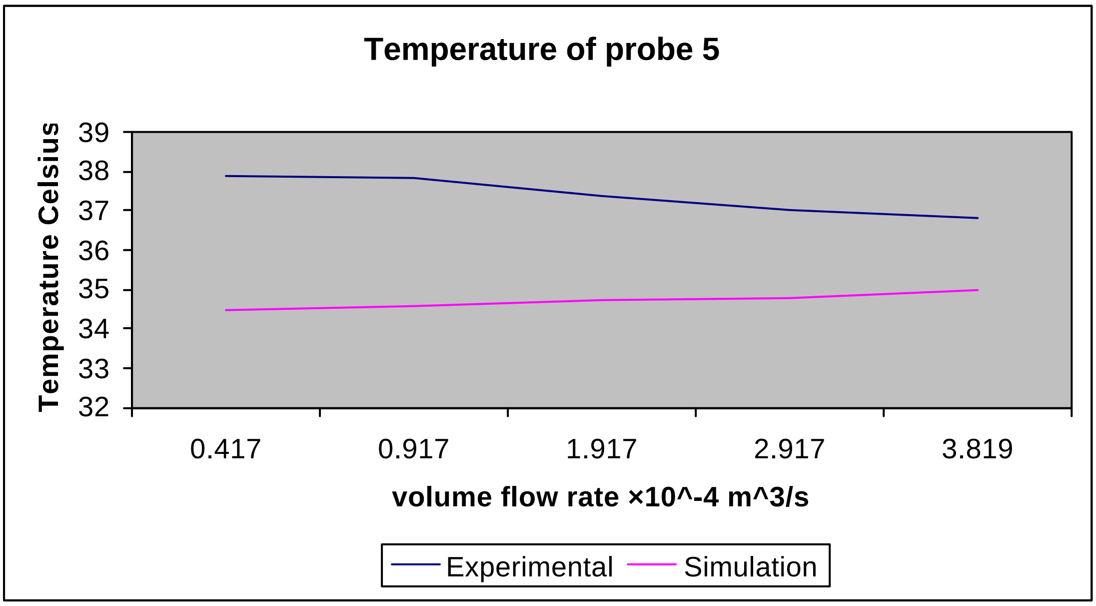


Figure 4.18 Experimental and simulation temperatures at different flowrates.

There is a difference of a few degrees Celsius in the simulation and experimental studies. This difference can be ascribed to different thermo physical details such as thermal conductivity, heat capacity, thermal diffusivity etc of the actual hotbox and that simulated. This difference of thermo-physical properties was because these could not be obtained and typical values had to be chosen from the ESP-r materials databases. Furthermore simulation was conducted with a start up period of 3 days with a constant temperature climate database. This would mean that any temperature and other climatic fluctuations because of weather conditions in the laboratory and hence around the hotbox were not accounted for in the simulation.

Validation study against experimental results was inconclusive.

CHAPTER 5

Simulation of the Test House

5.1 Model Details

The test house details were given by EBP (Environmental Building Partnership) and the plan of the house is shown in fig 5.1. It is intended that this house be simulated, built and monitored in order to give in-depth information about Dynamic Insulation, its energy saving potential, pollution filtration characteristics and thermal comfort. For the purpose of simulation the site for this house was chosen to be 50^0 North Latitude and 0^0 Longitude, the site exposure was a typical city centre where ground reflectance was 0.2. The climate associated with this house was the standard climate for Kew i.e. for the year 1967. These parameters were set because it is intended that the house be built in London.

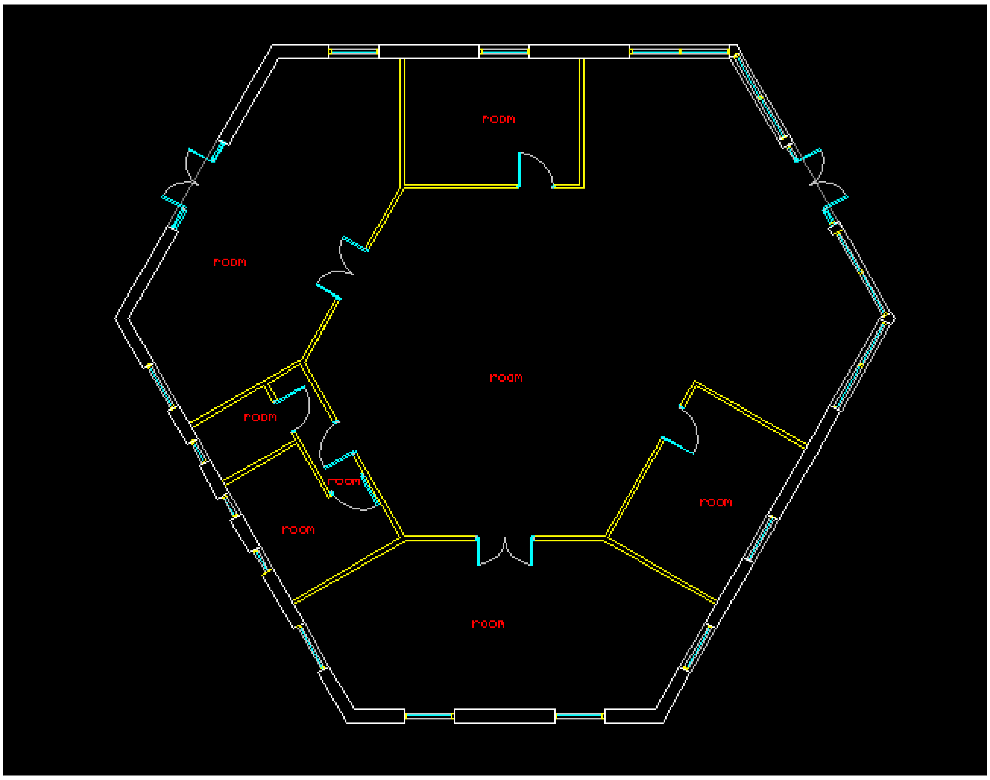


Figure 5.1 Test house as given by EBP.

The house was then modelled in ESP-r by inputting the coordinates of the base and the top vertex of the roof, defining the height of the construction and defining the location of various doors and windows in their respective walls. The proposed house now appeared as in fig 5.2 and fig 5.3. The house was divided up into nine zones the names of which are given in fig 5.2. It was considered to be quite fitting to define zones as per the actual rooms i.e. one room per zone because it is not such a very big building that more than one room formed a zone. Descriptions of the windows and glass doors were input to the program as separate files, which described their optical properties. This house represented the base case with which the test house with Dynamic Insulation was to be compared.

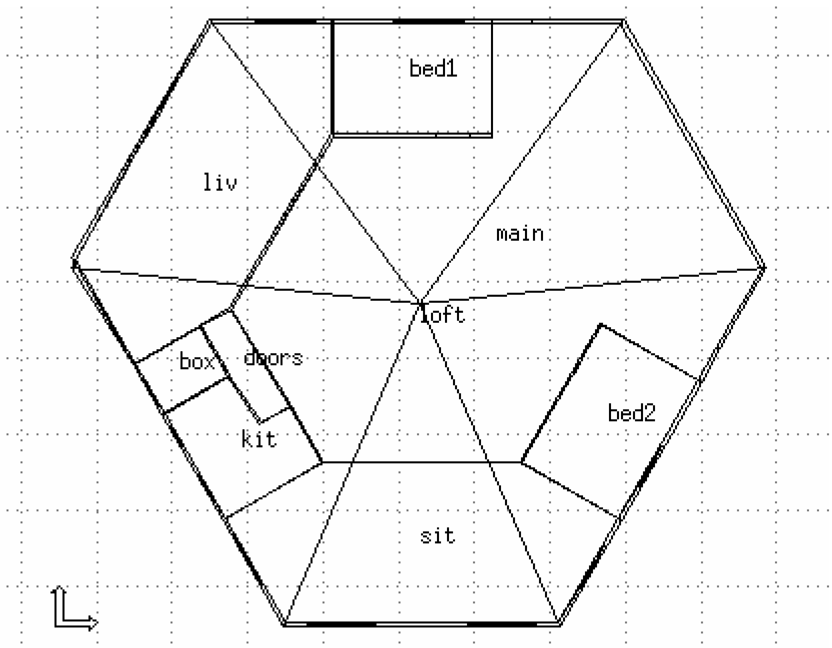


Figure 5.2 Test house as modelled in ESP-r (plan view).

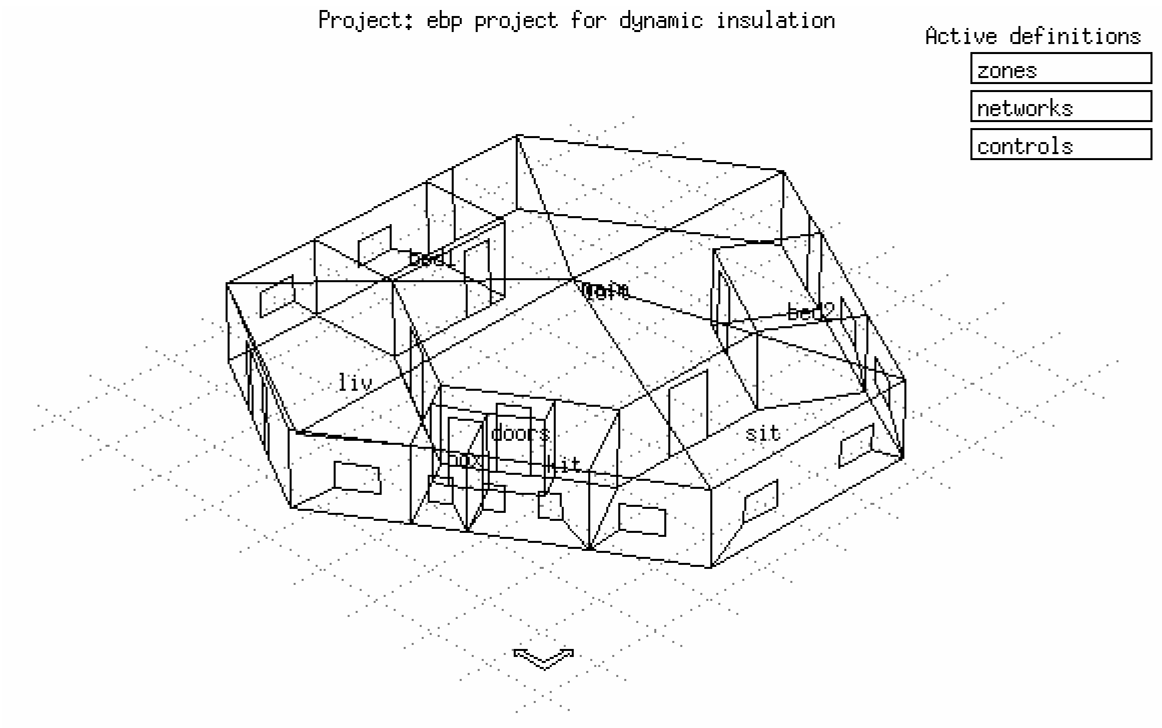


Figure 5.3 Test house as modelled in ESP-r (isometric view).

A second model was then considered it was exactly like the first model but with 18 additional zones to model the Dynamic Insulation. These additional zones were linked, three each, to all the zones with external walls except ‘main’. ‘Main’ was not made dynamic because most of its external wall is glass as it is a sunspace. It may be noted that since its external wall forms around a sixth of the total external area the full potential of Dynamic Insulation for this house was not realised. Airflow networks were then defined. The designed flow regime accepts air through the external dynamic walls; this air then flows to ‘main’ via doors or if the doors are closed the air then flows through small cracks the likes of which may be found underneath doors and around windows. From ‘main’ this air is then drawn into the loft. From the loft the air is then vented out to the atmosphere through an opening in the roof. Airflow was determined on the basis of the 6th Amendment to the Technical Standards for Compliance with the Building Standards (Scotland) Regulations 1990 - Part J [1], the principal requirement being to provide a minimum of 1ach to all living space except for bathrooms and kitchens where this requirement was a minimum of 3. Due to this, different flow rates were required through the different walls. To simulate such airflow it was found easier to put individual fans for each zone although in practice one fan would be sufficient. The fact that in most houses the room volume to exterior wall area ratio is different for each room may pose problems when designing a dynamically insulated house because air velocity through the dynamic wall, being a function of pressure difference, would be the same through all the walls (assuming a homogenous pressure difference throughout the house with respect to the exterior) and this would give different air change rates in the different rooms.

After describing the models a typical occupancy was imposed. The occupancy pattern is shown in table 5.1 and 5.2. Casual gains associated with this occupancy were also described in the operations file (90W sensible and 50W latent with a radiative/convective split of 0.2/0.8). In addition to these, miscellaneous loads were also added to represent lights, a refrigerator, a computer, water-heating system etc.

Time	Bed1	Bed2	Sit	Liv	Main	Kit	Total
0	2	4					6
1	2	4					6
2	2	4					6
3	2	4					6
4	2	4					6
5	2	4					6
6	2	4					6
7		4				1	5
8			6				6
9							0
10							0
11							0
12						1	1
13			4				4
14							0
15							0
16				3			3
17				3			3
18				3		1	4
19			6				6
20				6			6
21				6			6
22	2	4					6
23	2	4					6
24	2	4					6

Table 5.1 Occupancy for weekdays. (Time is starting time and numbers represent individuals present).

A detail of the various loads may be found in the appendices. Furthermore a complete detail of the models and associated design parameters used is given in the appendices

Time	Bed1	Bed2	Sit	Liv	Main	Kit	Total
0	2	4					6
1	2	4					6
2	2	4					6
3	2	4					6
4	2	4					6
5	2	4					6
6	2	4					6
7	1	4			1		6
8	1	4			1		6
9		4			1	1	6
10		4			1		5
11			5		1		6
12				2	3		5
13				2	3		5
14				2	3		5
15				2	3		5
16				2	3		5
17				2	3	1	6
18	2	2					4
19							0
20							0
21				2			2
22				2			2
23				2			2
24				2			2

Table 5.2 Occupancy for weekends.

There were four options for controlling the heating and ventilation systems of the test house

1. Heating is switched on in a room for the period it is occupied only.
2. The heating control is more typical with heating coming on from 6:30~8:30 and 16:30~23:30 during weekdays and from 7:00~21:00 at weekends.
3. Ventilation for Dynamic Insulation was kept on at all time.
4. Dynamic Insulation and heating were switched together.

	Option 1	Option 2
Option 3	✓	✗
Option 4	✗	✓

Table 5.3 Ventilation options.

These options are illustrated in table 5.3. Out of the four possible configurations, two were studied as shown in the table. These two were chosen because it was assumed that with an unplanned control of heating (option 1) it would be unlikely that an occupant would also control the ventilation at the same time (option 4). Furthermore it was assumed that with a planned heating control (option2) the ventilation would also be controlled (option4).

5.2 Plant Optimisation

The building was simulated against typical winter climate with different heating plant capacities, and heating loads over one week were plotted against plant capacity (fig 5.4). For each zone an optimal plant capacity was then chosen where the graph started to become parallel to the plant capacity axis.

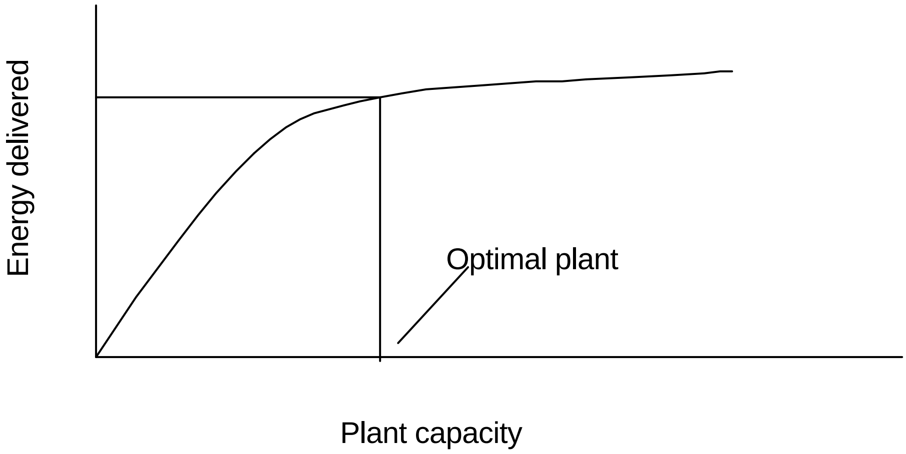


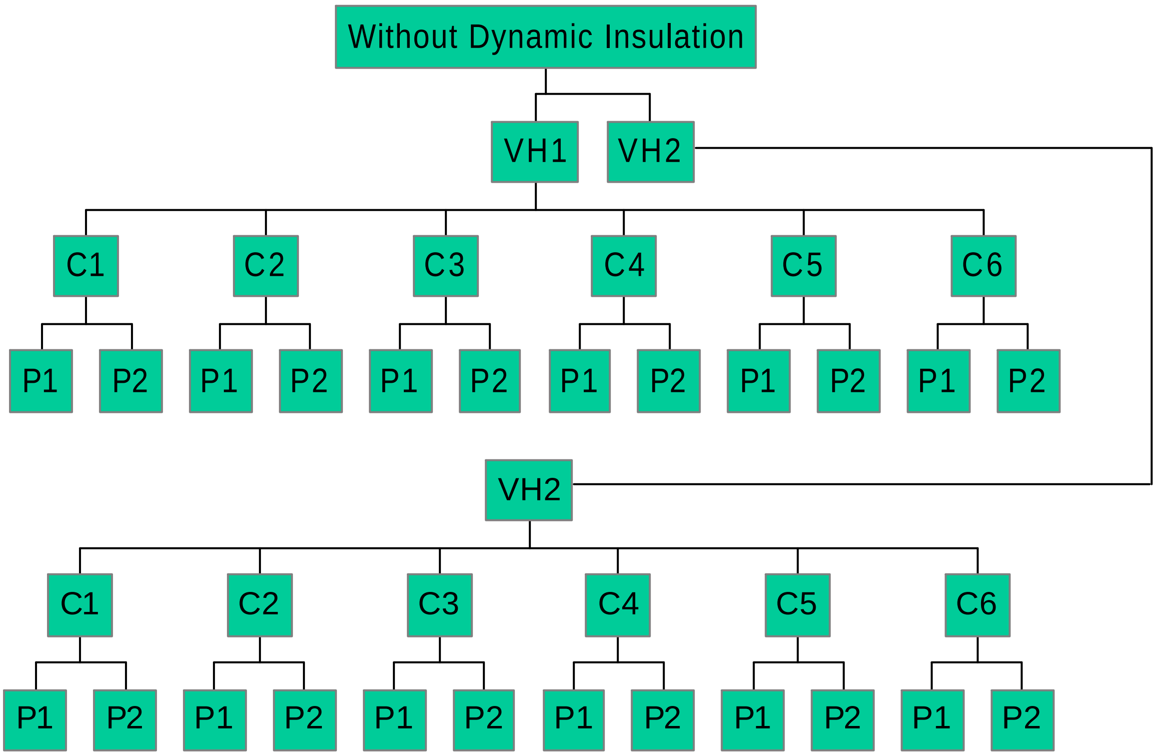
Figure 5.4 Plant optimisation by investigating rate of change of energy delivered with plant capacity.

5.3 Planned Simulation Studies

All these variations in the design parameters led to quite a large number of simulations. Table 5.5 and 5..6 show a logical grouping of the various simulation studies. The complete detail of these simulations is given in the next chapter. A total of six constructions were studied five of these were supplied by EBP and the sixth was a default external wall taken from the ESP-r constructions database. The constructions are given in table 5.4 and a complete detail is given in the appendices. Two ventilation levels were studied and also with the incorporation of an air-to-air heat recovery system that recovered heat from the exhausted air to the incoming air.

Number	Construction name	Comments
C1	Extern_wall	External wall from ESP-r constructions database
C2	Ebpconv1	Conventional external wall as given by EBP
C3	Ebpconv2	Conventional external wall as given by EBP
C4	Ebpconv3	Conventional external wall as given by EBP
C5	Ebptimber	Conventional timber external wall as given by EBP
C6	DI_compos	Proposed dynamic wall as given by EBP

Table 5.4 Detail of external wall constructions.



Legend:

VH1 Ventilation and heating scheme with options 1 and 3 (Table 5.3)
VH2 Ventilation and heating scheme with options 2 and 4 (Table 5.3)
C1 to 6 six different construction types
P1 Ventilation with 1.1 ach in all living space and 3.5 in bathrooms and kitchens
P2 Ventilation rate 150% of P1
P1X Ventilation rate similar to P1 but with a 75% efficient heat exchanger

Table 5.5 Scheme of proposed simulations (without Dynamic Insulation).

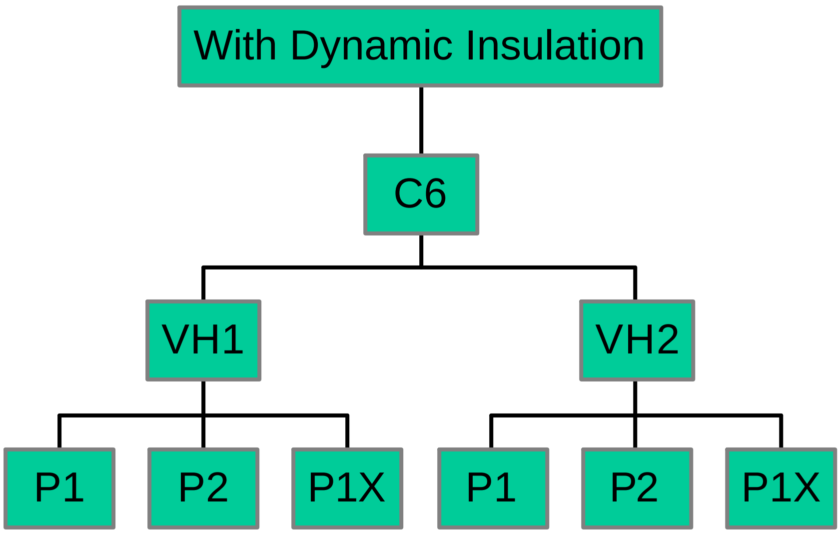


Table 5.6 Scheme of proposed simulations (with Dynamic Insulation).

Keeping track of such a large number of simulations and their comparisons was found to be quite difficult so a coding scheme was developed with the prefixes W and WO to signify with and without Dynamic Insulation respectively. The rest of the abbreviations follow hierarchically from the above two tables, hence WOVH2C3P2 would mean a simulation without Dynamic Insulation, with ventilation and heating strategy incorporating options 2 and 4 from table 5.3, on the third type of construction and with a ventilation rate 150% of 1.1ach in all living spaces and 3.5 in bathrooms and kitchens.

Simulation was carried out for four weeks, 9~15January, 9~15April, 9~15July and 9~15October, these signifying typical weeks in winter, spring, summer and autumn. Results that were assessed include total energy demand for heating for the 1-week periods, temperature profile of one zone (arbitrarily chosen to be main) for one day each week percentage people dissatisfied PPD[3] levels for the same day and zone, each week. The day chosen was Sunday because 'main' has occupancy for maximum time on this day.

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3 PPD is a measure of human comfort; it depends upon Predicted Mean Vote PMV that is an index that predicts the mean value of votes of a large number of people on a 7-point thermal sensation scale. It takes into account environmental parameters like air temperature, mean radiant temperature, air velocity, partial water vapour pressure, activity level affecting metabolic rate and clothing level affecting thermal resistance. Please refer to the bibliography pages for further reading.

CHAPTER 6

Results Analysis

6.1 Layout

Simulation results have been divided into three categories.

1. WO i.e. analysis of the six different construction types without Dynamic Insulation.
2. W i.e. analysis of the different Dynamic Insulation configurations simulated.
3. Comparison of Dynamic insulation with conventional to identify energy savings, temperature profiles and human comfort levels.

Simulation results have been listed in the following order

1. WOVH1C1P1 up to WOVH1C6P1
2. WOVH1C1P2 up to WOVH1C6P2
3. WOVH2C1P1 up to WOVH2C6P1
4. WOVH2C1P2 up to WOVH2C6P2

5. WOVH1C6P1-WOVH1C6P2
6. WOVH2C6P1-WOVH2C6P2

7. WOVH1C6P1-WOVH2C6P1
8. WOVH1C6P2-WOVH2C6P2

9. WVH1C6P1-WVH1C6P2-WVH1C6P1X
10. WVH2C6P1-WVH2C6P2-WVH2C6P1X

11. WVH1C6P1-WVH2C6P1
12. WVH1C6P2-WVH2C6P2
13. WVH1C6P1X-WVH2C6P1X

14. WOVH1C6P1-WVH1C6P1- WVH1C6P1X
15. WOVH1C6P2-WVH1C6P2

16. WOVH2C6P1-WVH2C6P1- WVH2C6P1X
17. WOVH1C6P2-WVH1C6P2

18. WOVH1C6P1-WVH1C6P1- WVH1C6P1X
19. WOVH1C6P2-WVH1C6P2

20. WOVH2C6P1-WVH2C6P1- WVH2C6P1X
21. WOVH1C6P2-WVH1C6P2

The coding scheme of chapter 5 should be kept in mind when analysing the results. There were three types of results associated with each of the above simulations i.e.

A) Energy Delivered during the week,
B) Temperature profiles of 'main' on Sunday,
C) PPD profile of 'main' on Sunday.

This categorisation i.e. A, B and C has correspondingly been included in the numbering scheme and 1A, 1B and 1C represent each of the above results respectively. The graphs for each of the above have not been numbered apart from the numbering given above to facilitate description. All the graphs referred to in the following text are presented in the appendices.

6.2 Total heating energy required

From 1A to 4A it can be seen that the energy delivered is almost the same for all six construction types considered. The energy delivered increases by an average of 120% when the ventilation rate is increased to 150% of that recommended by [1] It should be kept in view that the heating mechanism was also changed along with ventilation. The new fixed heating scheme (heating comes on at the same specific period(s) through the day whereas previously heating came on as per occupancy) provides heating for a greater time than the former scheme so some energy must be provided for the increased hours as well as for heating a greater mass of incoming air when ventilation is increased to 150%.

5A and 6A provide comparison when the ventilation rate is increased by 50%. It can be seen that energy delivered increases in both cases as expected. The energy increase is about 10%, which may be a small price to pay for a 150% ventilation for buildings with high air change rate demands e.g. some hospital wards and sports halls. 7A and 8A confirm the findings of 1A to 4A in that when heating is changed from occupancy based to fixed and ventilation is changed from permanent to fixed, energy demand increases by more than twice.

9A and 10A deal with Dynamic Insulation. Heating demand increases when ventilation rate increases but with the incorporation of a heat exchanger the energy delivered decreases as expected. This decrease is of the order of 5% in the wintertime. An optimal ventilation rate should be determined for every building that is to incorporate Dynamic Insulation in accordance with chapter 2.

11A to 13A show the effect of changing control from VH1 to VH2, With Dynamic Insulation the energy demand level increases to more than 200%. It is interesting to compare this with an almost similar increase in the non-dynamic case. This similarity can be explained by a compensation of increased heat capture with increased mass of air to be heated when ventilation through a dynamic wall is increased. With the inclusion of a heat exchanger energy demand drops by around a sixth in the winter months but remains more or less the same for the summer time.

From 14A and 15A a comparison of energy saving in the static and dynamic case can be obtained. For the test house with the design parameters mentioned a net saving of 8% without heat recovery and 14% with heat recovery was obtained. These figures are somewhat lower than theoretical maximums (up to 25% with a dynamically insulated, well built house). It should be noted that the building considered is not an ideal candidate for Dynamic Insulation furthermore one sixth of the envelope is not dynamically insulated. 16A and 17A are similar to the previous two graphs except that control strategy VH2 has been employed for these. The energy savings for this case are somewhat lower than previous. It must be stressed at this point that Dynamic Insulation can only be expected to work at its best with some ideal airflow rate. Simulation results predict strong correlation between airflow rate and energy requirements as outlined in chapter 3. 18A to 21A are similar to the previous four graphs except that they use a conventional construction for the non-dynamic case. These simulations can be considered to be the most realistic depiction of actuality. Energy savings are obtained that are at around the same level as previously obtained. It may further be concluded that a heat exchanger is useful in the winter months and if one is incorporated in a building, prospects of switching it off in the summer should be seriously considered.

6.3 Temperature Profiles

Graphs for 1B are shown but those for 2B, 3B and 4B are not shown because of their similarity to 1B. All of these show somewhat the same temperature profiles for all the six construction types and it can be concluded that all six construction types behave almost equally the same for the given climate (Kew '67).

Graphs 5B and 6B show a slight decrease in wintertime temperatures when ventilation rate is increased by 50%. This contrasts with the energy consumption, which increases quite dramatically. 7B and 8B show that with the heating scheme VH2 desired temperatures are more readily obtained and maintained than with VH1. It should be kept in mind that VH2 demands more than twice the energy than VH1. It would be wiser to seek out a compromise between these two heating and ventilation options for a real building.

The incorporation of a heat exchanger as shown in 9B and 10B has the general effect of slightly increasing the temperature but at a fraction of a degree Celsius this effect is negligible. Thus from a temperature point of view a heat exchanger is not required. It should be noted though that from the energy saving point of view a heat exchanger saved around 5%. Conclusions from 11B to 13B are similar to earlier conclusions regarding temperature profiles with VH1 as compared with VH2, in that VH2 gives higher temperatures for longer but with more than twice the energy.

Comparison of the test house with and without Dynamic Insulation and with a heat exchanger as in 14B and 15B above shows that with Dynamic Insulation slightly higher temperatures are obtained. Again this fact alone does not justify Dynamic Insulation but its energy saving potential. A peculiar trait exhibited in the network with the heat exchanger is that slightly lower temperatures are obtained in summer; this might encourage the operation of the heat exchanger in summer for temperature control. But the temperature benefits – for this case at least – do not justify its use on grounds of increased power use.

Conclusions from 16B and 17B are quite similar to 14B and 15B. The same discussion as above seems to hold for the higher flow rate of air. Conclusions from 18B to 21B are quite similar to those from 14B to 18B. The only difference between these sets of four is the construction material C6 in the latter has been replaced by C1 to give a semblance of reality. It can be seen that the overall temperatures for Dynamic Insulation are higher in winter and lower in summer. A heat exchanger in the dynamic case enhances this effect although slightly and increased ventilation rate does not overly affect temperature even though it increases energy demand from the plant.

6.4 PPD Profiles

Once again the six construction types studied show little variation if any in PPD values, in fact the total variation remains within 1% of PPD. For this reason the graphs pertaining to 1C have been shown and graphs 2C, 3C and 4C have been omitted. As shown by 5C and 6C increased ventilation increases comfort levels in the summer and decreases them in winter, as expected. The actual %PPD for both types of ventilation never differs by more than 2%. This might suggest that with a ventilation of 150% comfort levels are not changed significantly.

Interestingly 7C and 8C show that increased ventilation rates do not alter much the comfort level in the winter, it should be observed that temperatures for these sets of simulation are identical; hence there is no effect on comfort. The detrimental effect of a heat exchanger on comfort levels in the summer time is evident from 9C and 10C; in the wintertime the comfort levels achieved with and without it are almost identical. This suggests that a compromise needs to be made between energy delivered and human comfort.

Analysis of 11C to 13C above shows that with a ventilation rate of P2, PPD levels are raised somewhat. Hence it can safely be concluded that ventilation level of P2 is not suitable for the test house when compared with P1. P1 is also the minimum recommended ventilation level. As mentioned before 14C and 15C confirm that a heat exchanger lowers the comfort levels in the summer time because the exchanger recovers exhaust heat. This fact provides strong impetus to shut such devices in the summertime. The scene changes in the winter when a heat exchanger provides more comfort than Dynamic Insulation alone.

The comfort levels of Dynamic Insulation are better than conventional, apart from a few exceptions, for both summer and winter. 16C and 17C prove the earlier conclusions but at a larger ventilation rate. Dynamic Insulation provides better comfort levels than non-dynamic all year round. A heat recovery system along with Dynamic Insulation improves conditions in winter but has the reverse effect in summer. 18C to 21C show similar results and the same conclusions may be drawn as before.

CHAPTER 7

Conclusions & Recommendations

7.1 Conclusions

A significant amount of work seems to have been done in the development of Dynamic Insulation as far as erection and operation of such buildings is concerned. This has mainly been done in the Scandinavian countries and relatively small amount of developments have been made in the UK. No simulation studies of the Dynamic Insulation were available.

Literature review confirmed that there is very little experimental data on the subject that is suitable for simulation studies. As for analytical solutions, only a well-defined steady state solution could be found. It would be desirable to integrate the effects of wind and solar gains into the theory. Some pieces of work have tried to develop the theory further and a notable one is [2] in which a numerical solution to approximate the steady state and transient airflow through the wall fabric has been presented. Furthermore a large amount of integration remains to be done concerning this and other such work. Constructions incorporating Dynamic Insulation should be integrated into the building to get an appraisal of the technology and how it would react within an actual building, the ideal tool for doing this is of course a suitable computer based building simulation program.

Dynamic Insulation has the potential to save heating energy and at the same time provide a less polluted indoor environment. It can improve moisture diffusion through the building fabric to control indoor RH and also decrease the prospect of interstitial condensation. By keeping moisture levels within an optimal range health hazards e.g. mites etc may be controlled.

Houses that use Dynamic Insulation need to be made to higher levels of construction standards than are currently practiced. Ideally all leakage paths of air such as construction joints and cracks around doors and windows should be sealed exceptionally well. The occupants need to know something about the functioning of the building and would be expected to behave likewise e.g. it might not always be possible for windows to be opened. Dynamic Insulation is affected by wind and solar radiation to quite a large degree and for any structures that are to use the technology the probable effects of these two factors should be not be neglected.

Analytical studies found that the most important factor when appraising Dynamic Insulation is the air velocity in the building fabric. It is quite possible to achieve a dynamic U value of zero. At this value the total conduction loss through the fabric is reclaimed. More importantly though it needs to be appreciated that an optimal air velocity exists for every configuration of dynamic construction for which the heating energy consumed is a minimum. For air velocities lower than this value all the conduction heat loss is not recovered and for values higher than this a heating overhead is incurred in the form of increased air mass to be heated so that it comes to the room inside temperature. The external surface heat flux decreases with increased thermal resistance of the wall so construction with high thermal resistance might be feasible from an energy saving point of view.

The developed approach in the thesis is an engineering solution to the problem of modelling Dynamic Insulation in that heat is transferred from the construction to discrete points and not continuously as the process occurs in reality. This was shown to be quite a reasonable approximation to continuous transfer with error in the predicted temperature remaining of the order of 1% for flow rates from 2 to 10m/h. Errors in heat flux show greater variation ranging from 2% more than analytical at 2m/h to 10% less than analytical 10m/h. Interestingly both % errors show a linear variation with the air velocity.

Simulation results in comparison with experimental studies were inconclusive because all required data was unavailable. Effort was expended to find enough data for a reasonably accurate simulation but although readings associated with the different facets of the respective experimental models were quite well documented, requisite climate data was not.

When applied to the test house it was found that Dynamic Insulation had the potential for saving around 9% heating energy for the house considered. This figure went up by another 5% with additional heat recovery by the inclusion of an air-to-air heat exchanger. This finding alone may be reason enough to consider Dynamic Insulation in any type of construction be it residential of otherwise as long as there is need to heat it. Dynamic Insulation theory and previous research has shown that there is the added benefit of filtration of air pollution when air is drawn through the building fabric. Dynamic Insulation would be more suited to a building with a higher surface area to volume ratio because then larger air volumes may be drawn indoors and the energy saving potential realised to a greater extent, but this may not always be possible.

Dynamic Insulation provides better thermal comfort at a lower energy cost than conventional walls and heating systems. This is evident from the lower PPD values obtained in the simulation study. There is a marked lowering of PPD during summertime. This can be associated with thermal mass and more importantly to outdoor and indoor air temperature. If the temperature of outside air is lower, then the temperature of the air drawn in will be lower than that of the indoor air. This would not have as large an effect as when the air would be drawn in conventionally, but would nevertheless be important for certain buildings in which it might not be feasible to open windows e.g. because of noise. If the outdoor temperature is higher than the indoor temperature, then air drawn in gives up some heat to the fabric and is hence cooled down. Clearly more research needs to be done to investigate this effect.

When the building was simulated with Dynamic Insulation constantly switched on i.e. in the absence of heating it was found that the building cools down quite quickly once the heating is switched off. Temperature drops as high as 10^0C over a few hours were seen. Such behaviour of the building is clearly undesirable. Therefore it is advisable that Dynamic Insulation be used whilst the heating is switched on. This would cause a lesser overhead on the air extract fan and at the same time allow moisture and CO_2 to diffuse to the outside during the period Dynamic Insulation is switched off thus enhancing indoor air quality.

Important findings from the various simulations suggest that heating energy increases with ventilation rate and there is need to identify an ideal air velocity at which the energy consumption is minimum. Interestingly this increase in energy is less for Dynamic Insulation than conventional construction. A heat exchanger increases the energy savings but only in the winter months. Ventilation rate has minimal effect on temperature profiles in the living space even though it dramatically changes the energy requirements. Also the heat exchanger does not affect the temperature much. On the whole Dynamic Insulation gives internal air temperatures that are slightly higher in winter and lower in summer. Human comfort levels are somewhat more sensitive to the ventilation rate. Increasing the ventilation rate increases PPD in winter and decreases PPD in the summer as would be expected. The heat exchanger increases PPD in summer and lowers it in winter. In general Dynamic Insulation gives better comfort levels as compared with conventional constructions. In view of the above discussion Dynamic Insulation should be used only with a carefully determined airflow range. Heat exchangers if employed should be shut off in the summertime. Ventilation rates may also be increased in the summertime.

7.2 Recommendations

The incorporation of Dynamic Insulation in actual buildings though quite well adopted in the Scandinavian countries is still in its incubation in the UK. More research and development in this area is needed. A theory for the transient behaviour of Dynamic Insulation has been put forward at the Lund Institute of Technology, Sweden and theoretical advances have been made at the University of Aberdeen. Still a well-defined 3-D mathematical model is required to completely describe the physics. Furthermore the effects of wind direction, wind speed and solar radiation need to be quantified.

Over the years quite a number of test houses with Dynamic Insulation have been erected and monitored e.g. the Camphill Trust building in Aberdeen, the Optima House in Denmark, Rykkinnhallen Sports Hall, Baerum, Norway etc. Results from these have put energy efficiency at a minimum of 10% [1]. There is felt a need to develop a building that incorporates all the factors that help efficient use of energy regarding Dynamic Insulation and at the same time reduce adverse environmental effects. Such a building is under consideration by the Environmental Building Partnership (a partnership between James Campbell Architects and Environmental Consultants and the University of Aberdeen). There may be the possibility of constructing a structure that even has a net positive environmental impact in that it cleans up the atmosphere to such an extent that it has a net effect of reversing all the environmental impacts associated with it over its complete life cycle.

There are quite a number of important factors that need to be studied in further simulation studies. The developed approach can be bettered in a number of ways. The effect of increasing the number of zones may be studied. Results may be compared after distribution of zones is changed i.e. validating a model in which zones are unequal in thickness and are more concentrated in the region of maximum temperature gradient. Or better still a module to investigate fluid permeable walls can be developed, this would essentially consist of two parts; the addition of a mass transfer function as a function of pressure difference and inclusion of the associated heat energy transfer term in the standard energy balance of the program.

The filtration properties of Dynamic Insulation may be simulated from which a quantification of the potential for improving indoor air quality may be obtained. The outward diffusion of pollution and excess moisture when the Dynamic behaviour is exhibited and when it is not exhibited may also be researched into and an optimal compensation derived that optimises energy savings along with air quality. A conclusive analysis of the effect of wind may be undertaken and this can then be interpreted in conjunction with solar effects to provide rules for favourable orientation of a building. A study into how Dynamic Insulation affects mould growth and mite infestation may prove helpful in assessing health of the occupants. Investigation into the prospect of summertime cooling by reversing contra-flux conditions to pro-flux would also be interesting.

GLOSSARY

Absorptivity Absorptivity is a property of the body surface and is dependent on the temperature of the body and the wavelength of the incident radiation. It is a dimensionless value and measured as the fraction of incident radiation that is absorbed by the body

Air changes per hour ACH The total volume of air entering an enclosed space divided by the volume of that space

Adiabatic A process that involves no heat transfer. In ESP-r terminology an adiabatic surface has zero heat flux associated with it.

Airflow Network A network of nodes (air properties reference points) connected by components

Air-to-air heat recovery See Heat Exchanger (air-to-air)

Algorithm A calculation method that produces a control output by operating on an error signal or a time-series of error signals

Base Case / Reference Model (Standard) computer model of a particular building. The base case model can be used to assess the relative performance of a certain (new) feature of the building by changing the model parameters associated with that feature. Comparison of the results for the base case model with those for the changed model will reveal the relative performance of the feature. In case of an existing building the "as built" situation is often used as the base case.

Boundary Condition These are the temperature, flux and other environmental conditions that pertain on either side of a surface. According to the particular surface, they may be obtained from the climate data file, from the calculated values in an adjacent zone, or from user-specified values.

Casual Gains Heat energy dissipated to the surroundings by animal life, equipment, lighting and other such mechanisms.

Coefficient of overall heat transfer See U value

Component In ESP-r terminology a component is that part of a flow network that links two nodes in a connection.

Computational Fluid Dynamics CFD CFD is commonly accepted as referring to the broad topic encompassing the numerical solution, by computational methods, of the governing equations which describe fluid flow, the set of the Navier-Stokes equations, continuity and any additional conservation equations, for example energy or species concentrations.

Condensation The change of state of a substance from gas to liquid.

Conduction Heat conduction involves the transfer of heat from one molecule to an adjacent one as an inelastic impact in the case of fluids, as oscillations in solid non-conductors of electricity, and as motions of electrons in conducting solids such as metals. Conduction is the only mechanism of heat transfer through an opaque solid. Some heat may be transferred through transparent solids such as glass, quartz and certain plastics, by radiation. In fluids the conduction process is supplemented by convection and if the fluid is transparent, by radiation.

Connection In ESP-r terminology a connection is the linkage of two nodes in an airflow network

Contra-flux Fluid flow through a permeable surface in the same direction as heat flow.

Control The control is the ability of the system to respond to the changing requirements imposed upon it by the fluctuation of outside conditions.

Convection The essential process in the case of convection is the flow of a fluid over a solid surface, accompanied by a transfer of heat between the surface and the fluid. The movement of the fluid may be due to changes in its density caused by changes in its temperature, by natural convection; or it can be created by mechanical means, by forced convection.

Convective heat transfer coefficient The amount of heat transfer by convection across the opposite surfaces of a unit cube (cube of side 1m) per unit temperature difference.

Depth Filtration Filtration that takes places ‘inside’ a filter i.e. not on the surface, normally particles of order higher than the mean distance between filter fibres are removed by surface filtration, all other particles filtered are depth filtered (see also filter cake)

Diffuse Solar Radiation Diffuse solar radiation is the total amount of solar energy falling on a horizontal surface from all parts of the sky apart from the direct sun.

Diffusion The flow of a substance purely dependent on concentration.

Direct Solar Radiation Direct solar irradiance is a measure of the rate of solar energy arriving at the Earth's surface from the Sun's direct beam, on a plane perpendicular to the beam.

Dynamic Insulation Dynamic insulation (DI) is the combination, within a wall, of a conventional insulation and some kind of dynamic exchange between outside and inside temperatures, usually fluid based.

Efficiency The ratio of energy output to input.

Emissivity The ratio of the emissive power of the surface to that to a perfect black surface. The physical nature of the surface has a marked effect on the emission of heat by radiation

Ergonomics The application of scientific information concerning humans to the design of objects, systems and environment for human use.

ESP-r Computer based building simulation design tool.

ESRU Acronym for Energy Systems Research Unit

Filter Cake The residue deposited on a permeable medium when slurry is forced against the medium under a pressure

Finite Difference Analysis A numerical method of solving the Navier-Stokes equations, where the domain is divided up into small areas/volumes, with nodes (or grid points) placed at each corner. The fluid is then considered to exist only at these nodes. The difference between the nodes describes the property gradients in the fluid

Finite Element Analysis A numerical method of solving the Navier-Stokes equations, where the domain is divided up into small areas/volumes. A shape function is then placed over the volume; it should be representative of the shape of the variation over the volume.

Finite Volume Analysis A numerical method of solving the Navier-Stokes equations, where the domain is divided up into small areas/volumes, and the flow properties are considered to be constant across the volume.

Heat Exchanger (air-to-air) A device designed to transfer heat from two physically separated fluid streams. In buildings, it as generally used to transfer heat from exhaust warm air to incoming cooler outdoor air.

Heat Flux Amount of heat incident on a unit surface

High Efficiency Particulate Arrestor HEPA filter HEPA (High Efficiency Particulate Air) is a filtering efficiency specification for filters developed by the Atomic Energy Commission during World War II to effectively remove radioactive dust from plant exhausts without redistribution. A HEPA filter must be capable of capturing 99.97% of all particles as small as 0.3µm

HVAC Acronym for heating, ventilation and air conditioning

Indoor Air Quality The synthesis of day-to-day values of physical variables in a building e.g. temperature, humidity, air movement and air quality, etc, which affect the health and/or comfort of the occupants

Infiltration Infiltration is the movement of air from the outside (ambient) to the inside through cracks in the building envelope.

Insolation The magnitude of solar energy, which is incident on a particular building element (W/m2). Both the *direct* and *diffuse* components must be considered.

Interstitial Condensation This is condensation that occurs within external walls, floors and roofs. It occurs when warm moist air from inside the house passes through gaps in the internal surface and condenses at colder parts within.

Load Levelling Difference between maximum and minimum load, important for plant sizing.

Node In ESP-r terminology a node is a reference point for airflow calculations.

Operation In ESP-r terminology operations represent the casual gains, ventilation and infiltration configurations of a model.

Passive Without the active input of energy.

Percentage People Dissatisfied PPD Comfort rating derived from the work of Fanger. PPD is the predicted percent of dissatisfied people at each PMV

Permeability The volume of fluid that flows through one cubic meter of a material due to a pressure difference of 1Pa

Plant In ESP-r terminology plant is a machine that performs control.

Porous Containing pores, through which a fluid can pass. Ease of flow is defined by permeability.

Predicted Mean vote PMV Comfort rating derived from the work of Fanger. PMV is derived from the physics of heat transfer combined with an empirical fit to sensation.

Productivity The efficiency with which a person performing a specific function does a job, or the output of a worker under specific environments and conditions.

Pro-flux Fluid flow through a permeable surface in the opposite direction as heat flow.

Radiation The transmission of heat through space by the propagation of infrared energy; the passage of heat from one object to another without necessarily warming the space between. Radiation does not need a transport medium and so it can take place in vacuum (or in space; i.e. solar radiation). Heat and light are forms of electromagnetic radiation; other forms are microwaves, X-rays, radio broadcast waves.

Radiative heat transfer coefficient The amount of heat transfer by radiation across the opposite surfaces of a unit cube (cube of side 1m) per unit temperature difference

Reflectance The fraction of radiant energy incident upon a surface, which is reflected

Relative Humidity RH A ratio between the actual moisture content of the air compared with the moisture content of the air required for saturation at the same temperature, i.e., at 100% relative humidity (also known as saturation point).

Single fibre collection efficiency Efficiency based on the single fibre theory, which takes into account direct interception, inertial impaction and diffusional deposition of residue onto a filter.

Stack Effect Pressure-driven airflow produced by convection as heated air rises, creating a positive pressure area at the top of a building and a negative pressure area at the bottom of a building. The stack effect can overpower the mechanical system and disrupt ventilation and circulation in a building.

Start up period In ESP-r terminology it is the period before the actual simulations are performed that is taken into account while simulating.

Steady state A system that is invariant in time.

Surface Filtration / Filter Cake Filtration See filter cake

Sustainability Meeting the needs of the present without compromising the ability of future generations to meet their needs.

Temperature Gradient The rate of change of temperature with distance measured into a surface.

Thermal Conductivity Conductivity is the measure of conduction within a material. The conductivities of materials vary widely, being greatest for metals, less for non-metals, still less for liquids and least for gases. Any material, which has a low conductivity, may be considered an insulator.

Thermal Resistance Reciprocal of U value is a measure of how much insulation is offered per unit temperature difference.

U value The heat flow transmitted through a unit area of a given structure, divided by the difference between the effective ambient temperature on either side of the structure, under steady state conditions.

Vapour Barrier A moisture impervious layer applied to the surfaces enclosing a space or to the surface of thermal insulation to limit moisture migration through the surface.

Ventilation The process of supplying or removing air, by natural or mechanical means to and from a space. Ventilation refers to air movement between zones.

Wind Angle Angle between a leading surface and the wind. Is also taken to be the angle between the normal to the leading surface and the wind in some cases.

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APPENDIX A

Thermo-physical Details, Control, Airflow and Climate Data for Test Cell

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Test cell

The test cell is a 3×4×2.7m cuboid aligned along the cardinal directions. The West wall is dynamic. The cell consists of four zones, 1, 2, 3 and tc. The first three zones are ‘wall zones’ i.e. these make up the West wall.

Detail of 3 and tc are shown in fig A.1, zones 1 and 2 are congruent to zone 3 in every respect apart from the west wall of zone 1 as is detailed in the thermo-physical details below.

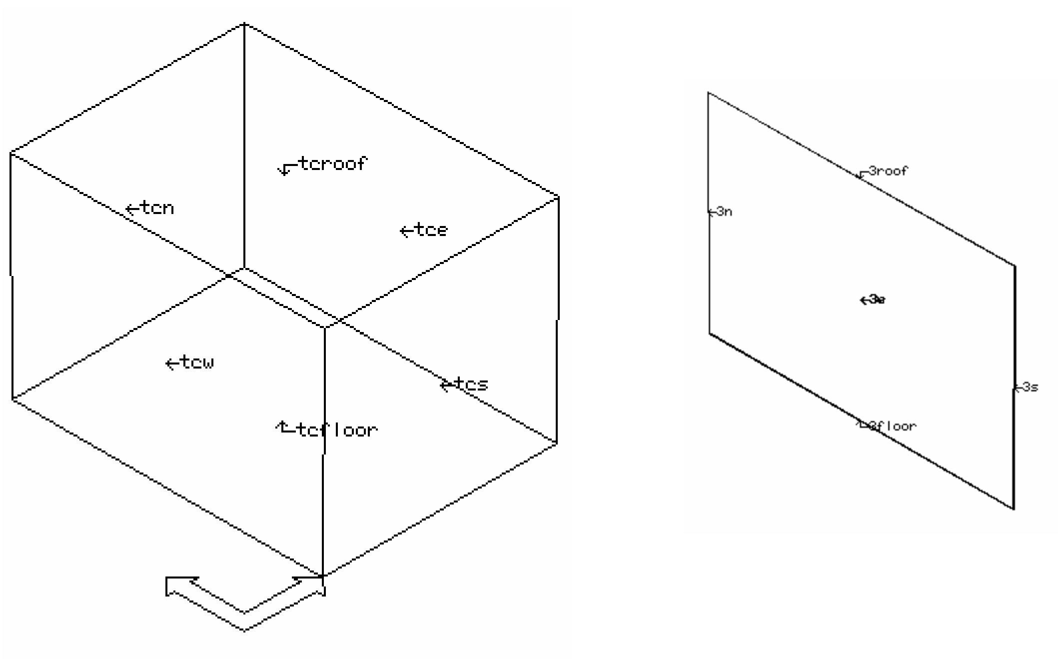


Figure A.1 Test cell for validation against analytical results.

Surfaces in this model have been named with respect to the direction they are facing, e.g. 1w is a surface in zone 1 and is facing west. Roofs and floors have been named as such hence tcfloor is the floor of the zone named tc.

Thermo-Physical Details

A summary of the surfaces in 1(4) follows:

Sur	Area m^2	Azim deg	Elev deg	surface name	geometry type	geometry loc	multilayer constr name	environment other side
1	0.03	180.	0.	1s	OPAQ	VERT	extern_wall	ADIABATIC
2	10.80	90.	0.	1e	OPAQ	VERT	DI_wall	2
3	0.03	0.	0.	1n	OPAQ	VERT	extern_wall	ADIABATIC
4	10.80	270.	0.	1w	OPAQ	VERT	DI_composit	EXTERIOR
5	0.04	0.	90.	1roof	OPAQ	CEIL	roof_1	ADIABATIC

```
  6     0.04   0. -90. 1floor       OPAQ FLOR floor_1       ADIABATIC


 All surfaces will receive diffuse insolation.

 Zone construction details for 1 ( 4)

Surface    |Layer|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
           |     |db | (m)   |tivity |        |heat  |emis|abs |
1s            1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
              2  211 0.0750    0.040   250.0   840.0           Glasswool
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
           Standard U value for construction extern_wall is   0.39
1e            1  301 0.0700    1.000     1.0   650.0 1.00 1.00 DI element
           Standard U value for construction DI_wall is   4.03
1n            1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
              2  211 0.0750    0.040   250.0   840.0           Glasswool
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
           Standard U value for construction extern_wall is   0.39
1w            1  302 0.0350    1.000     1.0   650.0 0.00 1.00 DI_e=0
              2  301 0.0350    1.000     1.0   650.0 1.00 1.00 DI element
           Standard U value for construction DI_composit is   4.03
1roof         1  162 0.0120    0.190   960.0   837.0 0.90 0.90 Roofing felt
              2   21 0.0500    0.380  1200.0   653.0           Light mix
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4  151 0.0080    0.380  1120.0   840.0 0.90 0.60 Ceiling (plaster)
           Standard U value for construction roof_1 is   1.77
1floor        1  263 0.1000    1.280  1460.0   879.0 0.90 0.85 Common earth
              2   82 0.1000    2.900  2650.0   900.0           Red granite
              3   32 0.0500    1.400  2100.0   653.0           Heavy mix concrete
              4  124 0.0500    1.400  2100.0   650.0 0.91 0.65 Cement screed
           Standard U value for construction floor_1 is   2.76

 Zone 2 ( 3) is composed of  6 surfaces and  8 vertices.
 It encloses a volume of     0.1m^3 of space, with a total surface
 area of    21.73m^2 & approx floor area of    0.04m^2
 2 describes a...

 A summary of the surfaces in 2( 3) follows:

 Sur| Area  |Azim|Elev| surface    |geometry| multilayer   |environment
    | m^2   |deg |deg | name       |type|loc| constr name  |other side
  1     0.03 180.   0. 2s           OPAQ VERT extern_wall   ADIABATIC
  2    10.80  90.   0. 2e           OPAQ VERT DI_wall       3
  3     0.03   0.   0. 2n           OPAQ VERT extern_wall   ADIABATIC
  4    10.80 270.   0. 2w           OPAQ VERT DI_wall       1
  5     0.04   0.  90. 2roof        OPAQ CEIL roof_1        ADIABATIC
  6     0.04   0. -90. 2floor       OPAQ FLOR floor_1       ADIABATIC


 All surfaces will receive diffuse insolation.

 Zone construction details for 2 ( 3)

Surface    |Layer|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
           |     |db | (m)   |tivity |        |heat  |emis|abs |
2s            1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
              2  211 0.0750    0.040   250.0   840.0           Glasswool
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
```

```
               4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
            Standard U value for construction extern_wall is   0.39
2e             1  301 0.0700    1.000     1.0   650.0 1.00 1.00 DI element
            Standard U value for construction DI_wall is   4.03
2n             1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
               2  211 0.0750    0.040   250.0   840.0           Glasswool
               3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
               4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
            Standard U value for construction extern_wall is   0.39
2w             1  301 0.0700    1.000     1.0   650.0 1.00 1.00 DI element
            Standard U value for construction DI_wall is   4.03
2roof          1  162 0.0120    0.190   960.0   837.0 0.90 0.90 Roofing felt
               2   21 0.0500    0.380  1200.0   653.0           Light mix
               3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
               4  151 0.0080    0.380  1120.0   840.0 0.90 0.60 Ceiling (plaster)
            Standard U value for construction roof_1 is   1.77
2floor         1  263 0.1000    1.280  1460.0   879.0 0.90 0.85 Common earch
               2   82 0.1000    2.900  2650.0   900.0           Red granite
               3   32 0.0500    1.400  2100.0   653.0           Heavy mix concrete
               4  124 0.0500    1.400  2100.0   650.0 0.91 0.65 Cement screed
            Standard U value for construction floor_1 is   2.76

 Zone 3 ( 2) is composed of  6 surfaces and  8 vertices.
 It encloses a volume of     0.1m^3 of space, with a total surface
 area of    21.73m^2 & approx floor area of    0.04m^2
 3 describes a...

 A summary of the surfaces in 3( 2) follows:

 Sur| Area  |Azim|Elev| surface    |geometry| multilayer   |environment
    | m^2   |deg |deg | name       |type|loc| constr name  |other side
  1     0.03 180.   0. 3s           OPAQ VERT extern_wall   ADIABATIC
  2    10.80  90.   0. 3e           OPAQ VERT DI_wall       tc
  3     0.03   0.   0. 3n           OPAQ VERT extern_wall   ADIABATIC
  4    10.80 270.   0. 3w           OPAQ VERT DI_wall       2
  5     0.04   0.  90. 3roof        OPAQ CEIL roof_1        ADIABATIC
  6     0.04   0. -90. 3floor       OPAQ FLOR floor_1       ADIABATIC


 All surfaces will receive diffuse insolation.

Zone construction details for 3 ( 2)

Surface    |Layer|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
           |     |db | (m)   |tivity |        |heat  |emis|abs |
3s             1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
               2  211 0.0750    0.040   250.0   840.0           Glasswool
               3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
               4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
            Standard U value for construction extern_wall is   0.39
3e             1  301 0.0700    1.000     1.0   650.0 1.00 1.00 DI element
            Standard U value for construction DI_wall is   4.03
3n             1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
               2  211 0.0750    0.040   250.0   840.0           Glasswool
               3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
               4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
            Standard U value for construction extern_wall is   0.39
3w             1  301 0.0700    1.000     1.0   650.0 1.00 1.00 DI element
            Standard U value for construction DI_wall is   4.03
3roof          1  162 0.0120    0.190   960.0   837.0 0.90 0.90 Roofing felt
               2   21 0.0500    0.380  1200.0   653.0           Light mix
```

```
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4  151 0.0080    0.380  1120.0   840.0 0.90 0.60 Ceiling (plaster)
           Standard U value for construction roof_1 is   1.77
3floor        1  263 0.1000    1.280  1460.0   879.0 0.90 0.85 Common earch
              2   82 0.1000    2.900  2650.0   900.0           Red granite
              3   32 0.0500    1.400  2100.0   653.0           Heavy mix concrete
              4  124 0.0500    1.400  2100.0   650.0 0.91 0.65 Cement screed
           Standard U value for construction floor_1 is   2.76

 Zone tc ( 1) is composed of  6 surfaces and  8 vertices.
 It encloses a volume of    32.4m^3 of space, with a total surface
 area of    61.80m^2 & approx floor area of   12.00m^2
 tc describes a testcell

 A summary of the surfaces in tc( 1) follows:

 Sur| Area  |Azim|Elev| surface    |geometry| multilayer   |environment
    | m^2   |deg |deg | name       |type|loc| constr name  |other side
  1     8.10 180.   0. tcs          OPAQ VERT extern_wall   ADIABATIC
  2    10.80  90.   0. tce          OPAQ VERT extern_wall   ADIABATIC
  3     8.10   0.   0. tcn          OPAQ VERT extern_wall   ADIABATIC
  4    10.80 270.   0. tcw          OPAQ VERT DI_wall       3
  5    12.00   0.  90. tcroof       OPAQ CEIL roof_1        ADIABATIC
  6    12.00   0. -90. tcfloor      OPAQ FLOR floor_1       ADIABATIC


 All surfaces will receive diffuse insolation.

 Zone construction details for tc ( 1)

Surface    |Layer|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
           |     |db | (m)   |tivity |        |heat  |emis|abs |
tcs           1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
              2  211 0.0750    0.040   250.0   840.0           Glasswool
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
           Standard U value for construction extern_wall is   0.39
tce           1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
              2  211 0.0750    0.040   250.0   840.0           Glasswool
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
           Standard U value for construction extern_wall is   0.39
tcn           1    4 0.1000    0.960  2000.0   650.0 0.90 0.93 Outer leaf brick
              2  211 0.0750    0.040   250.0   840.0           Glasswool
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4    2 0.1000    0.440  1500.0   650.0 0.90 0.65 Breeze block
           Standard U value for construction extern_wall is   0.39
tcw           1  301 0.0700    1.000     1.0   650.0 1.00 1.00 DI element
           Standard U value for construction DI_wall is   4.03
tcroof        1  162 0.0120    0.190   960.0   837.0 0.90 0.90 Roofing felt
              2   21 0.0500    0.380  1200.0   653.0           Light mix
              3    0 0.0500    0.000     0.0     0.0           air gap (R= 0.170)
              4  151 0.0080    0.380  1120.0   840.0 0.90 0.60 Ceiling (plaster)
           Standard U value for construction roof_1 is   1.77
tcfloor       1  263 0.1000    1.280  1460.0   879.0 0.90 0.85 Common earch
              2   82 0.1000    2.900  2650.0   900.0           Red granite
              3   32 0.0500    1.400  2100.0   653.0           Heavy mix concrete
              4  124 0.0500    1.400  2100.0   650.0 0.91 0.65 Cement screed
           Standard U value for construction floor_1 is   2.76
```

Control Data

Within the current project 1 control loop has been specified it consists of a 10^5W air temperature control device that operates 24h per day, it has a heating and cooling set point of 20^0C. Hence the air temperature is strictly controlled to this temperature. The control device is located in tc, the other three zones have free-floating conditions. Details are given below.

```
 The overall project control is <proj cntrl>
 and the zone control is <steady state>.

 The sensor for function  1 senses the temperature of the current zone.
 The actuator for function  1 is air point of the current zone
 There have been  1 day types defined.

 Day type  1 is valid Sat  1 Jan to Sun 31 Dec, 2000 with  1 periods.
 Per|Start|Sensing  |Actuating  | Control law       | Data
   1  0.00 db temp   > flux      basic control       100000.0 0.0 0.0 1.0 20.0 20.0
0.0
 zone ( 1) tc           << control  1
 zone ( 2) 3            << control  0
 zone ( 3) 2            << control  0
 zone ( 4) 1            << control  0

 Overall description: proj cntrl
 Zones control: steady state : 1 functions.

 The sensor for function  1 senses the temperature of the current zone.
 The actuator for function  1 is air point of the current zone
 There have been  1 day types defined.

 Day type  1 is valid Sat  1 Jan to Sun 31 Dec, 2000 with  1 periods.
 Per|Start|Sensing  |Actuating  | Control law       | Data
   1  0.00 db temp   > flux      basic control       100000.0 0.0 0.0 1.0 20.0 20.0
0.0

 Zone to contol loop linkages:
 zone ( 1) tc           << control  1
 zone ( 2) 3            << control  0
 zone ( 3) 2            << control  0
 zone ( 4) 1            << control  0
```

Air Flow Network

Airflow is from the surface 1w to the surface tce, this is illustrated in fig A.2. The flow is through $2m^2$ specific airflow openings, except through the surface tce where a constant volume flow rate component (fan) is installed.

Flow network description.

```
  6 nodes,   2 components,   5 connections;     wind reduction =  1.000
   Node      Fluid   Node Type            Height    Temperature    Data_1       Data_2
tc           air   internal & unknown    1.3500       20.000          0.        32.401
3            air   internal & unknown    1.3500       20.000          0.       0.10800
2            air   internal & unknown    1.3500       20.000          0.       0.10800
1            air   internal & unknown    1.3500       20.000          0.        32.401
ext_w        air   boundary & wind ind   1.3500           0.      1.0000        270.00
ext_e        air   boundary & wind ind   1.3500           0.      1.0000        90.000
```

```
Comp   Type C+ L+ Description

fan            30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    variable

opening       110  2  0 Specific air flow opening           m = rho.f(A,dP)
  Fluid, opening area.
   1.00    2.00

+Node   dHght   -Node   dHght   Comp     Snod1  Snod2
2             0.000   3             0.000   opening
3             0.000   tc            0.000   opening
tc            0.000   ext_e         0.000   fan
ext_w         0.000   1             0.000   opening
1             0.000   2             0.000   opening
```

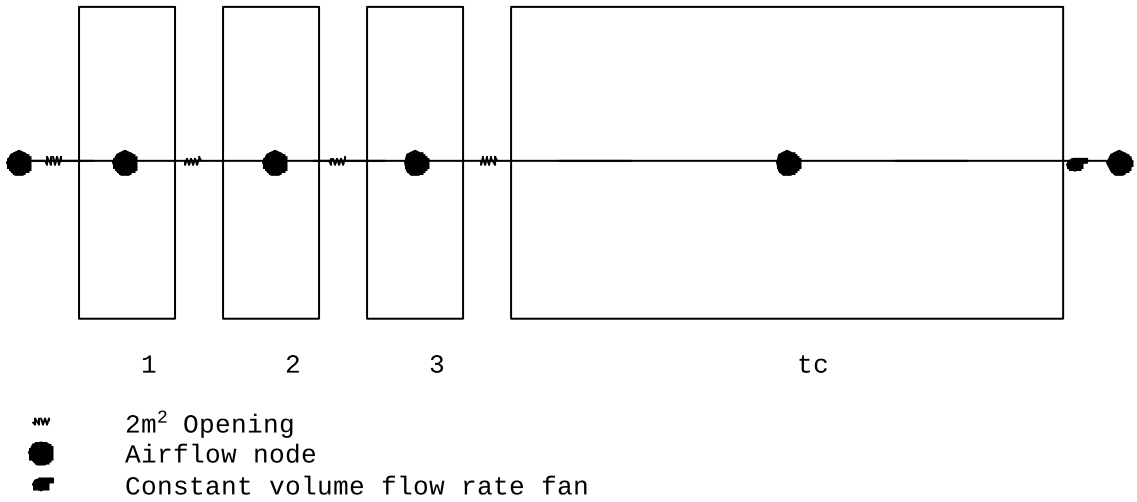


Figure A.2 Air flow network for test cell.

Climate Data

```
Year, latitude, longitude difference
1967,52.00,0.00
col 1: Diffuse solar on the horizontal (W/m^2)
col 2: External dry bulb temperature   (Tenths DEG.C)
col 3: Direct normal solar intensity   (W/m^2)
col 4: Prevailing wind speed           (Tenths m/s)
col 5: Wind direction     (clockwise deg from north)
col 6: Relative humidity               (Percent)

0,0,0,0,240,70,
0,0,0,0,240,70,
0,0,0,0,240,70,
0,0,0,0,240,70,
```

APPENDIX B

Thermo-physical Details of Construction Materials for Test House

Default surface names have not been changed for all surfaces in the test house except for windows and doors have been named win1, win2 etc and door1, door2 etc. Composition of all internal walls is intern_wall all glazed surfaces is d_glz and all doors is door. External walls in the non-dynamic case have been studied with six different types of composition C1 extern_wall, C2 ebpconv1, C3 ebpconv2, C4 ebpconv3, C5 ebptimber and C6 DI_compos. For the dynamic case DI_compos has been used but divided up into four layers corresponding to the actual zone the wall is a part of and three additional wall zones. The compositions are called DI_outer, DI_mid, DI_inner and DI_inside. All ceilings have composition ceiling, all floors have composition floor_1 and roofs have composition roof. Thermo-physical details are given below.

```
Details of transparent construction: d_glz        with DCF7671_06nb optics.
  Layer|Prim|Thick | Description
      |db  | (m)  | of material
    1  242  0.0060 Plate glass
    2    0  0.0120 air  0.17 0.17 0.17
    3  242  0.0060 Plate glass
 Standardised U value =    2.75

 Clear float 76/71,     6mm, no blind: with id of: DCF7671_06nb
 with 3 layers [including air gaps] and visible trn: 0.76
 Direct transmission @ 0, 40, 55, 70, 80 deg
   0.611 0.583 0.534 0.384 0.170
 Layer| absorption @ 0, 40, 55, 70, 80 deg
    1  0.157 0.172 0.185 0.201 0.202
    2  0.001 0.002 0.003 0.004 0.005
    3  0.117 0.124 0.127 0.112 0.077

 Details of opaque composite: floor_1
  Layer|Prim|Thick | Description
      |db  | (m)  | of material
    1  263  0.1000 Common earch
    2   82  0.1000 Red granite
    3   32  0.0500 Heavy mix concrete
    4  124  0.0500 Cement screed
 Standardised U value =    2.76

 Details of opaque composite: intern_wall
  Layer|Prim|Thick | Description
      |db  | (m)  | of material
    1    2  0.1500 Breeze block
    2  103  0.0120 Perlite plasterboard
 Standardised U value =    1.71

 Details of opaque composite: roof
  Layer|Prim|Thick | Description
      |db  | (m)  | of material
    1   43  0.0030 Aluminium
    2    0  0.0250 air  0.17 0.17 0.17
    3  281  0.0800 Glass Fibre Quilt
    4   43  0.0030 Aluminium
 Standardised U value =    0.43

 Details of opaque composite: ceiling
  Layer|Prim|Thick | Description
```

```
     |db  | (m)  | of material
   1  211  0.1000 Glasswool
   2  150  0.0100 Ceiling (mineral)
Standardised U value =    0.33

Details of opaque composite: door
Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1   72  0.0100 Plywood
Standardised U value =    4.09

Details of opaque composite: DI_compos
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1   42  0.0007 Steel
   2    0  0.0200 air  0.17 0.17 0.17
   3   64  0.0200 Fir (20% mc)
   4  222  0.0500 Simulated sheeps wool
   5   64  0.0200 Fir (20% mc)
   6    0  0.0200 air  0.17 0.17 0.17
   7  101  0.0125 Dense plaster
Standardised U value =    0.60

Details of opaque composite: DI_outer
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1   42  0.0007 Steel
   2    0  0.0200 air  0.17 0.17 0.17
   3   64  0.0200 Fir (20% mc)
   4  226  0.0050 e=1Simulated sheeps wool
   5  222  0.0050 Simulated sheeps wool
Standardised U value =    1.52

Details of opaque composite: DI_mid
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1  226  0.0075 e=1Simulated sheeps wool
Standardised U value =    3.30

Details of opaque composite: DI_inner
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1  226  0.0050 e=1Simulated sheeps wool
   2  222  0.0050 Simulated sheeps wool
Standardised U value =    2.90

Details of opaque composite: DI_inside
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1   64  0.0200 Fir (20% mc)
   2    0  0.0200 air  0.17 0.17 0.17
   3  101  0.0125 Dense plaster
Standardised U value =    1.94

Details of opaque composite: ebpconv1
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1  125  0.0180 White dry render
   2   32  0.1000 Heavy mix concrete
   3    0  0.0500 air  0.17 0.17 0.17
   4    2  0.1000 Breeze block
```

```
   5    0  0.0250 air  0.17 0.17 0.17
   6  214  0.0750 EPS
   7  107  0.0125 Gypsum plasterboard
Standardised U value =    0.29

Details of opaque composite: ebpconv2
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1  125  0.0180 White dry render
   2   32  0.1000 Heavy mix concrete
   3    0  0.0500 air  0.17 0.17 0.17
   4    2  0.1000 Breeze block
   5  205  0.0750 Polyurethane foam board
   6  107  0.0125 Gypsum plasterboard
Standardised U value =    0.31

Details of transparent construction: ebpconv3
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1  125  0.0180 White dry render
   2   32  0.1000 Heavy mix concrete
   3    0  0.0250 air  0.17 0.17 0.17
   4  203  0.0750 UF foam
   5  107  0.0125 Gypsum plasterboard
Standardised U value =    0.33

Details of opaque composite: ebptimber
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1    1  0.1000 Paviour brick
   2   70  0.0125 Plywood
   3   61  0.1000 Block (wood)
   4  217  0.0750 Cork insulation
   5  107  0.0125 Gypsum plasterboard
Standardised U value =    0.34

Details of opaque composite: extern_wall
 Layer|Prim|Thick | Description
     |db  | (m)  | of material
   1    4  0.1000 Outer leaf brick
   2  211  0.0750 Glasswool
   3    0  0.0500 air  0.17 0.17 0.17
   4    2  0.1000 Breeze block
Standardised U value =    0.39
U value assumes: external wall with Rso = 0.055m**2deg.C/W
                 and Rsi = 0.123m**2deg.C/W
```

APPENDIX C

Control Data for Test House

Two schemes of control have been used for simulation of the test house as outlined in Chapter 5. These have been called VH1 and VH2 respectively. The naming corresponds to the legend in table 4, chapter 5. VH1 relates to a heating mechanism that is occupancy controlled i.e. heating in a zone comes on only when that zone is occupied, dynamic insulation is independent of occupancy or any other parameter and remains on 24h per day. VH2 relates to a fixed pattern of heating 6:30~8:30 and 16:30~23:30 during weekdays and from 7:00~21:00 at weekends, dynamic insulation comes on for the same time periods. Details of plant and control are given below

```
VH1:
Within the current project  6 control loops have been specified.
 The overall project control is <proj cntrl>
 and the zone control is <bed2>.

 The sensor for function  1 senses the temperature of the current zone.
 The actuator for function  1 is air point of the current zone
 The function day types are Weekdays, Saturdays & Sundays
 Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
 Per|Start|Sensing  |Actuating  | Control law      | Data
   1  0.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   2  7.00 db temp   > flux      free floating
   3 22.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
 Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  2 periods.
 Per|Start|Sensing  |Actuating  | Control law      | Data
   1  0.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   2  9.00 db temp   > flux      free floating
 Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  2 periods.
 Per|Start|Sensing  |Actuating  | Control law      | Data
   1  0.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   2  9.00 db temp   > flux      free floating

 The sensor for function  2 senses the temperature of the current zone.
 The actuator for function  2 is air point of the current zone
 The function day types are Weekdays, Saturdays & Sundays
 Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
 Per|Start|Sensing  |Actuating  | Control law      | Data
   1  0.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   2  8.00 db temp   > flux      free floating
   3 22.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
 Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  2 periods.
 Per|Start|Sensing  |Actuating  | Control law      | Data
   1  0.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   2 11.00 db temp   > flux      free floating
 Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  2 periods.
 Per|Start|Sensing  |Actuating  | Control law      | Data
   1  0.00 db temp   > flux      basic control      1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   2 11.00 db temp   > flux      free floating

 The sensor for function  3 senses the temperature of the current zone.
 The actuator for function  3 is air point of the current zone
 The function day types are Weekdays, Saturdays & Sundays
 Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  7 periods.
```

```
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  8.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3  9.00 db temp   > flux      free floating
  4 13.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  5 14.00 db temp   > flux      free floating
  6 19.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  7 20.00 db temp   > flux      free floating
Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2 11.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 12.00 db temp   > flux      free floating
Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2 11.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 12.00 db temp   > flux      free floating

The sensor for function  4 senses the temperature of the current zone.
The actuator for function  4 is air point of the current zone
The function day types are Weekdays, Saturdays & Sundays
Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  5 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2 16.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 19.00 db temp   > flux      free floating
  4 20.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  5 22.00 db temp   > flux      free floating
Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  4 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2 12.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 18.00 db temp   > flux      free floating
  4 21.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  4 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2 12.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 18.00 db temp   > flux      free floating
  4 21.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0

The sensor for function  5 senses the temperature of the current zone.
The actuator for function  5 is air point of the current zone
The function day types are Weekdays, Saturdays & Sundays
Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  1 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 18.00 db temp   > flux      free floating
Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 18.00 db temp   > flux      free floating

The sensor for function  6 senses the temperature of the current zone.
The actuator for function  6 is air point of the current zone
```

```
 The function day types are Weekdays, Saturdays & Sundays
 Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  7 periods.
 Per|Start|Sensing  |Actuating  | Control law       | Data
   1  0.00 db temp   > flux      free floating
   2  7.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   3  8.00 db temp   > flux      free floating
   4 12.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   5 13.00 db temp   > flux      free floating
   6 18.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   7 19.00 db temp   > flux      free floating
 Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  5 periods.
 Per|Start|Sensing  |Actuating  | Control law       | Data
   1  0.00 db temp   > flux      free floating
   2  9.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   3 10.00 db temp   > flux      free floating
   4 17.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   5 18.00 db temp   > flux      free floating
 Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  5 periods.
 Per|Start|Sensing  |Actuating  | Control law       | Data
   1  0.00 db temp   > flux      free floating
   2  9.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   3 10.00 db temp   > flux      free floating
   4 17.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
   5 18.00 db temp   > flux      free floating

Linkage of control functions to zones
 zone ( 1) sit          << control  3
 zone ( 2) kit          << control  6
 zone ( 3) box          << control  0
 zone ( 4) liv          << control  4
 zone ( 5) bed1         << control  1
 zone ( 6) bed2         << control  2
 zone ( 7) doors        << control  0
 zone ( 8) main         << control  5
 zone ( 9) loft         << control  0
 zone (10) sit3         << control  0
 zone (11) sit2         << control  0
 zone (12) sit1         << control  0
 zone (13) bed23        << control  0
 zone (14) bed22        << control  0
 zone (15) bed21        << control  0
 zone (16) bed13        << control  0
 zone (17) bed12        << control  0
 zone (18) bed11        << control  0
 zone (19) liv3         << control  0
 zone (20) liv2         << control  0
 zone (21) liv1         << control  0
 zone (22) kit3         << control  0
 zone (23) kit2         << control  0
 zone (24) kit1         << control  0
 zone (25) box3         << control  0
 zone (26) box2         << control  0
 zone (27) box1         << control  0

VH2:
Within the current project  3 control loops have been specified.
 The overall project control is <proj cntrl>
 and the zone control is <no descrip>.

 The sensor for function  1 senses the temperature of the current zone.
 The actuator for function  1 is air point of the current zone
```

```
The function day types are Weekdays, Saturdays & Sundays
Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  5 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  6.50 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
  3  8.50 db temp   > flux      free floating
  4 16.50 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
  5 23.50 db temp   > flux      free floating
Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 21.00 db temp   > flux      free floating
Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 21.00 db temp   > flux      free floating

The sensor for function  2 senses the temperature of the current zone.
The actuator for function  2 is air point of the current zone
The function day types are Weekdays, Saturdays & Sundays
Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  5 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  6.50 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3  8.50 db temp   > flux      free floating
  4 16.50 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  5 23.50 db temp   > flux      free floating
Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 21.00 db temp   > flux      free floating
Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       3500.0 0.0 0.0 0.0 20.0 100.0 0.0
  3 21.00 db temp   > flux      free floating

The sensor for function  3 senses the temperature of the current zone.
The actuator for function  3 is air point of the current zone
The function day types are Weekdays, Saturdays & Sundays
Weekday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  5 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  6.50 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 18.0 100.0 0.0
  3  8.50 db temp   > flux      free floating
  4 16.50 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 18.0 100.0 0.0
  5 23.50 db temp   > flux      free floating
Saturday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 18.0 100.0 0.0
  3 21.00 db temp   > flux      free floating
Sunday control is valid Sat  1 Jan to Sun 31 Dec, 2000 with  3 periods.
Per|Start|Sensing  |Actuating  | Control law       | Data
  1  0.00 db temp   > flux      free floating
  2  7.00 db temp   > flux      basic control       1000.0 0.0 0.0 0.0 18.0 100.0 0.0
  3 21.00 db temp   > flux      free floating
```

```
Linkage of control functions to zones
 zone ( 1) sit          << control  2
 zone ( 2) kit          << control  1
 zone ( 3) box          << control  0
 zone ( 4) liv          << control  2
 zone ( 5) bed1         << control  3
 zone ( 6) bed2         << control  3
 zone ( 7) doors        << control  0
 zone ( 8) main         << control  2
 zone ( 9) loft         << control  0
 zone (10) sit3         << control  0
 zone (11) sit2         << control  0
 zone (12) sit1         << control  0
 zone (13) bed23        << control  0
 zone (14) bed22        << control  0
 zone (15) bed21        << control  0
 zone (16) bed13        << control  0
 zone (17) bed12        << control  0
 zone (18) bed11        << control  0
 zone (19) liv3         << control  0
 zone (20) liv2         << control  0
 zone (21) liv1         << control  0
 zone (22) kit3         << control  0
 zone (23) kit2         << control  0
 zone (24) kit1         << control  0
 zone (25) box3         << control  0
 zone (26) box2         << control  0
 zone (27) box1         << control  0
```

APPENDIX D

Air Flow Network for Test House

Three different airflow networks were used in the various simulations

1. P1 for which airflow is dictated by the 6th Amendment to the Technical Standards for Compliance with the Building Standards (Scotland) Regulations 1990 - Part J. These were designed to give a ventilation with 1.1 ach in all living space and 3.5 in bathrooms and kitchens
2. P2 which has the same pattern of airflow as P1 except for the flow rates which are 150% those for P1
3. P1X, this has the same pattern and flow rate as P1, but 75% of the exhaust air is redirected for the purpose of dynamic insulation. Hence reclaiming heat and emulating a 75% efficient heat exchanger.

Flow network for 1 and 2 is shown in fig A.3 and flow network for 3 is shown in fig A.4

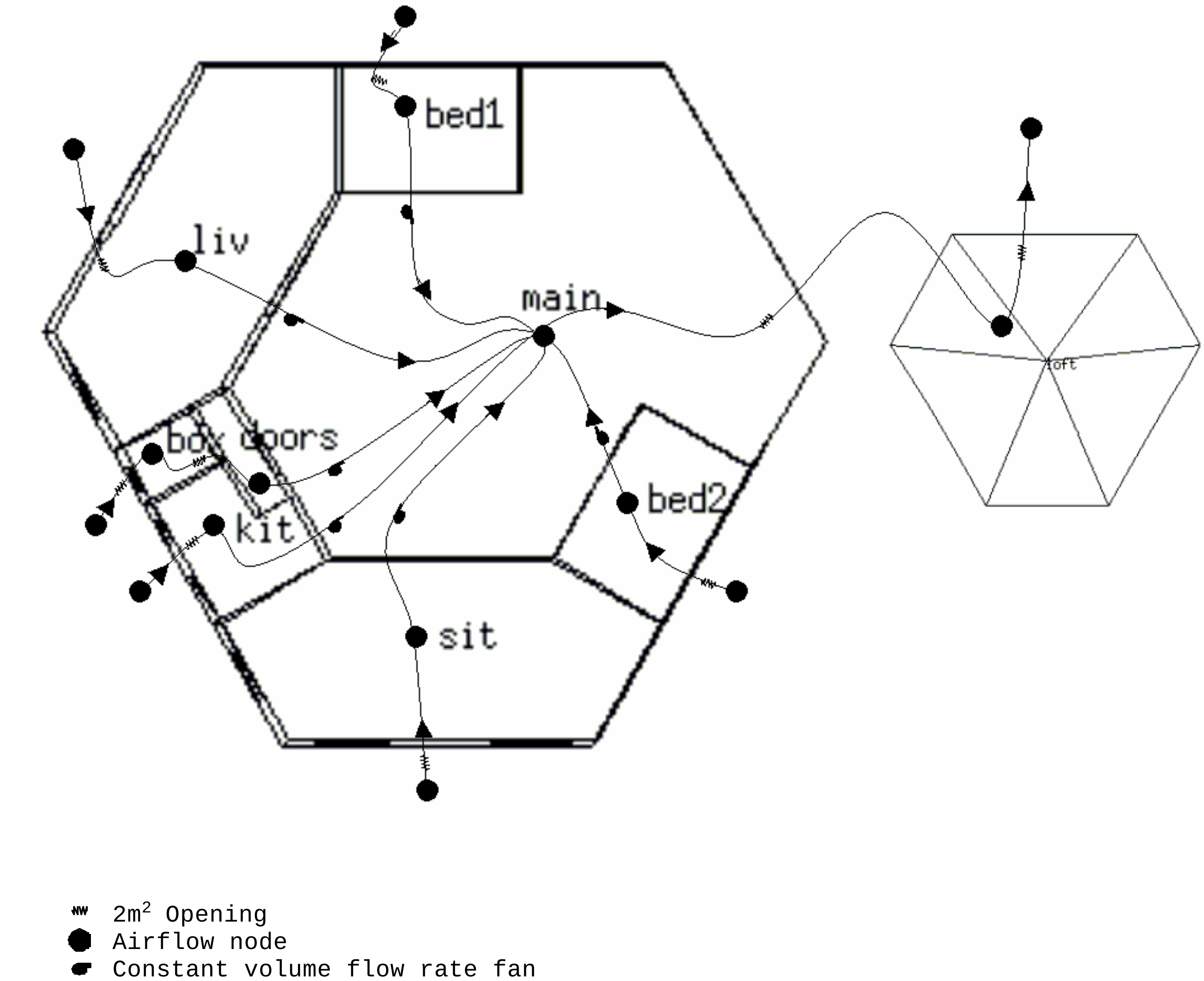
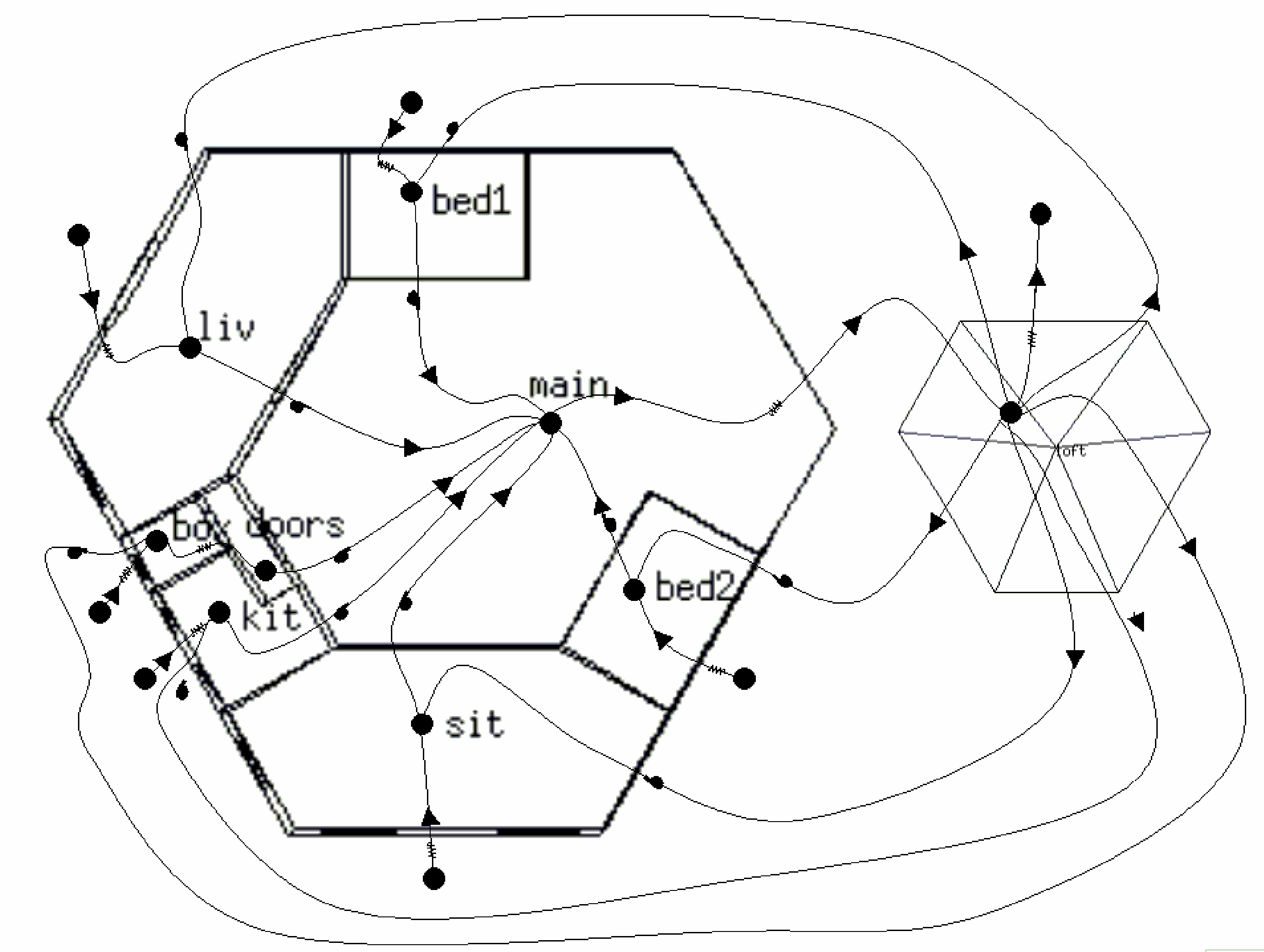


Figure A.3 Flow network for P1 and P2.



2m² Opening
Airflow node
Constant volume flow rate fan

Figure A.4 Flow network for P1X.

NOTE More than one fan has been employed in the model to improve ease of operation and control. In actual practice one fan with suitable ducting would be sufficient.

Details of the airflow network are given below

Flow network description for test house without dynamic insulation P1

16 nodes, 7 components, 15 connections; wind reduction = 1.000

Node	Fluid	Node Type	Height	Temperature	Data_1	Data_2
sit	air	internal & unknown	1.2000	20.000	0.	86.887
kit	air	internal & unknown	1.2000	20.000	0.	19.620
box	air	internal & unknown	1.2000	20.000	0.	7.1990
liv	air	internal & unknown	1.2000	20.000	0.	86.575
bed1	air	internal & unknown	1.2000	20.000	0.	30.240
bed2	air	internal & unknown	1.2000	20.000	0.	30.240
doors	air	internal & unknown	1.2000	20.000	0.	6.6591
main	air	internal & unknown	1.2000	20.000	0.	242.67
loft	air	internal & unknown	2.9000	20.000	0.	70.757
site	air	boundary & wind ind	1.0000	0.	1.0000	180.00
bed2e	air	boundary & wind ind	1.0400	0.	1.0000	120.00

```
lofte        air   boundary & wind ind   2.7333          0.       1.0000       59.999
bed1e        air   boundary & wind ind   1.0400          0.       1.0000       1.0000
live         air   boundary & wind ind   1.1250          0.       1.0000       300.00
boxe         air   boundary & wind ind   1.0400          0.       1.0000       59.995
kite         air   boundary & wind ind   1.0000          0.       1.0000       240.00

  Comp   Type C+ L+ Description
  crack        110  2  0 Specific air flow opening          m = rho.f(A,dP)
    Fluid, opening area.
     1.00    0.50
  fan_site      30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.04
  fan_bed2e     30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.01
  fan_bed1e     30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.01
  fan_live      30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.04
  fan_boxe      30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.01
  fan_kite      30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.03

  +Node   dHght   -Node   dHght   Comp     Snod1  Snod2
  site          0.100   sit          -0.100   crack
  kite          0.100   kit          -0.100   crack
  boxe          0.080   box          -0.080   crack
  live          0.038   liv          -0.038   crack
  bed1e         0.080   bed1         -0.080   crack
  bed2e         0.080   bed2         -0.080   crack
  box           0.000   doors         0.000   crack
  sit           0.000   main          0.000   fan_site
  kit           0.000   main          0.000   fan_kite
  doors         0.000   main          0.000   fan_boxe
  liv           0.000   main          0.000   fan_live
  bed1          0.000   main          0.000   fan_bed1e
  bed2          0.000   main          0.000   fan_bed2e
  main          0.850   loft         -0.850   crack
  loft         -0.083   lofte         0.083   crack
```

Flow network description.
P2

```
 16 nodes,   7 components,  15 connections;     wind reduction =  1.000
   Node      Fluid   Node Type            Height    Temperature    Data_1       Data_2
sit          air   internal & unknown    1.2000       20.000          0.       86.887
kit          air   internal & unknown    1.2000       20.000          0.       19.620
box          air   internal & unknown    1.2000       20.000          0.       7.1990
liv          air   internal & unknown    1.2000       20.000          0.       86.575
bed1         air   internal & unknown    1.2000       20.000          0.       30.240
bed2         air   internal & unknown    1.2000       20.000          0.       30.240
doors        air   internal & unknown    1.2000       20.000          0.       6.6591
main         air   internal & unknown    1.2000       20.000          0.       242.67
loft         air   internal & unknown    2.9000       20.000          0.       70.757
site         air   boundary & wind ind   1.0000          0.       1.0000       180.00
```

```
bed2e         air   boundary & wind ind   1.0400           0.       1.0000       120.00
lofte         air   boundary & wind ind   2.7333           0.       1.0000       59.999
bed1e         air   boundary & wind ind   1.0400           0.       1.0000       1.0000
live          air   boundary & wind ind   1.1250           0.       1.0000       300.00
boxe          air   boundary & wind ind   1.0400           0.       1.0000       59.995
kite          air   boundary & wind ind   1.0000           0.       1.0000       240.00

  Comp   Type C+ L+ Description
  crack         110  2  0 Specific air flow opening           m = rho.f(A,dP)
    Fluid, opening area.
     1.00    0.50
  fan_site       30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.03
  fan_bed2e      30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.01
  fan_bed1e      30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.01
  fan_live       30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.03
  fan_boxe       30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.01
  fan_kite       30  2  0 Constant vol. flow rate component   m = rho.a
    Fluid, flow rate (m^3/s).
     1.00    0.02

  +Node   dHght   -Node   dHght   Comp     Snod1  Snod2
  site          0.100   sit          -0.100   crack
  kite          0.100   kit          -0.100   crack
  boxe          0.080   box          -0.080   crack
  live          0.038   liv          -0.038   crack
  bed1e         0.080   bed1         -0.080   crack
  bed2e         0.080   bed2         -0.080   crack
  box           0.000   doors         0.000   crack
  sit           0.000   main          0.000   fan_site
  kit           0.000   main          0.000   fan_kite
  doors         0.000   main          0.000   fan_boxe
  liv           0.000   main          0.000   fan_live
  bed1          0.000   main          0.000   fan_bed1e
  bed2          0.000   main          0.000   fan_bed2e
  main          0.850   loft         -0.850   crack
  loft         -0.083   lofte         0.083   crack
```

Flow network description for test house with dynamic insulation.
P1

```
  34 nodes,   7 components,  32 connections;     wind reduction =  1.000
   Node      Fluid   Node Type            Height    Temperature    Data_1       Data_2
sit           air   internal & unknown    1.2000       20.000          0.       86.887
kit           air   internal & unknown    1.2000       20.000          0.       19.620
box           air   internal & unknown    1.2000       20.000          0.       7.1990
liv           air   internal & unknown    1.2000       20.000          0.       86.575
bed1          air   internal & unknown    1.2000       20.000          0.       30.240
bed2          air   internal & unknown    1.2000       20.000          0.       30.240
doors         air   internal & unknown    1.2000       20.000          0.       6.6591
main          air   internal & unknown    1.2000       20.000          0.       242.67
```

```
loft         air   internal & unknown    2.9000       20.000           0.       70.757
sit3         air   internal & unknown    1.2000       20.000           0.      0.57724
sit2         air   internal & unknown    1.2000       20.000           0.      0.50087
sit1         air   internal & unknown    1.2000       20.000           0.      0.50086
bed23        air   internal & unknown    1.2000       20.000           0.      0.20142
bed22        air   internal & unknown    1.2000       20.000           0.      0.20144
bed21        air   internal & unknown    1.2000       20.000           0.      0.20142
bed13        air   internal & unknown    1.2000       20.000           0.      0.20044
bed12        air   internal & unknown    1.2000       20.000           0.      0.20043
bed11        air   internal & unknown    1.2000       20.000           0.      0.20044
liv3         air   internal & unknown    1.2000       20.000           0.      0.47391
liv2         air   internal & unknown    1.2000       20.000           0.      0.47394
liv1         air   internal & unknown    1.2000       20.000           0.      0.47394
kit3         air   internal & unknown    1.2000       20.000           0.      0.13294
kit2         air   internal & unknown    1.2000       20.000           0.      0.13294
kit1         air   internal & unknown    1.2000       20.000           0.      0.13294
box3         air   internal & unknown    1.2000       20.000           0.      0.062312
box2         air   internal & unknown    1.2000       20.000           0.      0.062312
box1         air   internal & unknown    1.2000       20.000           0.      0.062309
site         air   boundary & wind ind   1.0000           0.      1.0000           0.
bed2e        air   boundary & wind ind   1.0400           0.      1.0000       300.00
bed1e        air   boundary & wind ind   1.0400           0.      1.0000       180.00
live         air   boundary & wind ind   1.1250           0.      1.0000       119.91
kite         air   boundary & wind ind   1.0000           0.      1.0000       60.000
boxe         air   boundary & wind ind   1.0400           0.      1.0000       59.995
lofte        air   boundary & wind ind   2.7333           0.      1.0000       59.999

Comp   Type C+ L+ Description
crack         110  2  0 Specific air flow opening           m = rho.f(A,dP)
  Fluid, opening area.
   1.00    0.50
fan_site       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.03
fan_bed2e      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_bed1e      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_live       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.03
fan_boxe       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_kite       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.02

+Node   dHght   -Node   dHght   Comp     Snod1  Snod2
site          0.100   sit1         -0.100   crack
sit1          0.000   sit2          0.000   crack
sit2          0.000   sit3          0.000   crack
sit3          0.000   sit           0.000   crack
sit           0.000   main          0.000   fan_site
bed2e         0.080   bed21        -0.080   crack
bed21         0.000   bed22         0.000   crack
bed22         0.000   bed23         0.000   crack
bed23         0.000   bed2          0.000   crack
bed2          0.000   main          0.000   fan_bed2e
```

bed1e	0.080	bed11	-0.080	crack
bed11	0.000	bed12	0.000	crack
bed12	0.000	bed13	0.000	crack
bed13	0.000	bed1	0.000	crack
bed1	0.000	main	0.000	fan_bed1e
live	0.038	liv1	-0.038	crack
liv1	0.000	liv2	0.000	crack
liv2	0.000	liv3	0.000	crack
liv3	0.000	liv	0.000	crack
liv	0.000	main	0.000	fan_live
kite	0.100	kit1	-0.100	crack
kit1	0.000	kit2	0.000	crack
kit2	0.000	kit3	0.000	crack
kit3	0.000	kit	0.000	crack
kit	0.000	main	0.000	fan_kite
boxe	0.080	box1	-0.080	crack
box1	0.000	box2	0.000	crack
box2	0.000	box3	0.000	crack
box3	0.000	box	0.000	crack
box	0.000	main	0.000	fan_boxe
main	0.850	loft	-0.850	crack
loft	-0.083	lofte	0.083	crack

Flow network description.
P2

34 nodes,   7 components, 32 connections;   wind reduction = 1.000

Node	Fluid	Node Type	Height	Temperature	Data_1	Data_2
sit	air	internal & unknown	1.2000	20.000	0.	86.887
kit	air	internal & unknown	1.2000	20.000	0.	19.620
box	air	internal & unknown	1.2000	20.000	0.	7.1990
liv	air	internal & unknown	1.2000	20.000	0.	86.575
bed1	air	internal & unknown	1.2000	20.000	0.	30.240
bed2	air	internal & unknown	1.2000	20.000	0.	30.240
doors	air	internal & unknown	1.2000	20.000	0.	6.6591
main	air	internal & unknown	1.2000	20.000	0.	242.67
loft	air	internal & unknown	2.9000	20.000	0.	70.757
sit3	air	internal & unknown	1.2000	20.000	0.	0.57724
sit2	air	internal & unknown	1.2000	20.000	0.	0.50087
sit1	air	internal & unknown	1.2000	20.000	0.	0.50086
bed23	air	internal & unknown	1.2000	20.000	0.	0.20142
bed22	air	internal & unknown	1.2000	20.000	0.	0.20144
bed21	air	internal & unknown	1.2000	20.000	0.	0.20142
bed13	air	internal & unknown	1.2000	20.000	0.	0.20044
bed12	air	internal & unknown	1.2000	20.000	0.	0.20043
bed11	air	internal & unknown	1.2000	20.000	0.	0.20044
liv3	air	internal & unknown	1.2000	20.000	0.	0.47391
liv2	air	internal & unknown	1.2000	20.000	0.	0.47394
liv1	air	internal & unknown	1.2000	20.000	0.	0.47394
kit3	air	internal & unknown	1.2000	20.000	0.	0.13294
kit2	air	internal & unknown	1.2000	20.000	0.	0.13294
kit1	air	internal & unknown	1.2000	20.000	0.	0.13294
box3	air	internal & unknown	1.2000	20.000	0.	0.062312
box2	air	internal & unknown	1.2000	20.000	0.	0.062312
box1	air	internal & unknown	1.2000	20.000	0.	0.062309
site	air	boundary & wind ind	1.0000	0.	1.0000	0.
bed2e	air	boundary & wind ind	1.0400	0.	1.0000	300.00
bed1e	air	boundary & wind ind	1.0400	0.	1.0000	180.00
live	air	boundary & wind ind	1.1250	0.	1.0000	119.91
kite	air	boundary & wind ind	1.0000	0.	1.0000	60.000
boxe	air	boundary & wind ind	1.0400	0.	1.0000	59.995

```
lofte        air   boundary & wind ind   2.7333          0.       1.0000       59.999

Comp   Type C+ L+ Description
crack         110  2  0 Specific air flow opening           m = rho.f(A,dP)
  Fluid, opening area.
   1.00    0.50
fan_site       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.04
fan_bed2e      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_bed1e      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_live       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.04
fan_boxe       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_kite       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.03

+Node   dHght   -Node   dHght   Comp     Snod1  Snod2
site          0.100   sit1         -0.100   crack
sit1          0.000   sit2          0.000   crack
sit2          0.000   sit3          0.000   crack
sit3          0.000   sit           0.000   crack
sit           0.000   main          0.000   fan_site
bed2e         0.080   bed21        -0.080   crack
bed21         0.000   bed22         0.000   crack
bed22         0.000   bed23         0.000   crack
bed23         0.000   bed2          0.000   crack
bed2          0.000   main          0.000   fan_bed2e
bed1e         0.080   bed11        -0.080   crack
bed11         0.000   bed12         0.000   crack
bed12         0.000   bed13         0.000   crack
bed13         0.000   bed1          0.000   crack
bed1          0.000   main          0.000   fan_bed1e
live          0.038   liv1         -0.038   crack
liv1          0.000   liv2          0.000   crack
liv2          0.000   liv3          0.000   crack
liv3          0.000   liv           0.000   crack
liv           0.000   main          0.000   fan_live
kite          0.100   kit1         -0.100   crack
kit1          0.000   kit2          0.000   crack
kit2          0.000   kit3          0.000   crack
kit3          0.000   kit           0.000   crack
kit           0.000   main          0.000   fan_kite
boxe          0.080   box1         -0.080   crack
box1          0.000   box2          0.000   crack
box2          0.000   box3          0.000   crack
box3          0.000   box           0.000   crack
box           0.000   main          0.000   fan_boxe
main          0.850   loft         -0.850   crack
loft         -0.083   lofte         0.083   crack
```

Flow network description.
P1X

```
 34 nodes,  13 components,  38 connections;     wind reduction =  1.000
   Node      Fluid   Node Type            Height    Temperature    Data_1       Data_2
sit          air   internal & unknown    1.2000      20.000           0.       86.887
kit          air   internal & unknown    1.2000      20.000           0.       19.620
box          air   internal & unknown    1.2000      20.000           0.       7.1990
liv          air   internal & unknown    1.2000      20.000           0.       86.575
bed1         air   internal & unknown    1.2000      20.000           0.       30.240
bed2         air   internal & unknown    1.2000      20.000           0.       30.240
doors        air   internal & unknown    1.2000      20.000           0.       6.6591
main         air   internal & unknown    1.2000      20.000           0.       242.67
loft         air   internal & unknown    2.9000      20.000           0.       70.757
sit3         air   internal & unknown    1.2000      20.000           0.      0.57724
sit2         air   internal & unknown    1.2000      20.000           0.      0.50087
sit1         air   internal & unknown    1.2000      20.000           0.      0.50086
bed23        air   internal & unknown    1.2000      20.000           0.      0.20142
bed22        air   internal & unknown    1.2000      20.000           0.      0.20144
bed21        air   internal & unknown    1.2000      20.000           0.      0.20142
bed13        air   internal & unknown    1.2000      20.000           0.      0.20044
bed12        air   internal & unknown    1.2000      20.000           0.      0.20043
bed11        air   internal & unknown    1.2000      20.000           0.      0.20044
liv3         air   internal & unknown    1.2000      20.000           0.      0.47391
liv2         air   internal & unknown    1.2000      20.000           0.      0.47394
liv1         air   internal & unknown    1.2000      20.000           0.      0.47394
kit3         air   internal & unknown    1.2000      20.000           0.      0.13294
kit2         air   internal & unknown    1.2000      20.000           0.      0.13294
kit1         air   internal & unknown    1.2000      20.000           0.      0.13294
box3         air   internal & unknown    1.2000      20.000           0.      0.062312
box2         air   internal & unknown    1.2000      20.000           0.      0.062312
box1         air   internal & unknown    1.2000      20.000           0.      0.062309
site         air   boundary & wind ind   1.0000          0.       1.0000           0.
bed2e        air   boundary & wind ind   1.0400          0.       1.0000       300.00
bed1e        air   boundary & wind ind   1.0400          0.       1.0000       180.00
live         air   boundary & wind ind   1.1250          0.       1.0000       119.91
kite         air   boundary & wind ind   1.0000          0.       1.0000       60.000
boxe         air   boundary & wind ind   1.0400          0.       1.0000       59.995
lofte        air   boundary & wind ind   2.7333          0.       1.0000       59.999

Comp    Type C+ L+ Description
crack         110  2  0 Specific air flow opening           m = rho.f(A,dP)
  Fluid, opening area.
   1.00    0.50
fan_site       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.03
fan_bed2e      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_bed1e      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_live       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.03
fan_boxe       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_kite       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
```

```
   1.00    0.02
fan_sitl       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.02
fan_bed2l      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_bed1l      30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_livl       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.02
fan_kitl       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01
fan_boxl       30  2  0 Constant vol. flow rate component   m = rho.a
  Fluid, flow rate (m^3/s).
   1.00    0.01

+Node   dHght   -Node   dHght   Comp     Snod1  Snod2
site          0.100   sit1         -0.100   crack
sit1          0.000   sit2          0.000   crack
sit2          0.000   sit3          0.000   crack
sit3          0.000   sit           0.000   crack
sit           0.000   main          0.000   fan_site
bed2e         0.080   bed21        -0.080   crack
bed21         0.000   bed22         0.000   crack
bed22         0.000   bed23         0.000   crack
bed23         0.000   bed2          0.000   crack
bed2          0.000   main          0.000   fan_bed2e
bed1e         0.080   bed11        -0.080   crack
bed11         0.000   bed12         0.000   crack
bed12         0.000   bed13         0.000   crack
bed13         0.000   bed1          0.000   crack
bed1          0.000   main          0.000   fan_bed1e
live          0.038   liv1         -0.038   crack
liv1          0.000   liv2          0.000   crack
liv2          0.000   liv3          0.000   crack
liv3          0.000   liv           0.000   crack
liv           0.000   main          0.000   fan_live
kite          0.100   kit1         -0.100   crack
kit1          0.000   kit2          0.000   crack
kit2          0.000   kit3          0.000   crack
kit3          0.000   kit           0.000   crack
kit           0.000   main          0.000   fan_kite
boxe          0.080   box1         -0.080   crack
box1          0.000   box2          0.000   crack
box2          0.000   box3          0.000   crack
box3          0.000   box           0.000   crack
box           0.000   main          0.000   fan_boxe
main          0.850   loft         -0.850   crack
loft         -0.083   lofte         0.083   crack
loft         -0.850   sit           0.850   fan_sitl
loft         -0.850   bed2          0.850   fan_bed2l
loft         -0.850   bed1          0.850   fan_bed1l
loft         -0.850   liv           0.850   fan_livl
loft         -0.850   kit           0.850   fan_kitl
loft         -0.850   box           0.850   fan_boxl
```

APPENDIX E

Casual Gains for Test House

Different gains have been specified for each zone namely occupancy, lights and equipment some of which comes on at specific times and other which remains on 24h per day. Basic equipment like television, refrigerator and stove has been accounted for. Details are given below:

Description : zone sit
Number of Weekday Sat Sun casual gains= 5 2 2

Day	Gain No.	Type labl	Period Hours	Sensible Magn.(W)	Latent Magn. (W)	Radiant Frac	Convec Frac
Wkd	1	OccuptW	8 - 9	540.0	300.0	0.20	0.80
Wkd	2	OccuptW	13 - 14	360.0	200.0	0.20	0.80
Wkd	3	EquiptW	12 - 20	700.0	700.0	0.50	0.50
Wkd	4	LightsW/m^2	19 - 20	10.0	0.0	0.70	0.30
Wkd	5	OccuptW	19 - 20	540.0	300.0	0.20	0.80
Sat	1	OccuptW	11 - 12	450.0	250.0	0.20	0.80
Sat	2	EquiptW	12 - 20	700.0	700.0	0.50	0.50
Sun	1	OccuptW	11 - 12	450.0	250.0	0.20	0.80
Sun	2	EquiptW	12 - 20	700.0	700.0	0.50	0.50

Description : zone kit
Number of Weekday Sat Sun casual gains= 7 4 4

Day	Gain No.	Type labl	Period Hours	Sensible Magn.(W)	Latent Magn. (W)	Radiant Frac	Convec Frac
Wkd	1	OccuptW	7 - 8	90.0	50.0	0.20	0.80
Wkd	2	OccuptW	12 - 13	90.0	50.0	0.20	0.80
Wkd	3	LightsW/m^2	18 - 19	10.0	0.0	0.70	0.30
Wkd	4	EquiptW	7 - 8	1000.0	0.0	0.50	0.50
Wkd	5	EquiptW	12 - 13	1000.0	0.0	0.50	0.50
Wkd	6	EquiptW	18 - 19	1000.0	0.0	0.50	0.50
Wkd	7	OccuptW	18 - 19	90.0	50.0	0.20	0.80
Sat	1	OccuptW	9 - 10	90.0	50.0	0.20	0.80
Sat	2	EquiptW	9 - 10	1000.0	0.0	0.50	0.50
Sat	3	EquiptW	17 - 18	1000.0	0.0	0.50	0.50
Sat	4	OccuptW	17 - 18	90.0	50.0	0.20	0.80
Sun	1	OccuptW	9 - 10	90.0	50.0	0.20	0.80
Sun	2	EquiptW	9 - 10	1000.0	0.0	0.50	0.50
Sun	3	EquiptW	17 - 18	1000.0	0.0	0.50	0.50
Sun	4	OccuptW	17 - 18	90.0	50.0	0.20	0.80

Description : box
Number of Weekday Sat Sun casual gains= 0 0 0

Description : zone liv
Number of Weekday Sat Sun casual gains= 5 5 5

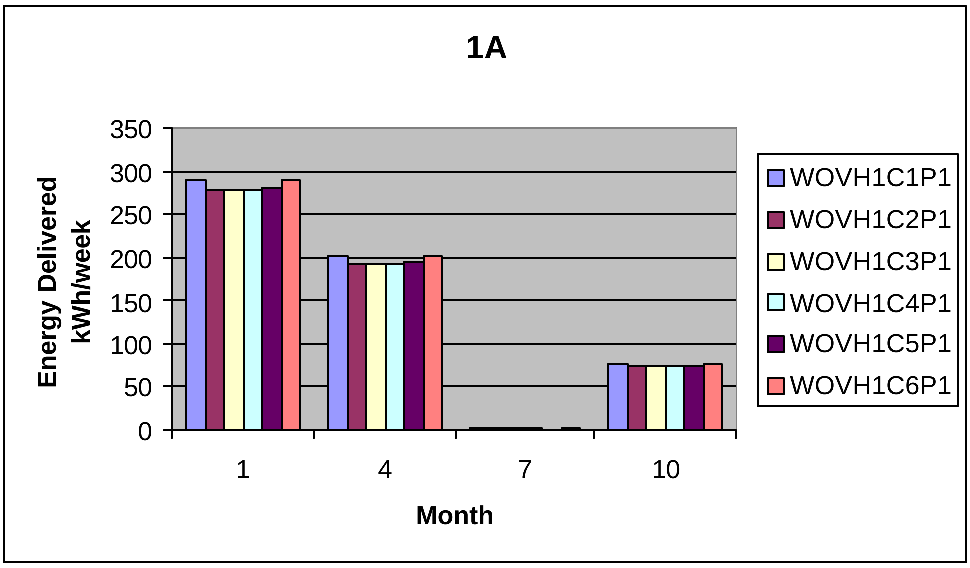
Day	Gain No.	Type labl	Period Hours	Sensible Magn.(W)	Latent Magn. (W)	Radiant Frac	Convec Frac
Wkd	1	OccuptW	16 - 19	270.0	150.0	0.20	0.80
Wkd	2	LightsW/m^2	20 - 22	10.0	0.0	0.70	0.30
Wkd	3	LightsW/m^2	18 - 19	10.0	0.0	0.70	0.30
Wkd	4	EquiptW	16 - 22	800.0	0.0	0.50	0.50
Wkd	5	OccuptW	20 - 22	540.0	300.0	0.20	0.80
Sat	1	OccuptW	12 - 18	180.0	100.0	0.20	0.80
Sat	2	LightsW/m^2	21 - 24	10.0	0.0	0.70	0.30

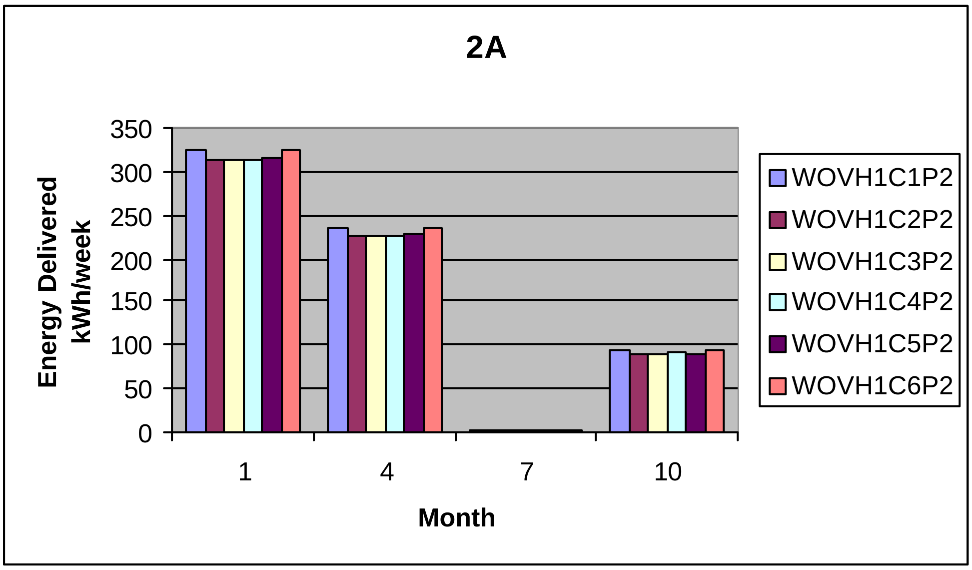
```
Sat  3 EquiptW   12 - 18    800.0      0.0       0.50       0.50
Sat  4 EquiptW   21 - 24    800.0      0.0       0.50       0.50
Sat  5 OccuptW   21 - 24    180.0    100.0       0.20       0.80
Sun  1 OccuptW   12 - 18    180.0    100.0       0.20       0.80
Sun  2 LightsW/m2 21 - 24    10.0      0.0       0.70       0.30
Sun  3 EquiptW   12 - 18    800.0      0.0       0.50       0.50
Sun  4 EquiptW   21 - 24    800.0      0.0       0.50       0.50
Sun  5 OccuptW   21 - 24    180.0    100.0       0.20       0.80

 Description : zone bed1
 Number of Weekday Sat Sun casual gains=  2  3  3
Day Gain Type     Period Sensible  Latent     Radiant    Convec
    No.  labl     Hours  Magn.(W)  Magn. (W)  Frac       Frac
Wkd  1 OccuptW    0 -  7    180.0    100.0       0.20       0.80
Wkd  2 OccuptW   22 - 24    180.0    100.0       0.20       0.80
Sat  1 OccuptW    0 -  7    180.0    100.0       0.20       0.80
Sat  2 OccuptW    7 -  9     90.0     50.0       0.20       0.80
Sat  3 OccuptW   18 - 19    180.0    100.0       0.20       0.80
Sun  1 OccuptW    0 -  7    180.0    100.0       0.20       0.80
Sun  2 OccuptW    7 -  9     90.0     50.0       0.20       0.80
Sun  3 OccuptW   18 - 19    180.0    100.0       0.20       0.80

 Description : zone bed2
 Number of Weekday Sat Sun casual gains=  2  2  2
Day Gain Type     Period Sensible  Latent     Radiant    Convec
    No.  labl     Hours  Magn.(W)  Magn. (W)  Frac       Frac
Wkd  1 OccuptW    0 -  8    360.0    200.0       0.20       0.80
Wkd  2 OccuptW   22 - 24    360.0    200.0       0.20       0.80
Sat  1 OccuptW    0 - 11    360.0    200.0       0.20       0.80
Sat  2 OccuptW   18 - 19    180.0    100.0       0.20       0.80
Sun  1 OccuptW    0 - 11    360.0    200.0       0.20       0.80
Sun  2 OccuptW   18 - 19    180.0    100.0       0.20       0.80

 Description : doors
 Number of Weekday Sat Sun casual gains=  0  0  0

 Description : zone main
 Number of Weekday Sat Sun casual gains=  1  4  4
Day Gain Type     Period Sensible  Latent     Radiant    Convec
    No.  labl     Hours  Magn.(W)  Magn. (W)  Frac       Frac
Wkd  1 EquiptW    0 - 24    300.0      0.0       0.50       0.50
Sat  1 OccuptW    7 - 12     90.0     50.0       0.20       0.80
Sat  2 EquiptW    7 - 18    400.0      0.0       0.50       0.50
Sat  3 EquiptW    0 - 24    300.0      0.0       0.50       0.50
Sat  4 OccuptW   12 - 18    270.0    150.0       0.20       0.80
Sun  1 OccuptW    7 - 12     90.0     50.0       0.20       0.80
Sun  2 EquiptW    7 - 18    400.0      0.0       0.50       0.50
Sun  3 EquiptW    0 - 24    300.0      0.0       0.50       0.50
Sun  4 OccuptW   12 - 18    270.0    150.0       0.20       0.80

 Description : loft
 Number of Weekday Sat Sun casual gains=  0  0  0

 Description : sit3
 Number of Weekday Sat Sun casual gains=  0  0  0

 Description : sit2
 Number of Weekday Sat Sun casual gains=  0  0  0

 Description : sit1
 Number of Weekday Sat Sun casual gains=  0  0  0
```

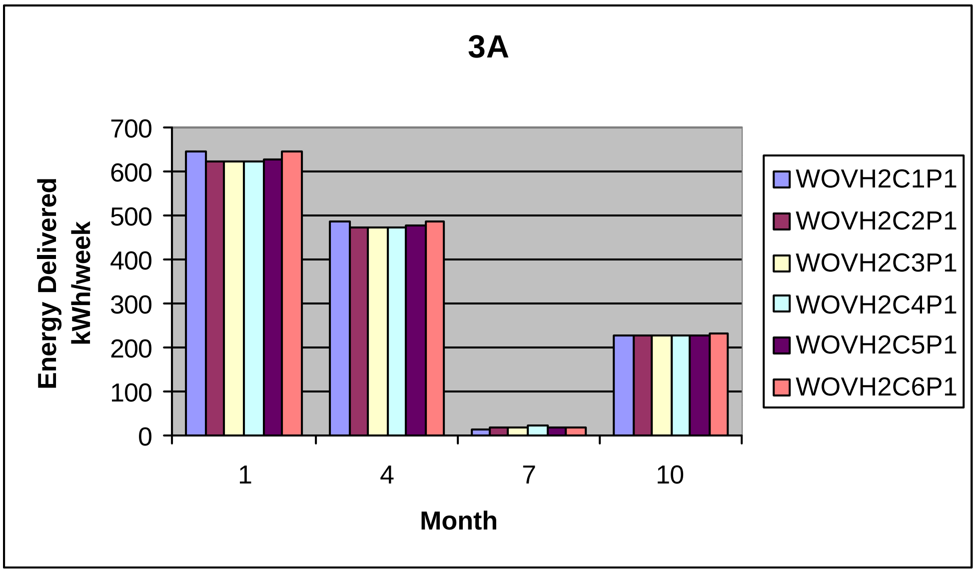
```
Description : bed23
Number of Weekday Sat Sun casual gains=  0  0  0

Description : bed22
Number of Weekday Sat Sun casual gains=  0  0  0

Description : bed21
Number of Weekday Sat Sun casual gains=  0  0  0

Description : bed13
Number of Weekday Sat Sun casual gains=  0  0  0

Description : bed12
Number of Weekday Sat Sun casual gains=  0  0  0

Description : bed11
Number of Weekday Sat Sun casual gains=  0  0  0

Description : liv3
Number of Weekday Sat Sun casual gains=  0  0  0

Description : liv2
Number of Weekday Sat Sun casual gains=  0  0  0

Description : liv1
Number of Weekday Sat Sun casual gains=  0  0  0

Description : kit3
Number of Weekday Sat Sun casual gains=  0  0  0

Description : kit2
Number of Weekday Sat Sun casual gains=  0  0  0

Description : kit1
Number of Weekday Sat Sun casual gains=  0  0  0

Description : box3
Number of Weekday Sat Sun casual gains=  0  0  0

Description : box2
Number of Weekday Sat Sun casual gains=  0  0  0

Description : box1
 Number of Weekday Sat Sun casual gains=  0  0  0
```

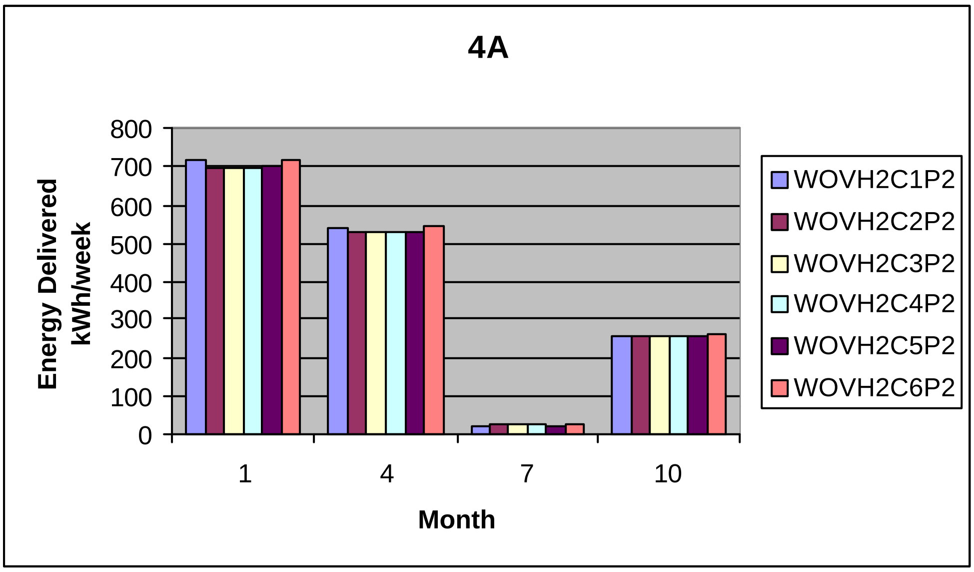
APPENDIX F

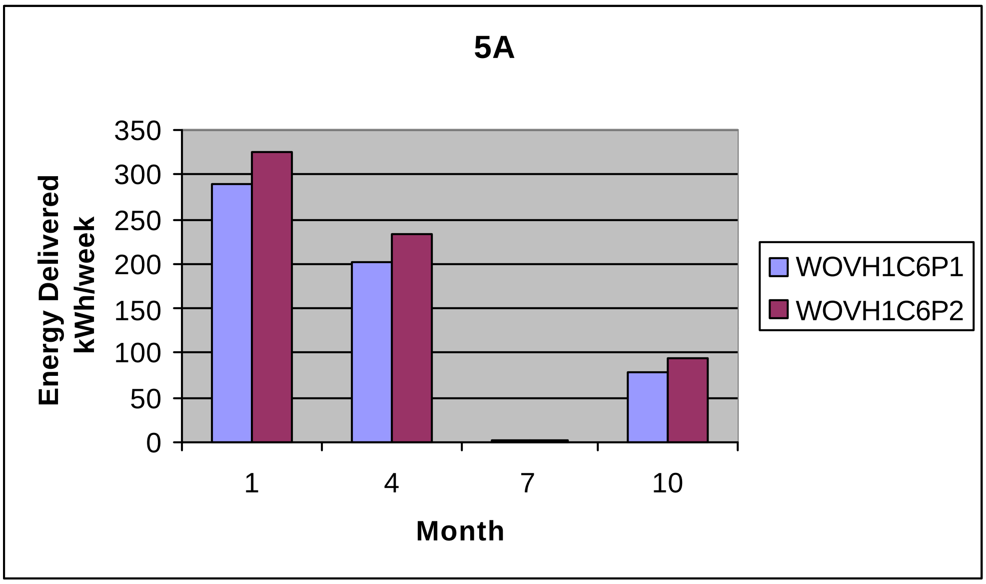
Energy, Temperature and PPD profiles

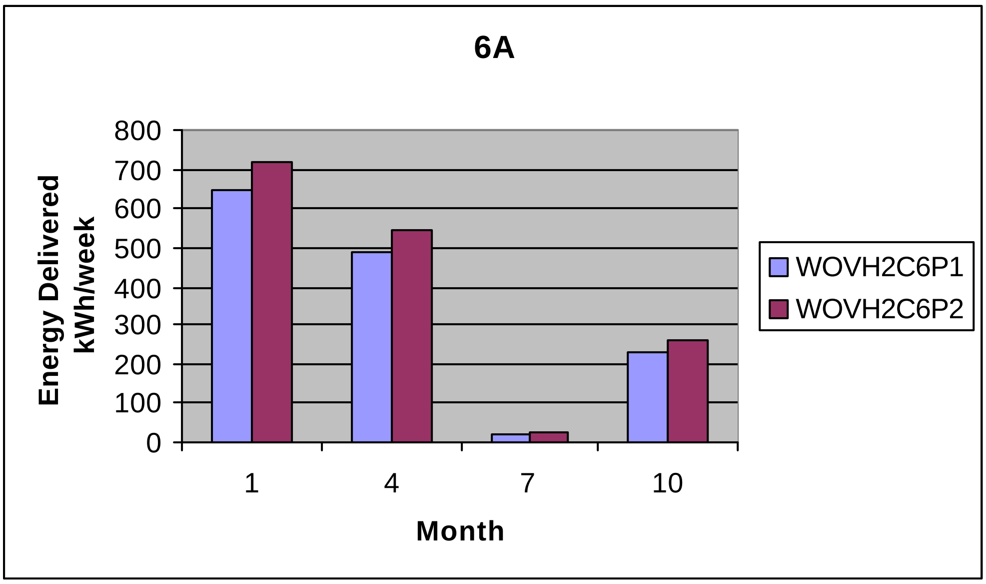


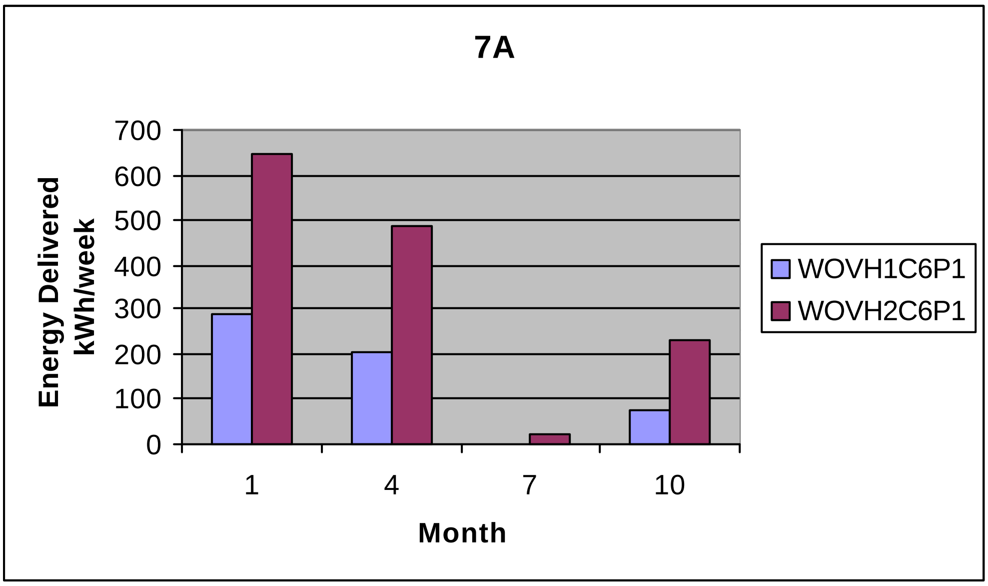


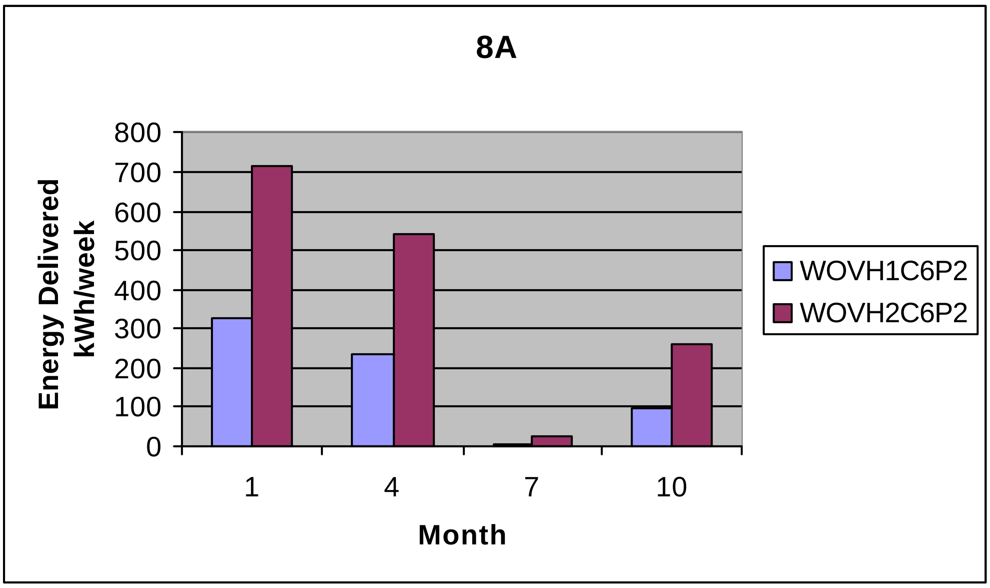


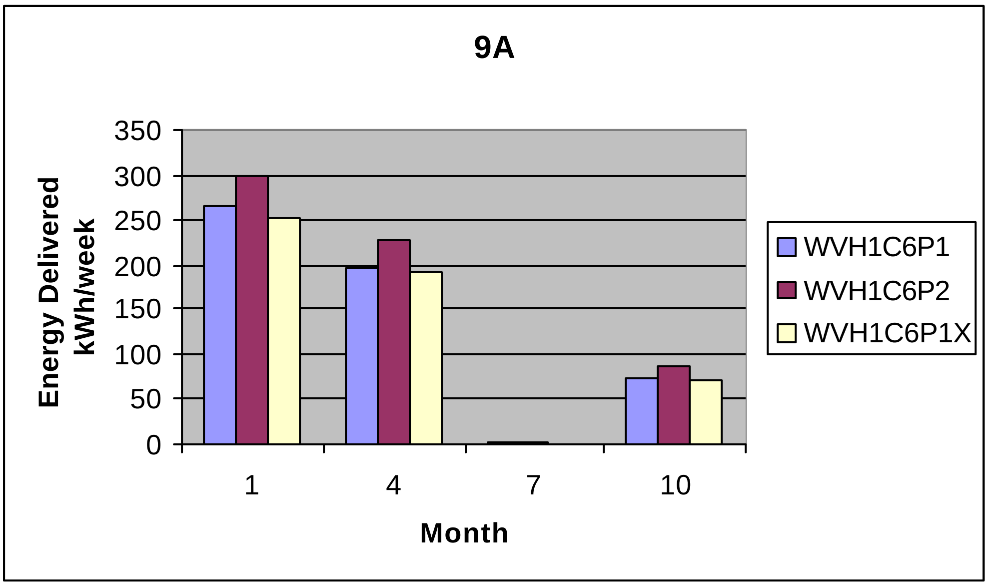

4A
800
700
600
500
400
300
200
100
0
Energy Delivered kWh/week
1
4
7
10
Month
WOVH2C1P2
WOVH2C2P2
WOVH2C3P2
WOVH2C4P2
WOVH2C5P2
WOVH2C6P2

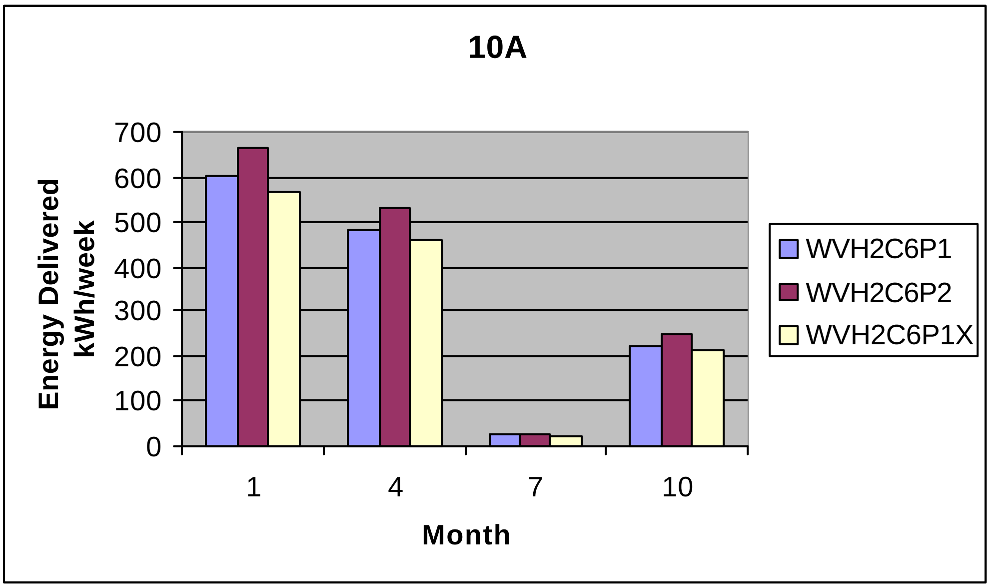

5A
350
300
250
200
150
100
50
0
Energy Delivered kWh/week
1
4
7
10
Month
WOVH1C6P1
WOVH1C6P2

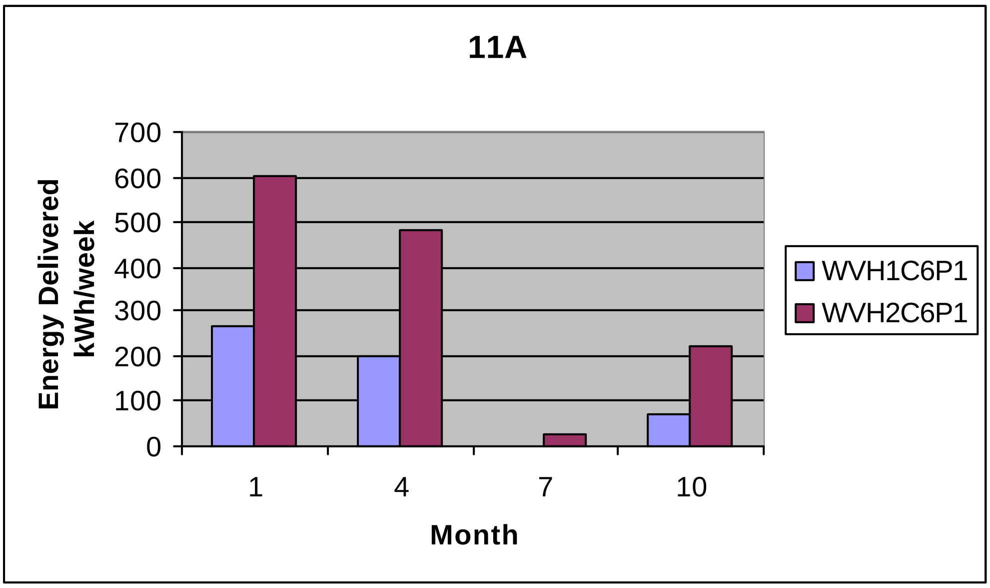

6A
800
700
600
500
400
300
200
100
0
Energy Delivered kWh/week
1
4
7
10
Month
WOVH2C6P1
WOVH2C6P2

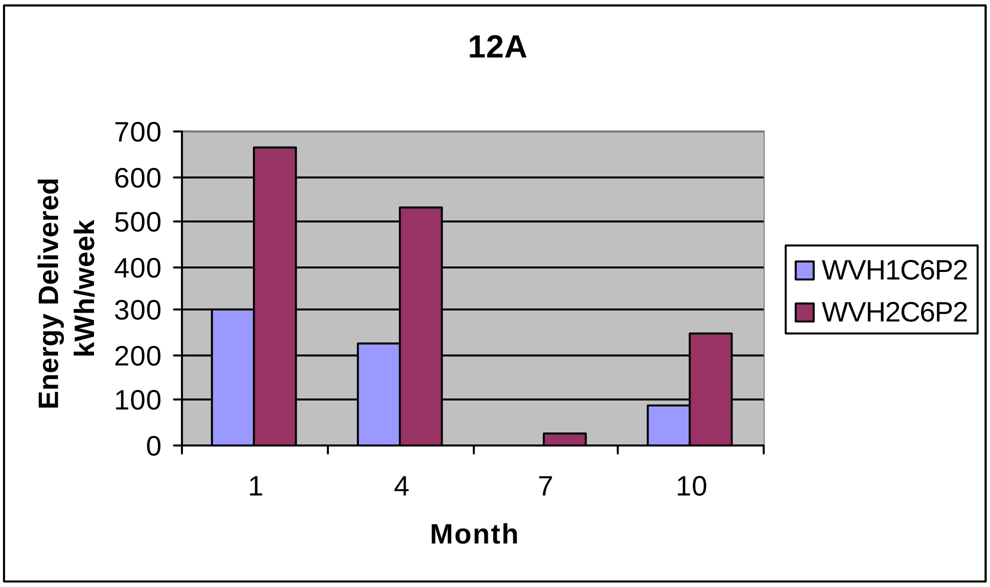

7A
Energy Delivered kWh/week
700
600
500
400
300
200
100
0
1
4
7
10
Month
WOVH1C6P1
WOVH2C6P1

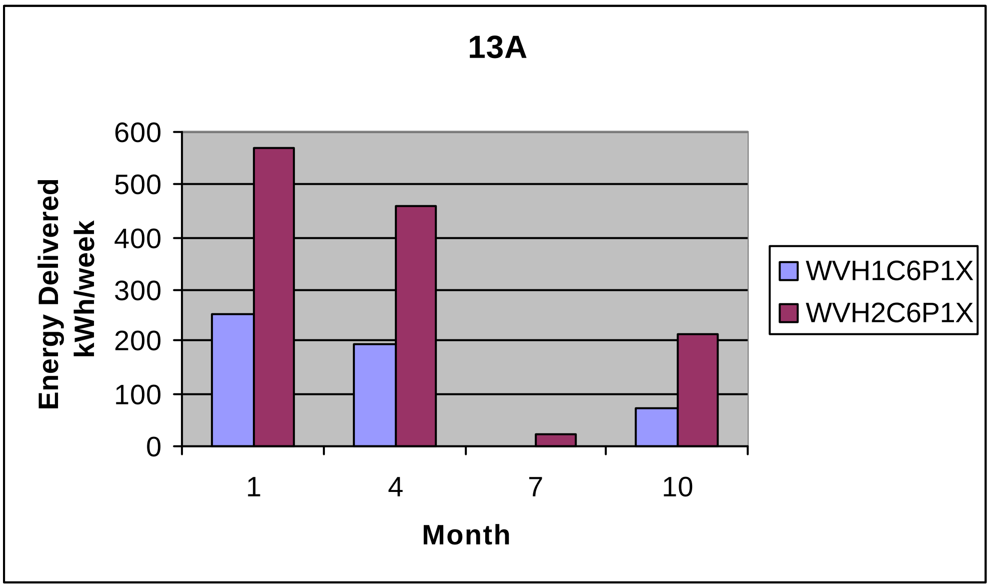

8A
Energy Delivered kWh/week
800
700
600
500
400
300
200
100
0
1
4
7
10
Month
WOVH1C6P2
WOVH2C6P2

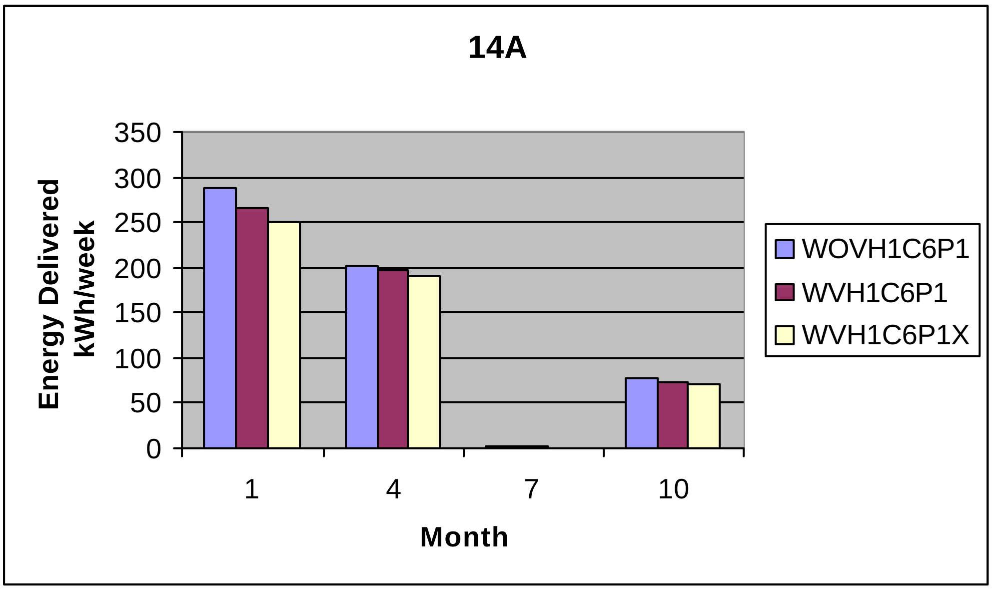

9A
Energy Delivered kWh/week
350
300
250
200
150
100
50
0
1
4
7
10
Month
WVH1C6P1
WVH1C6P2
WVH1C6P1X

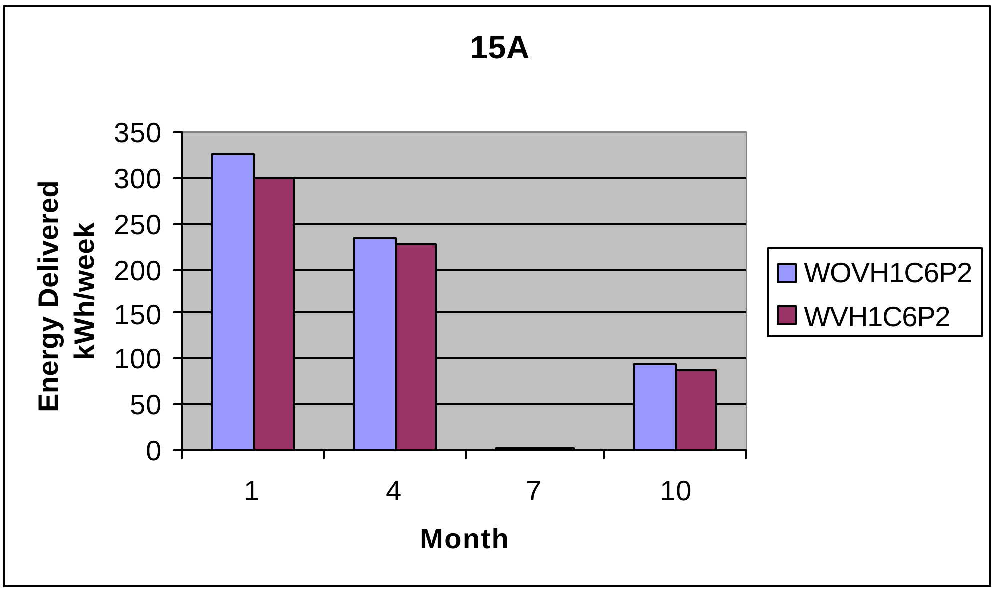

10A
Energy Delivered kWh/week
700
600
500
400
300
200
100
0
1
4
7
10
Month
WVH2C6P1
WVH2C6P2
WVH2C6P1X

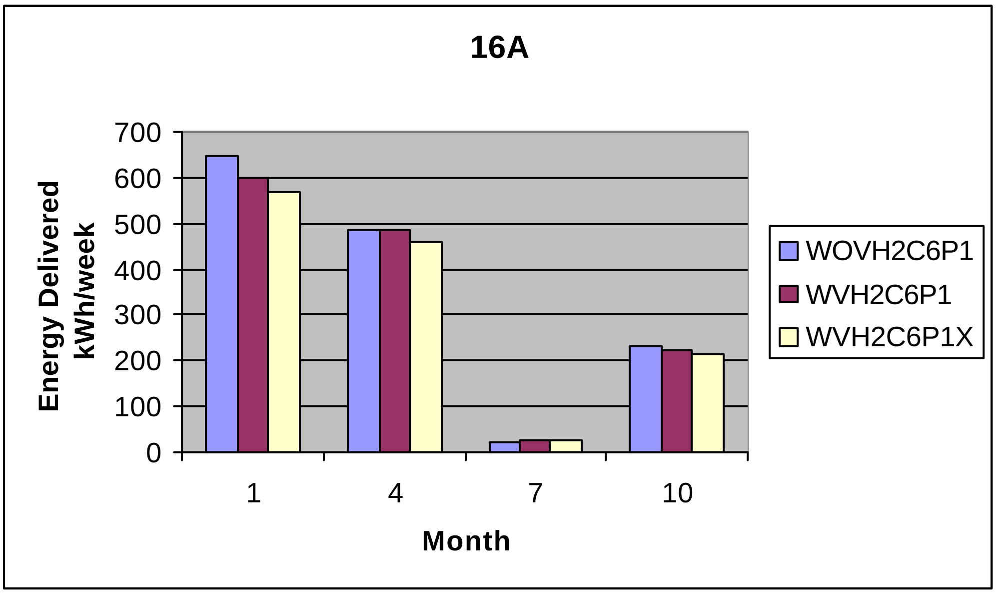

11A
Energy Delivered kWh/week
700
600
500
400
300
200
100
0
1
4
7
10
Month
WVH1C6P1
WVH2C6P1

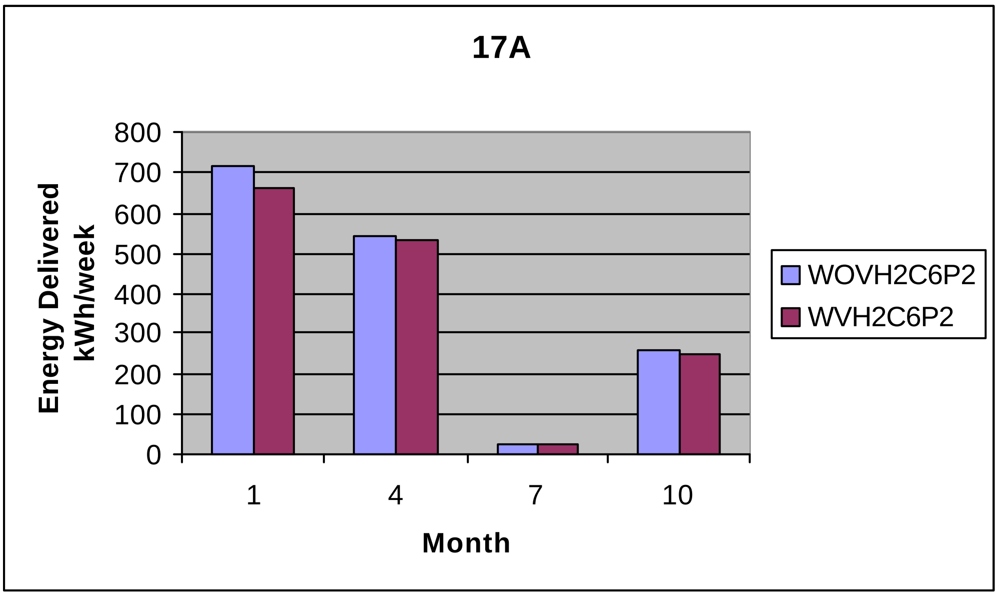

12A
Energy Delivered kWh/week
700
600
500
400
300
200
100
0
1
4
7
10
Month
WVH1C6P2
WVH2C6P2

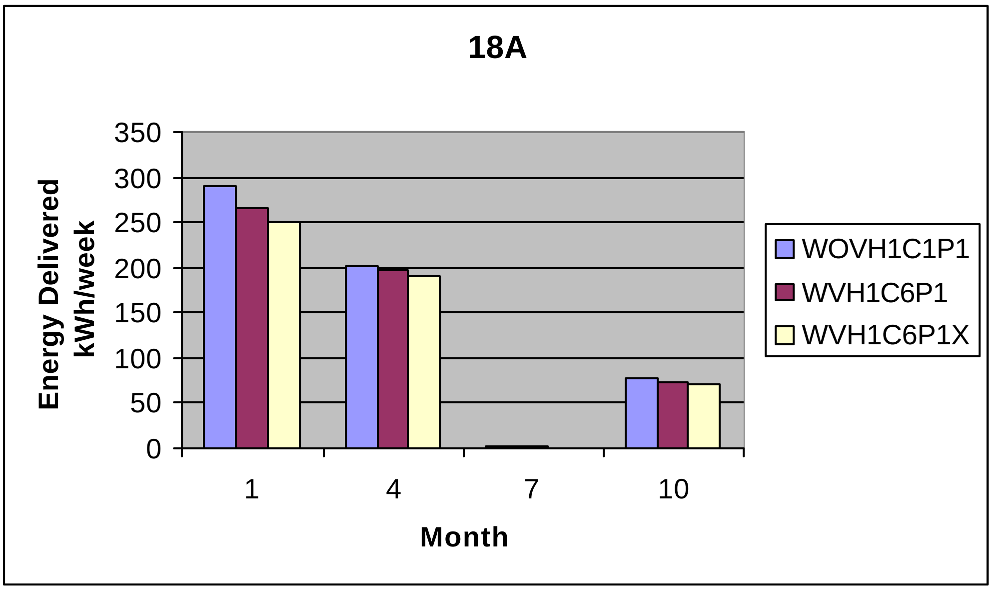

13A
Energy Delivered kWh/week
600
500
400
300
200
100
0
1
4
7
10
Month
WVH1C6P1X
WVH2C6P1X

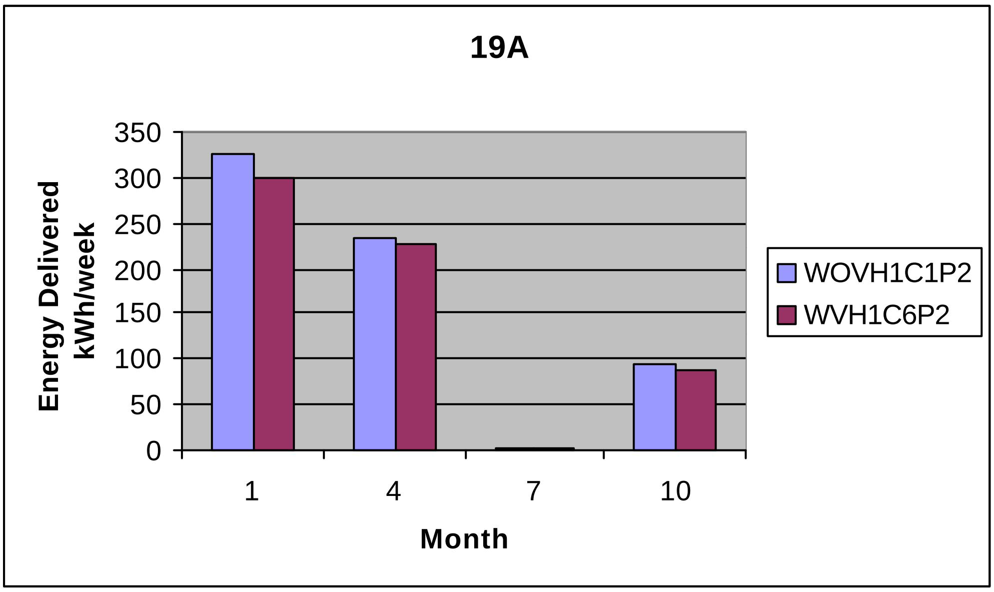

14A
Energy Delivered kWh/week
350
300
250
200
150
100
50
0
1
4
7
10
Month
WOVH1C6P1
WVH1C6P1
WVH1C6P1X

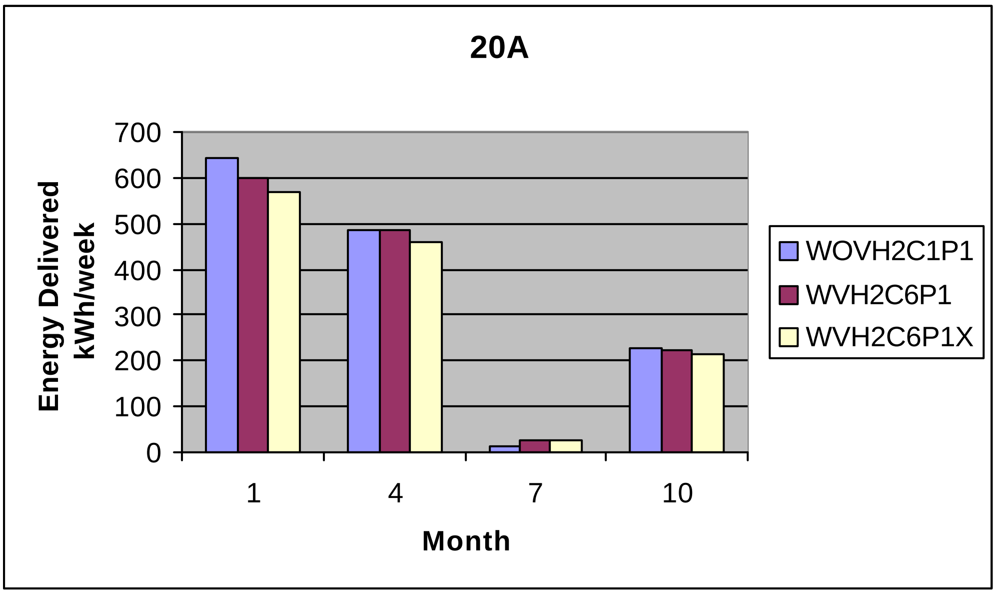

15A
Energy Delivered kWh/week
350
300
250
200
150
100
50
0
1
4
7
10
Month
WOVH1C6P2
WVH1C6P2

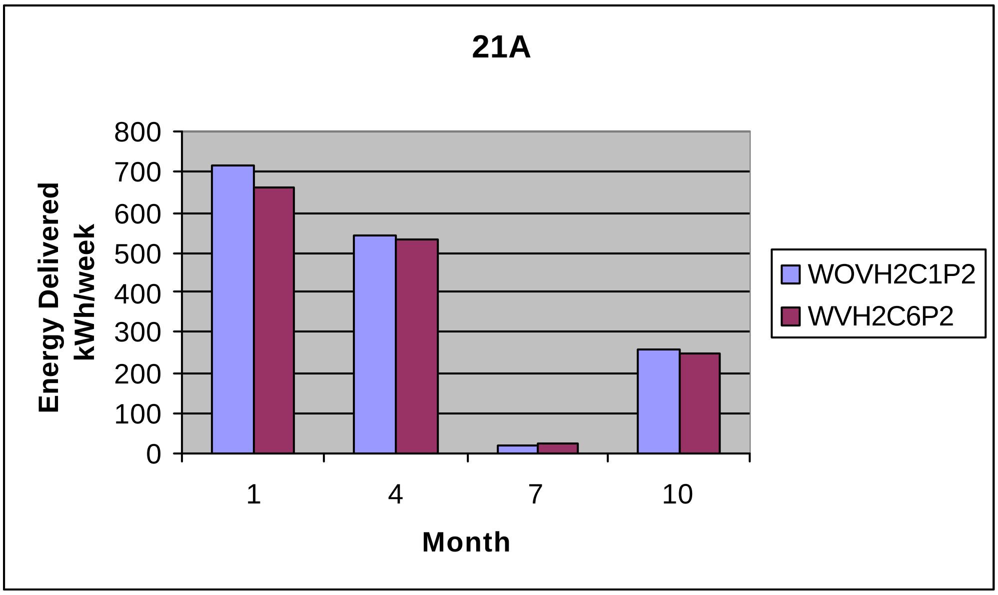

16A
Energy Delivered kWh/week
700
600
500
400
300
200
100
0
1
4
7
10
Month
WOVH2C6P1
WVH2C6P1
WVH2C6P1X

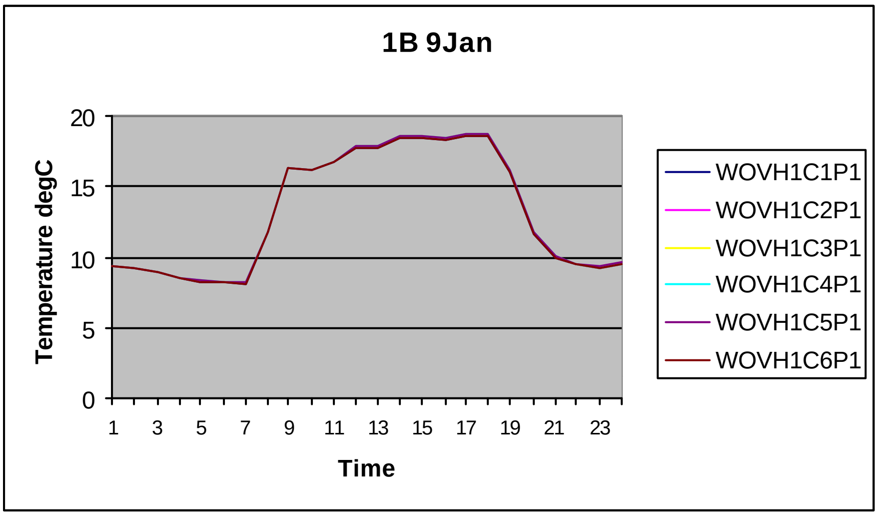

17A
Energy Delivered kWh/week
800
700
600
500
400
300
200
100
0
1
4
7
10
Month
WOVH2C6P2
WVH2C6P2

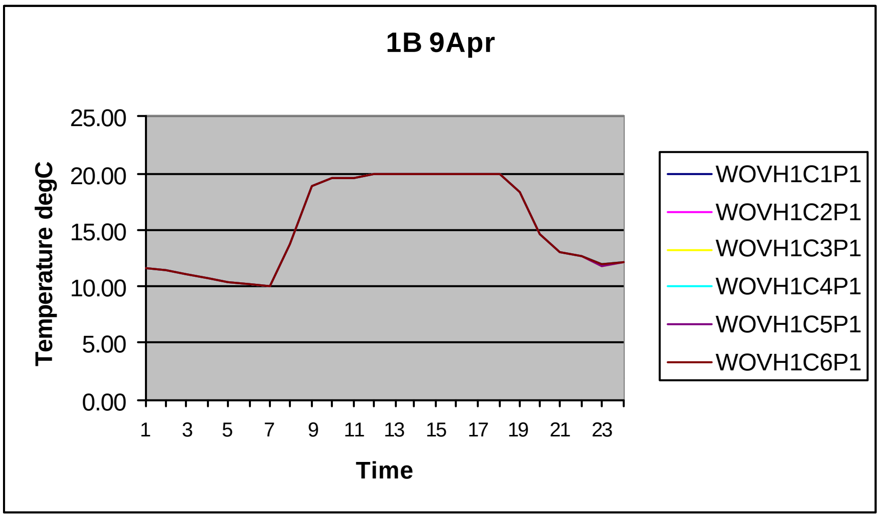

18A
Energy Delivered kWh/week
350
300
250
200
150
100
50
0
1
4
7
10
Month
WOVH1C1P1
WVH1C6P1
WVH1C6P1X

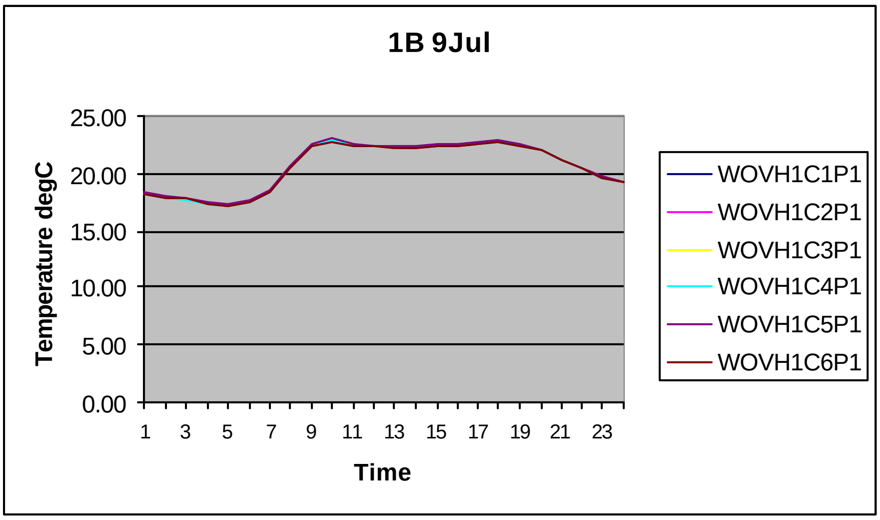

19A
Energy Delivered kWh/week
350
300
250
200
150
100
50
0
1
4
7
10
Month
WOVH1C1P2
WVH1C6P2

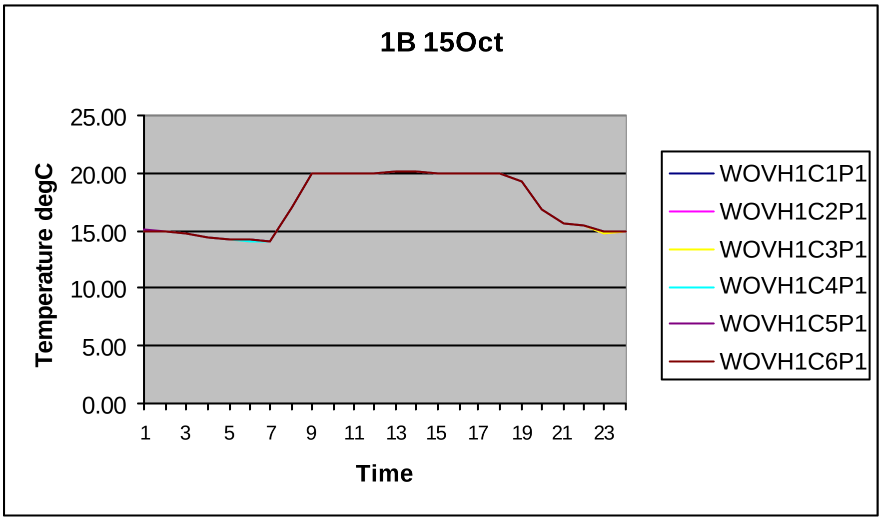

20A
Energy Delivered kWh/week
700
600
500
400
300
200
100
0
1
4
7
10
Month
WOVH2C1P1
WVH2C6P1
WVH2C6P1X

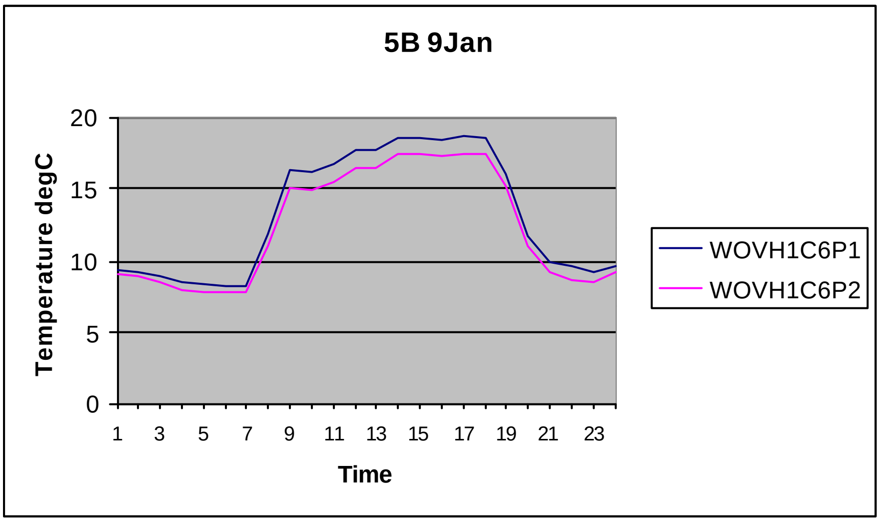

21A
Energy Delivered kWh/week
800
700
600
500
400
300
200
100
0
1
4
7
10
Month
WOVH2C1P2
WVH2C6P2

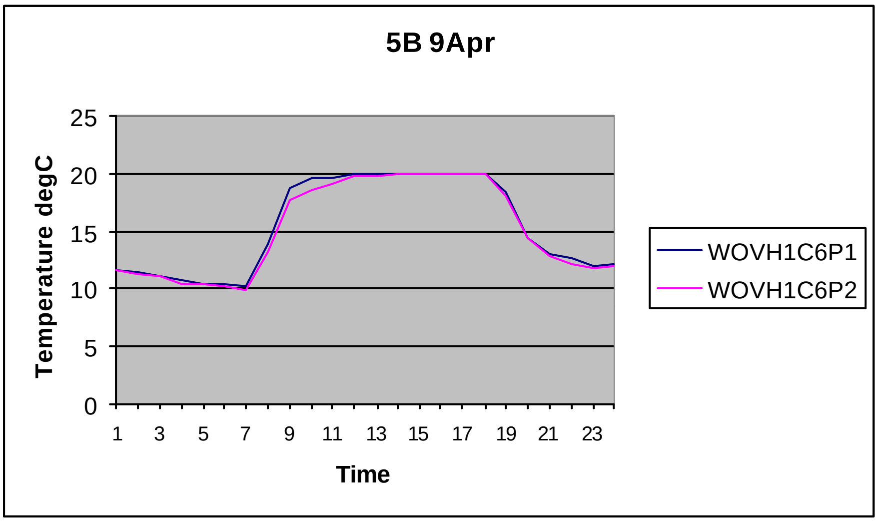

1B 9Jan
Temperature degC
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C1P1
WOVH1C2P1
WOVH1C3P1
WOVH1C4P1
WOVH1C5P1
WOVH1C6P1

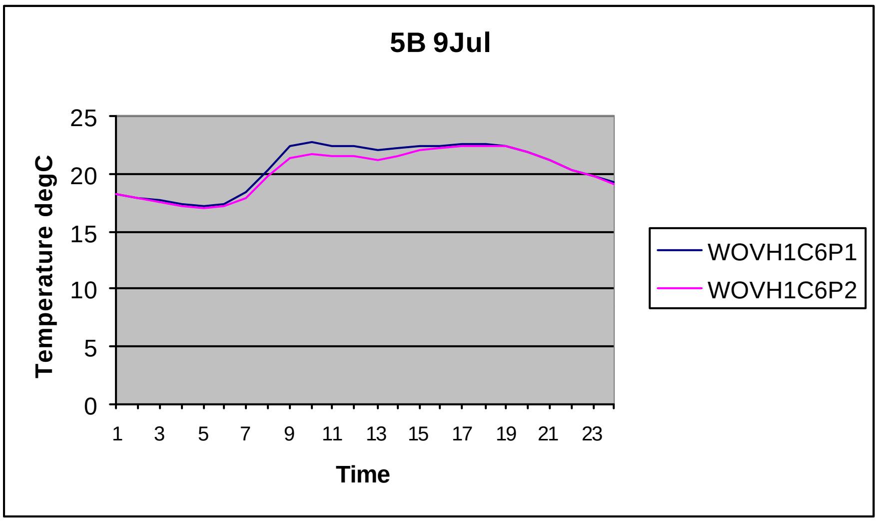

1B 9Apr
Temperature degC
25.00
20.00
15.00
10.00
5.00
0.00
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C1P1
WOVH1C2P1
WOVH1C3P1
WOVH1C4P1
WOVH1C5P1
WOVH1C6P1

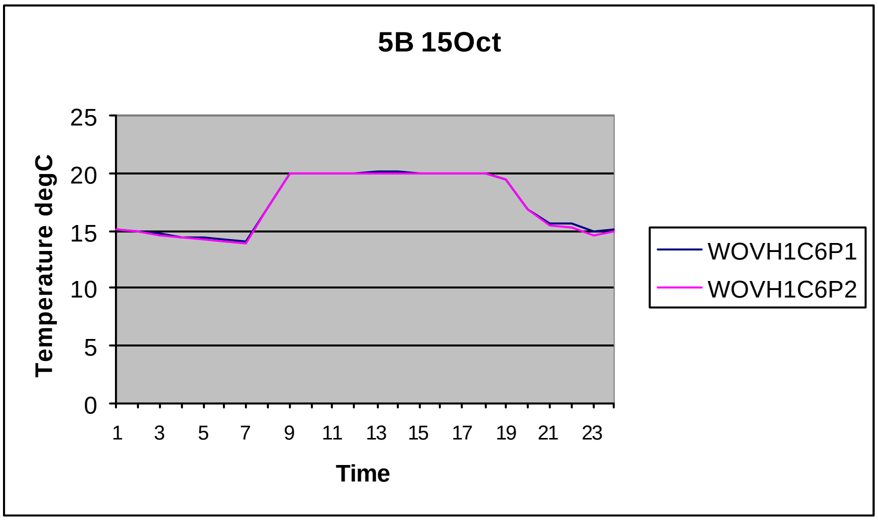

1B 9Jul
Temperature degC
25.00
20.00
15.00
10.00
5.00
0.00
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C1P1
WOVH1C2P1
WOVH1C3P1
WOVH1C4P1
WOVH1C5P1
WOVH1C6P1

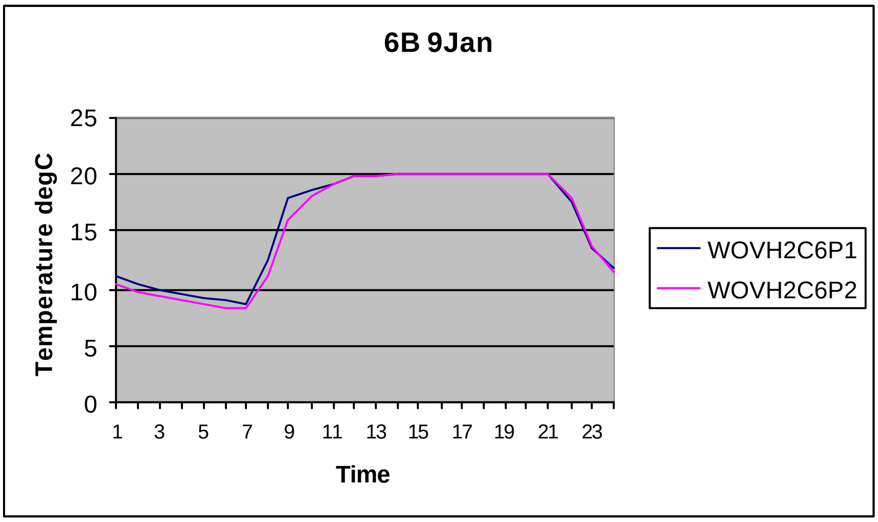

1B 15Oct
Temperature degC
25.00
20.00
15.00
10.00
5.00
0.00
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C1P1
WOVH1C2P1
WOVH1C3P1
WOVH1C4P1
WOVH1C5P1
WOVH1C6P1

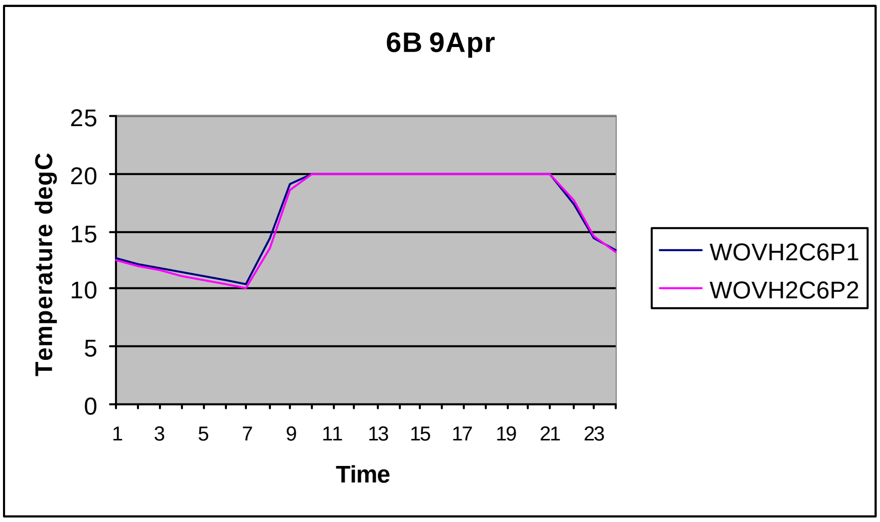

5B 9Jan
Temperature degC
Time
WOVH1C6P1
WOVH1C6P2

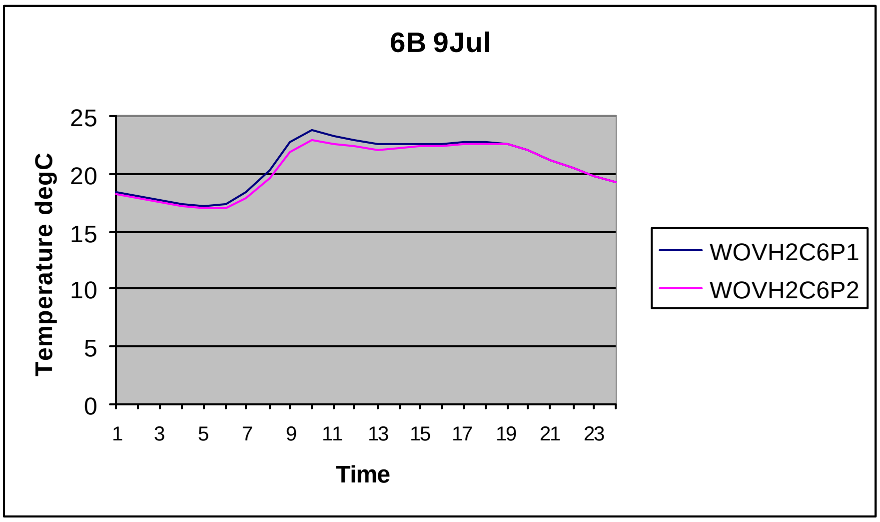

5B 9Apr
Temperature degC
Time
WOVH1C6P1
WOVH1C6P2

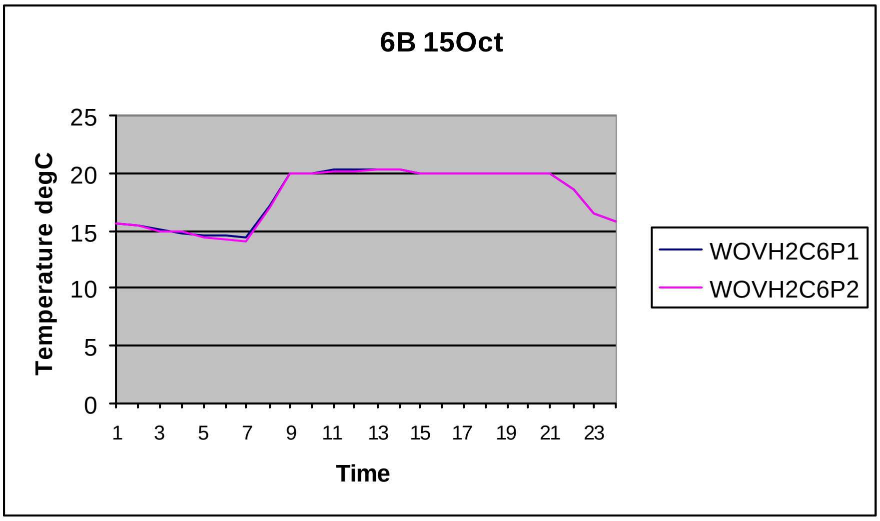

5B 9Jul
Temperature degC
Time
WOVH1C6P1
WOVH1C6P2

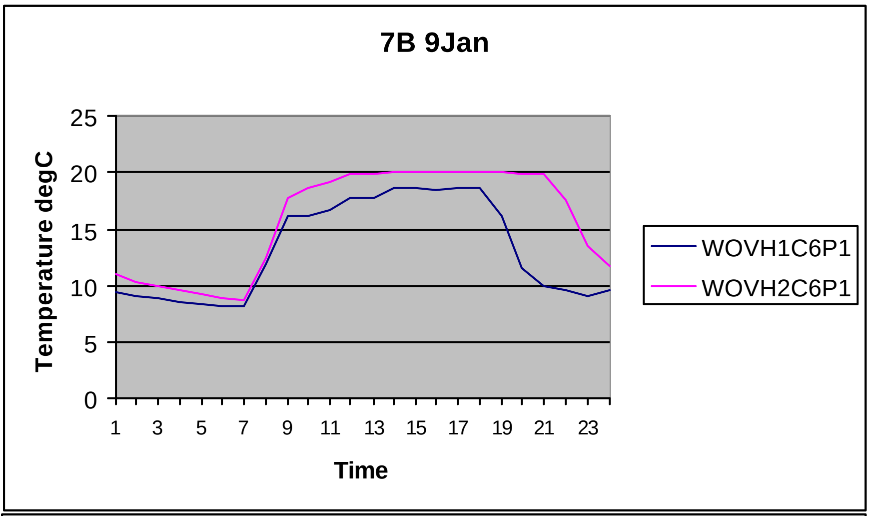

5B 15Oct
Temperature degC
Time
WOVH1C6P1
WOVH1C6P2

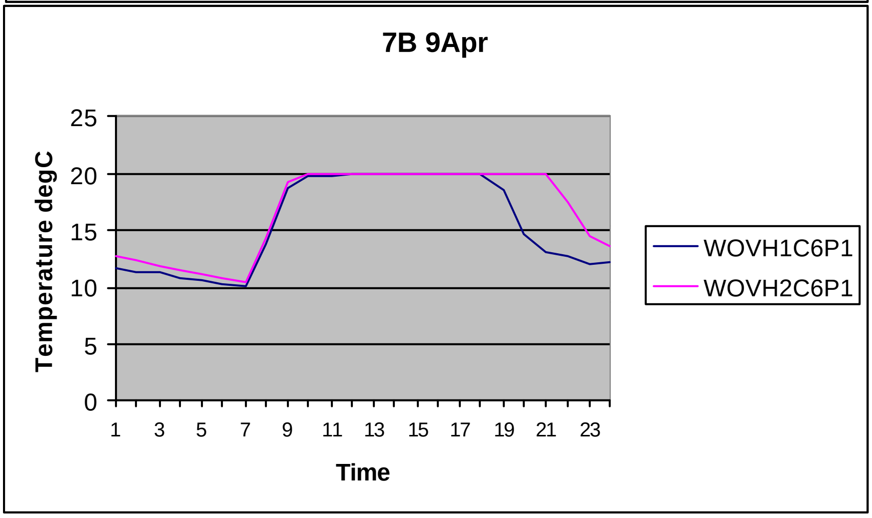

6B 9Jan
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH2C6P1
WOVH2C6P2

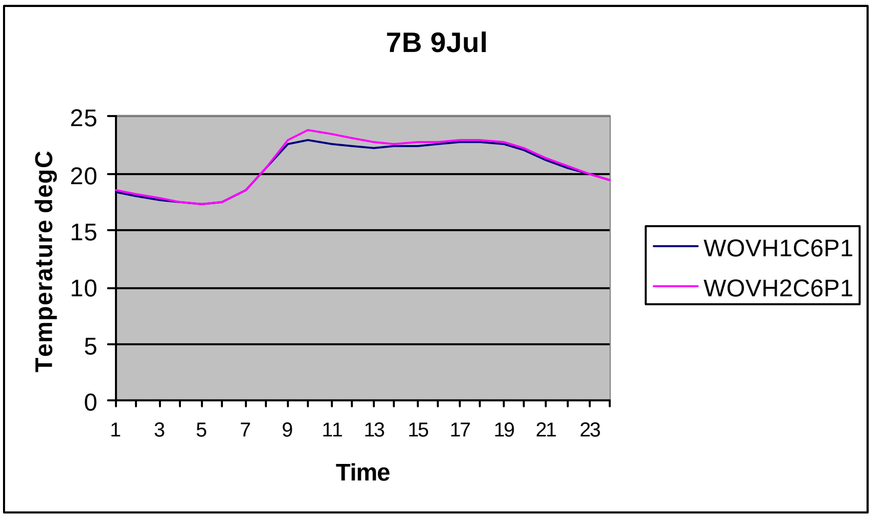

6B 9Apr
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH2C6P1
WOVH2C6P2

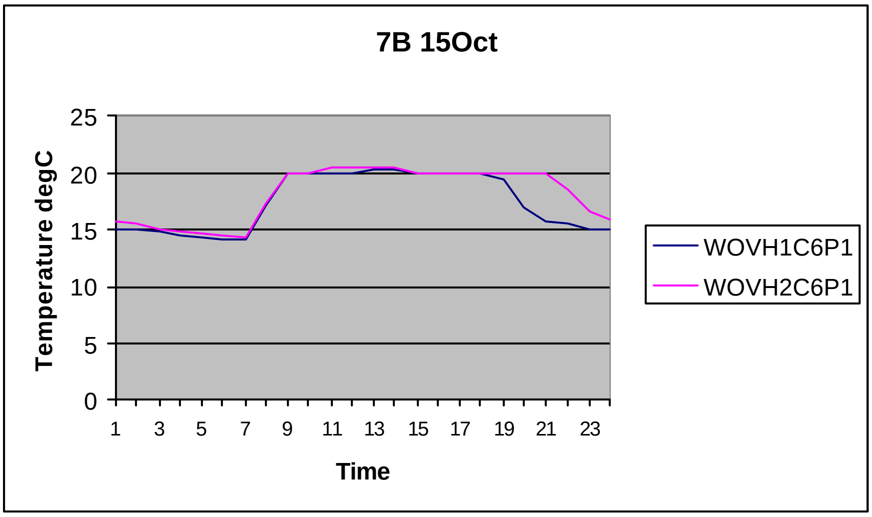

6B 9Jul
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH2C6P1
WOVH2C6P2

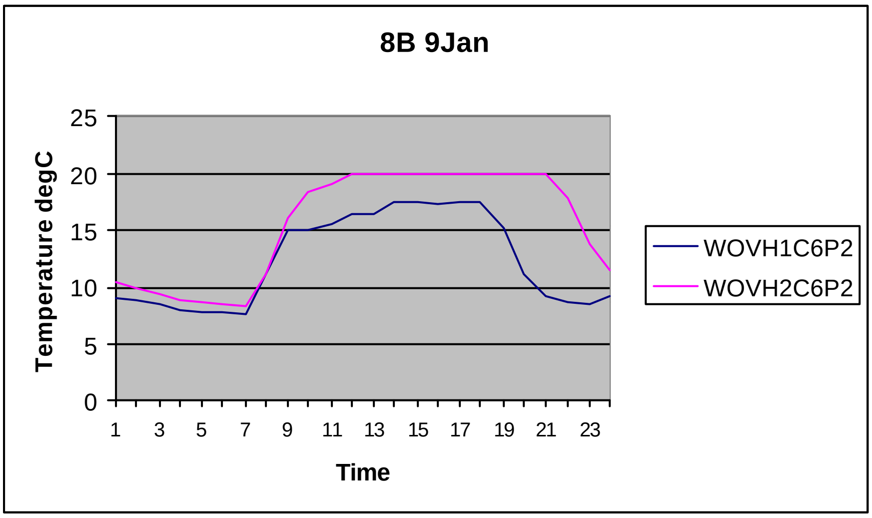

6B 15Oct
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH2C6P1
WOVH2C6P2


7B 9Jan
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C6P1
WOVH2C6P1

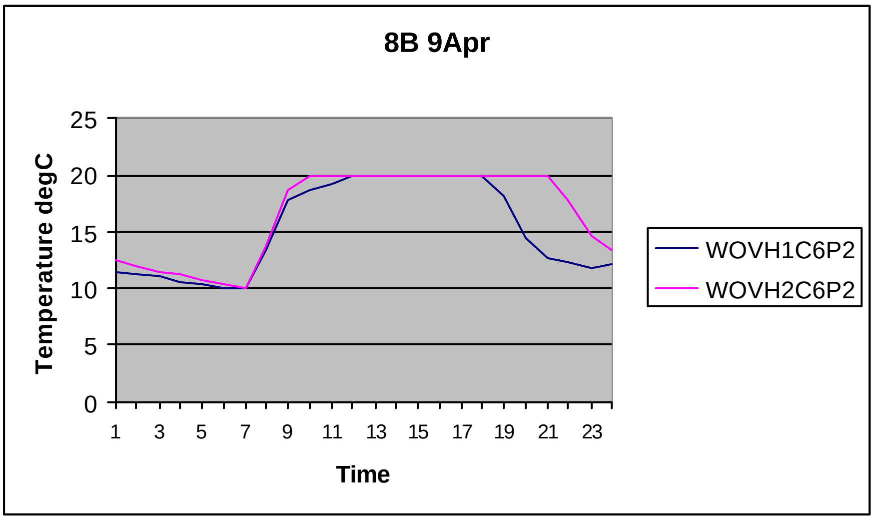

7B 9Apr
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C6P1
WOVH2C6P1


7B 9Jul
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C6P1
WOVH2C6P1

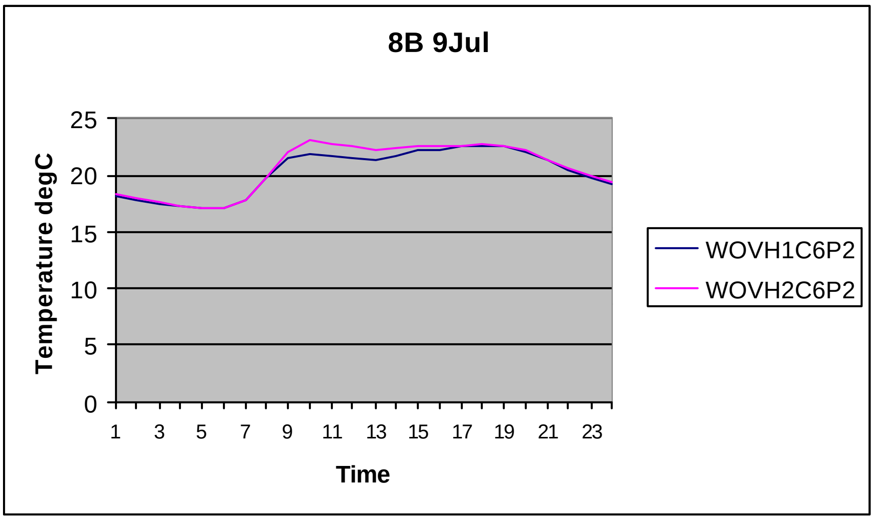

7B 15Oct
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WOVH1C6P1
WOVH2C6P1



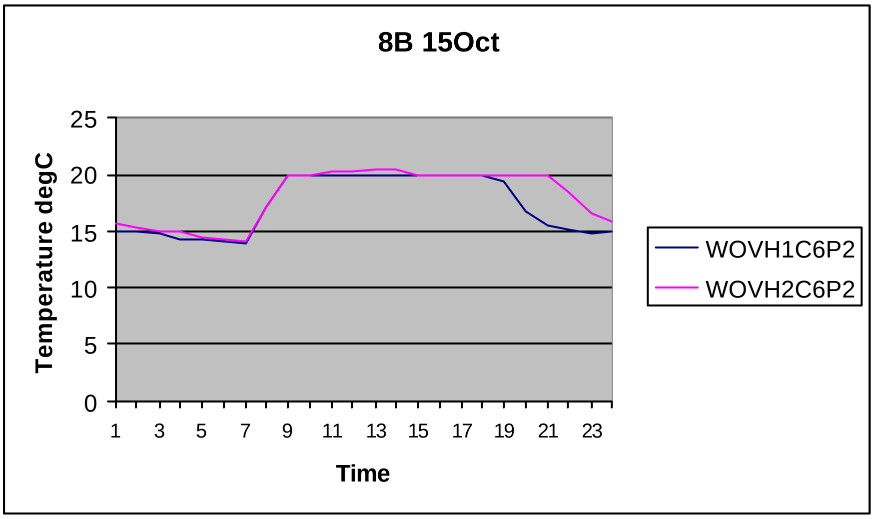
8B 9Jan
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH1C6P2
WOVH2C6P2



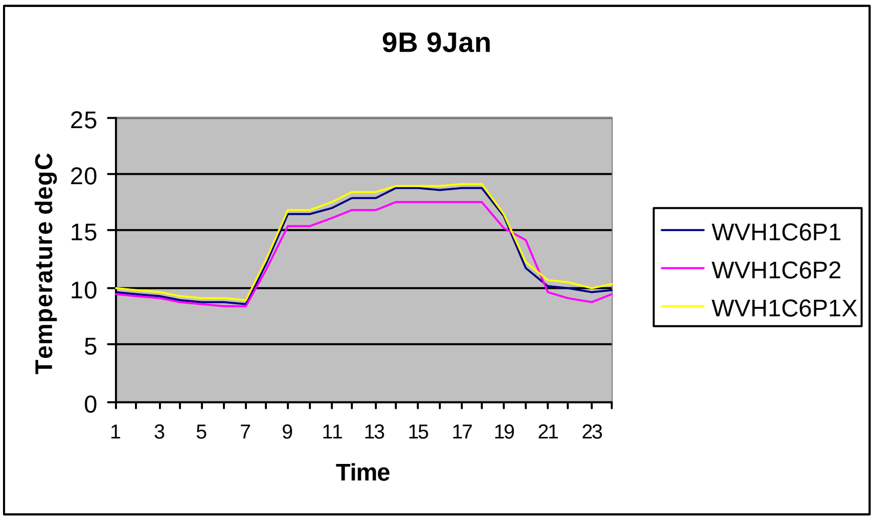
8B 9Apr
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH1C6P2
WOVH2C6P2

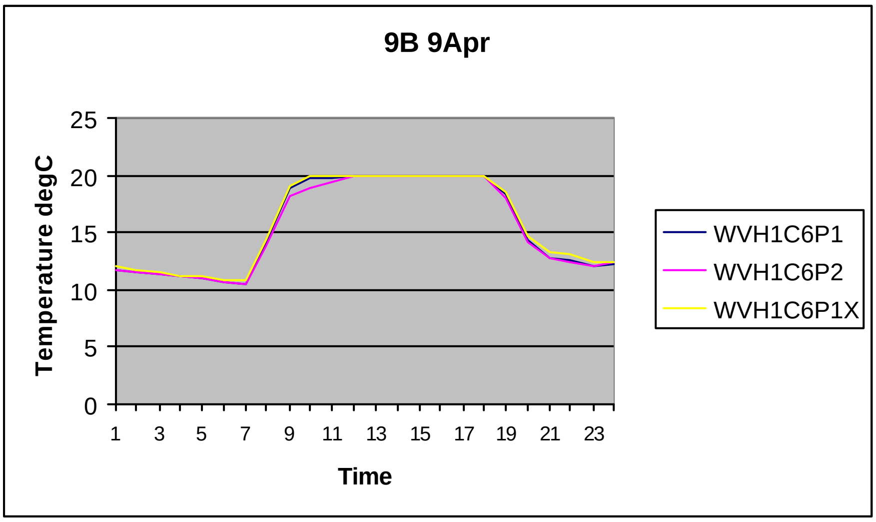


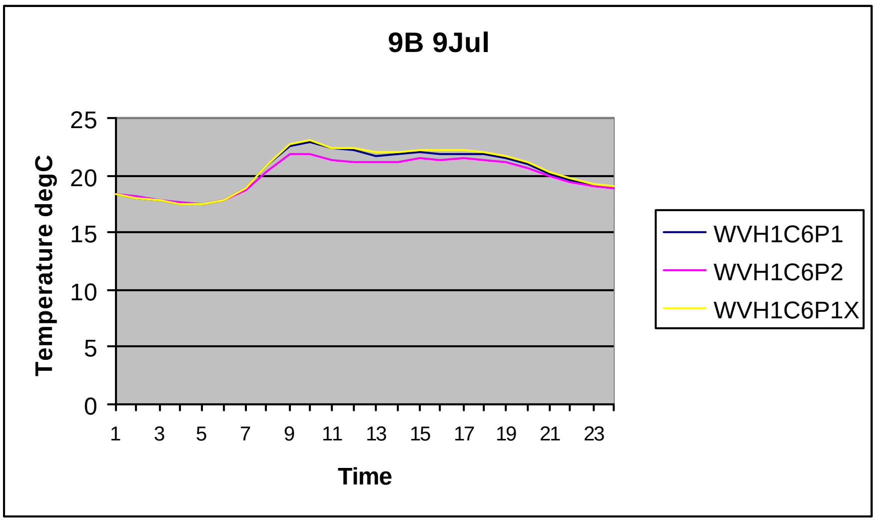
8B 9Jul
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH1C6P2
WOVH2C6P2

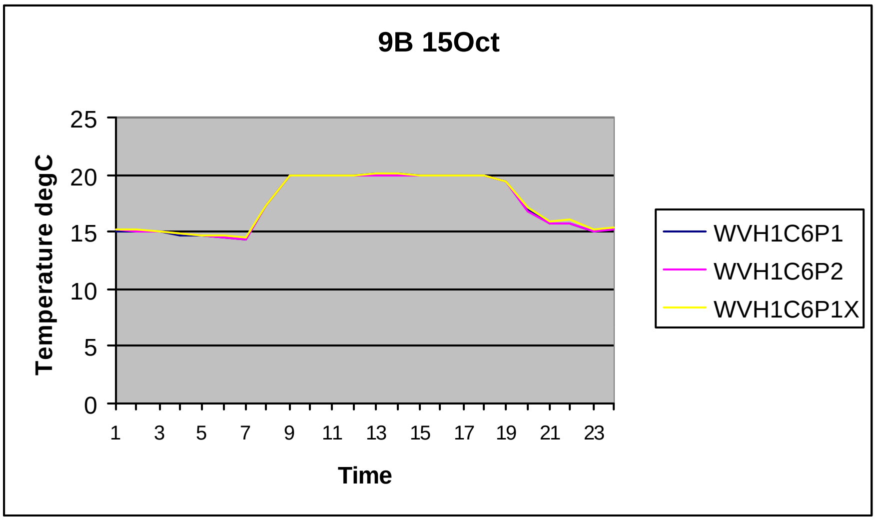


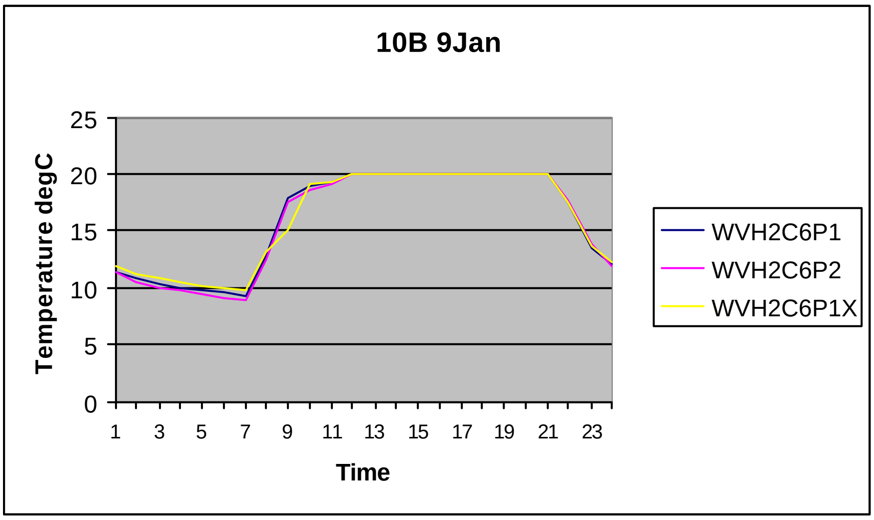
8B 15Oct
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WOVH1C6P2
WOVH2C6P2

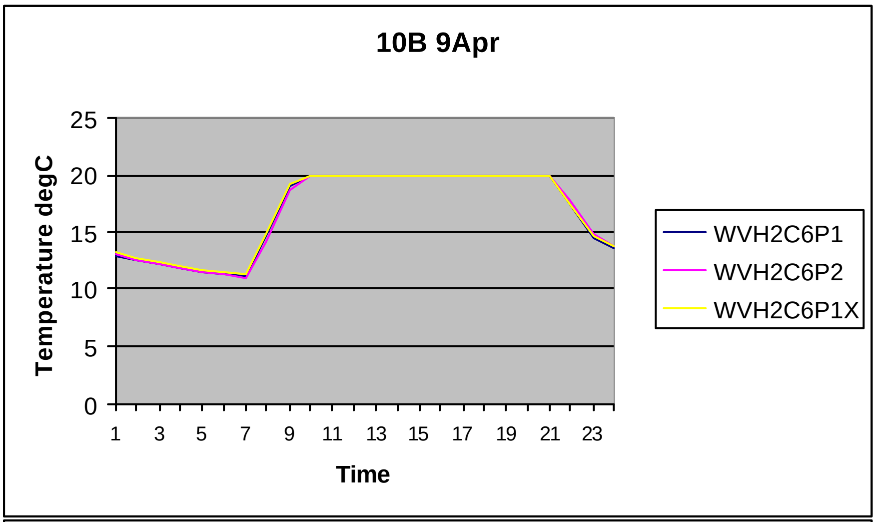

9B 9Jan
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH1C6P1
WVH1C6P2
WVH1C6P1X

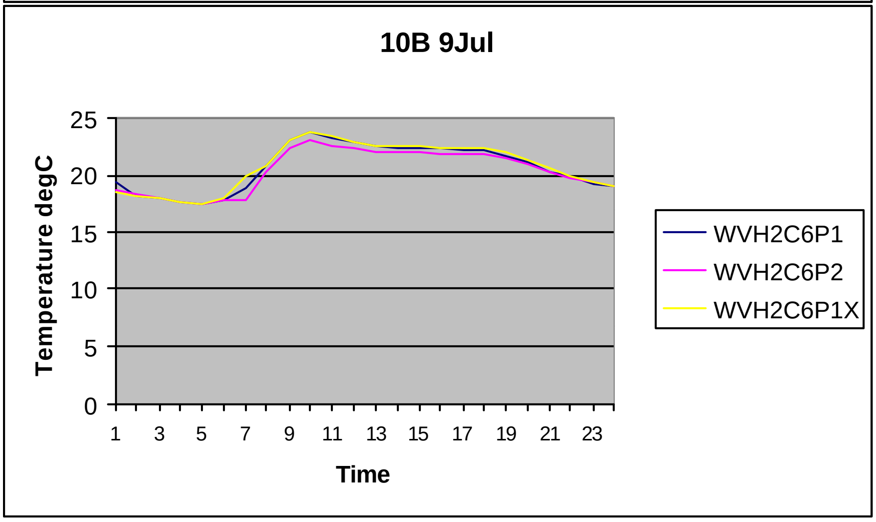

9B 9Apr
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH1C6P1
WVH1C6P2
WVH1C6P1X

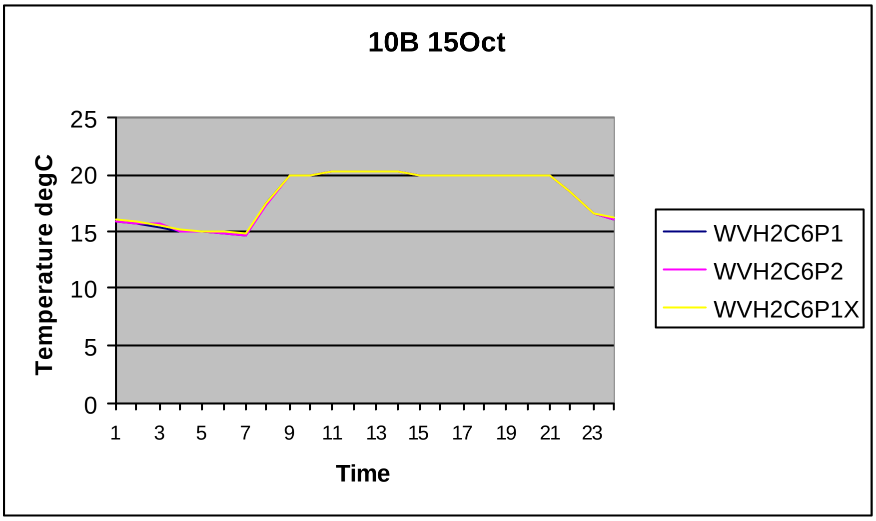

9B 9Jul
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH1C6P1
WVH1C6P2
WVH1C6P1X

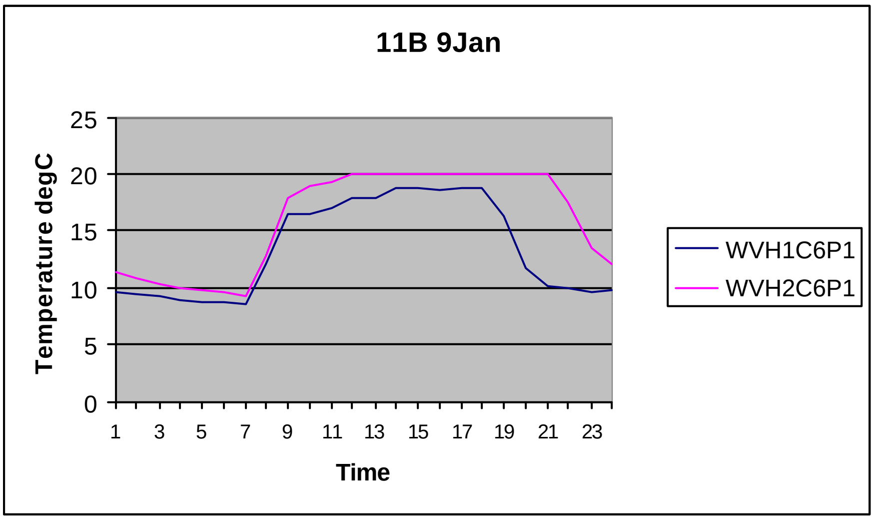

9B 15Oct
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH1C6P1
WVH1C6P2
WVH1C6P1X

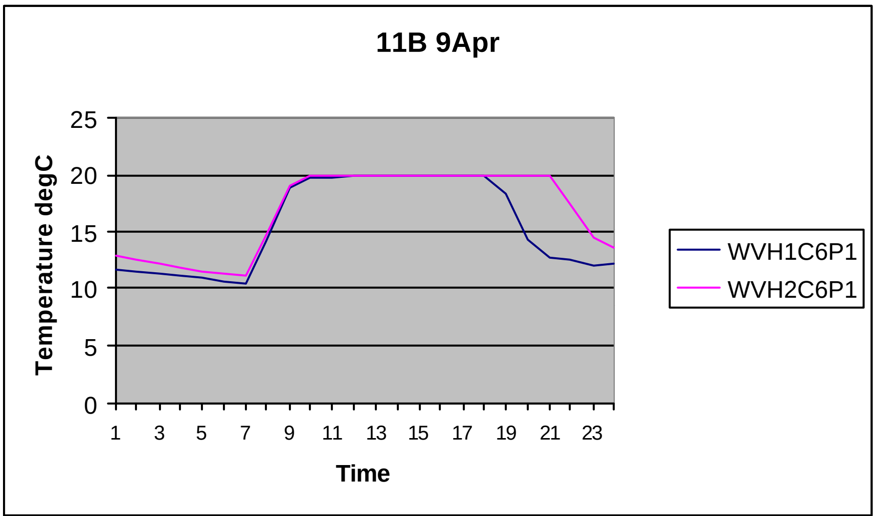

10B 9Jan
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH2C6P1
WVH2C6P2
WVH2C6P1X

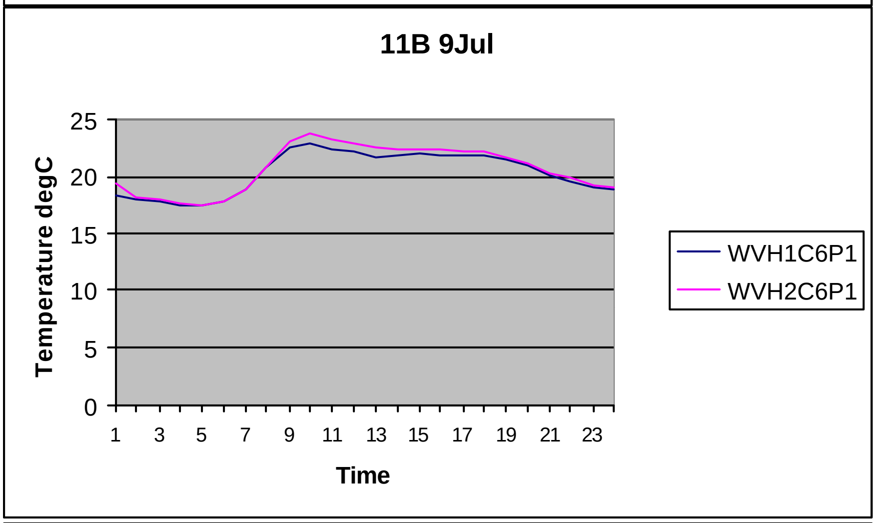

10B 9Apr
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH2C6P1
WVH2C6P2
WVH2C6P1X

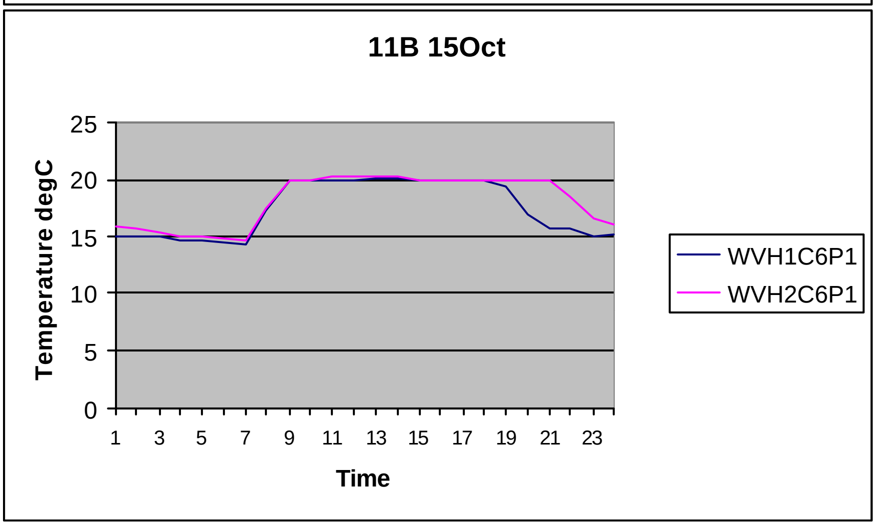

10B 9Jul
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH2C6P1
WVH2C6P2
WVH2C6P1X

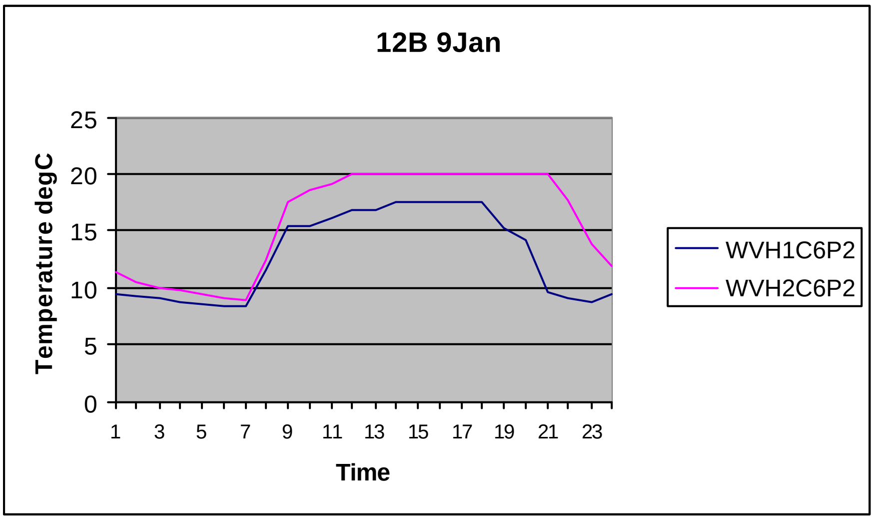

10B 15Oct
Temperature degC
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23
Time
WVH2C6P1
WVH2C6P2
WVH2C6P1X

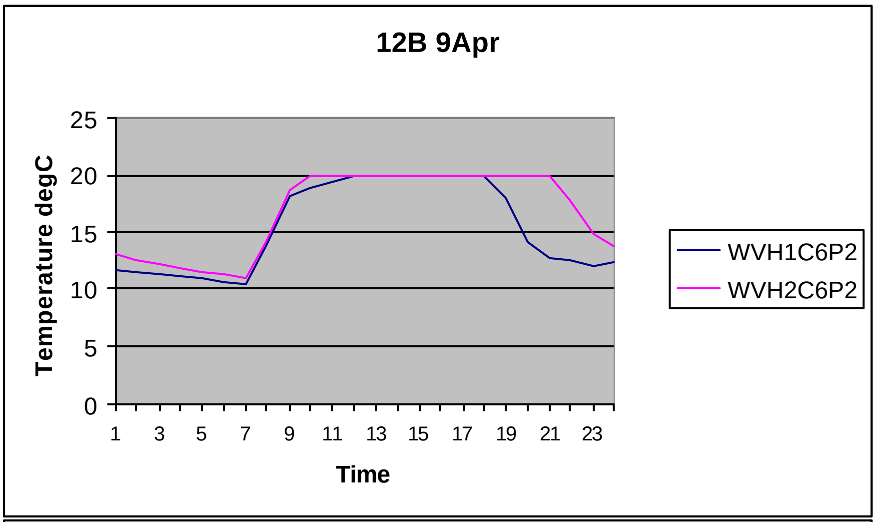

11B 9Jan
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WVH1C6P1
WVH2C6P1

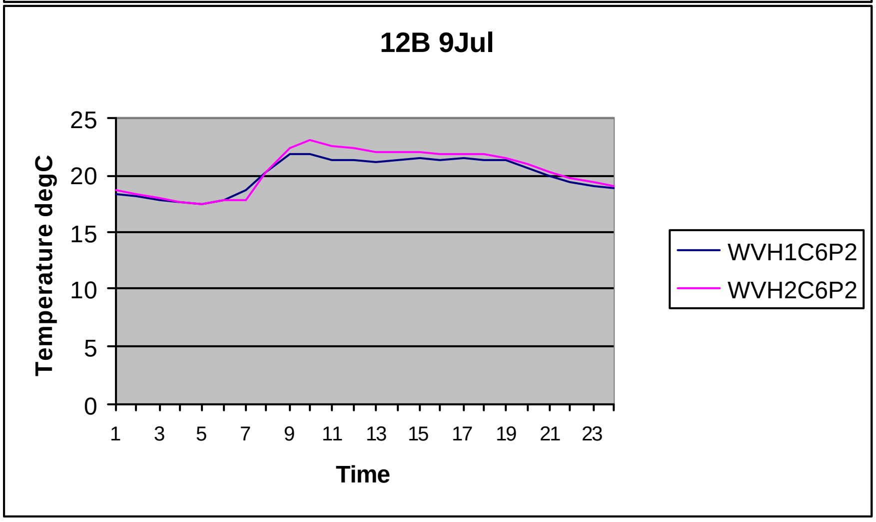

11B 9Apr
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WVH1C6P1
WVH2C6P1


11B 9Jul
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WVH1C6P1
WVH2C6P1


11B 15Oct
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WVH1C6P1
WVH2C6P1


12B 9Jan
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WVH1C6P2
WVH2C6P2


12B 9Apr
Temperature degC
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
Time
WVH1C6P2
WVH2C6P2


12B 9Jul
Temperature degC
25
20
15
10
5
0
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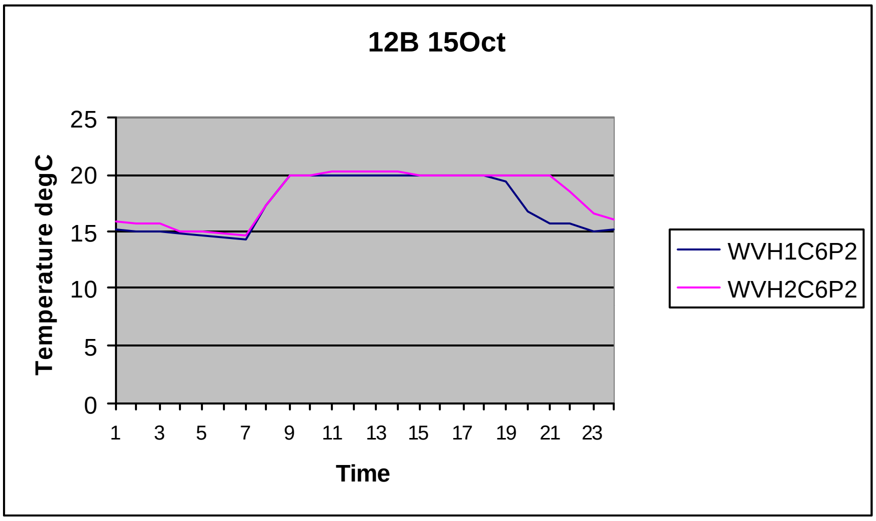
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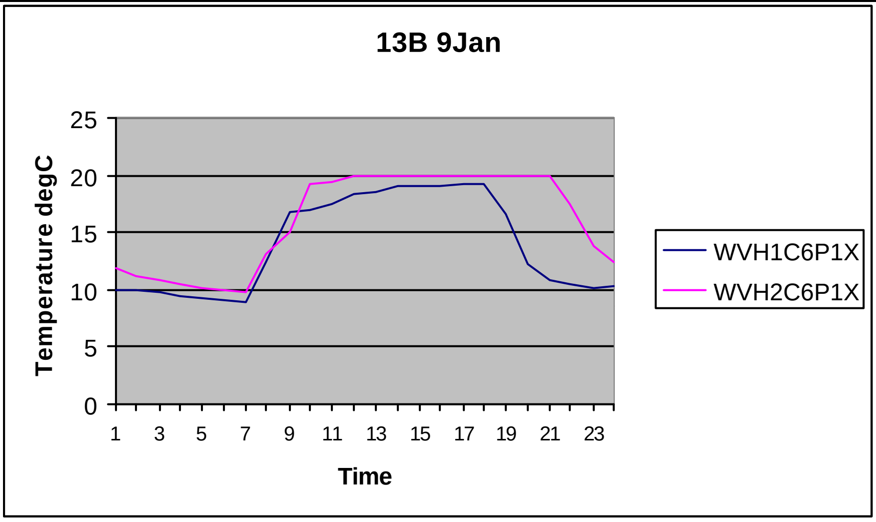
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Time
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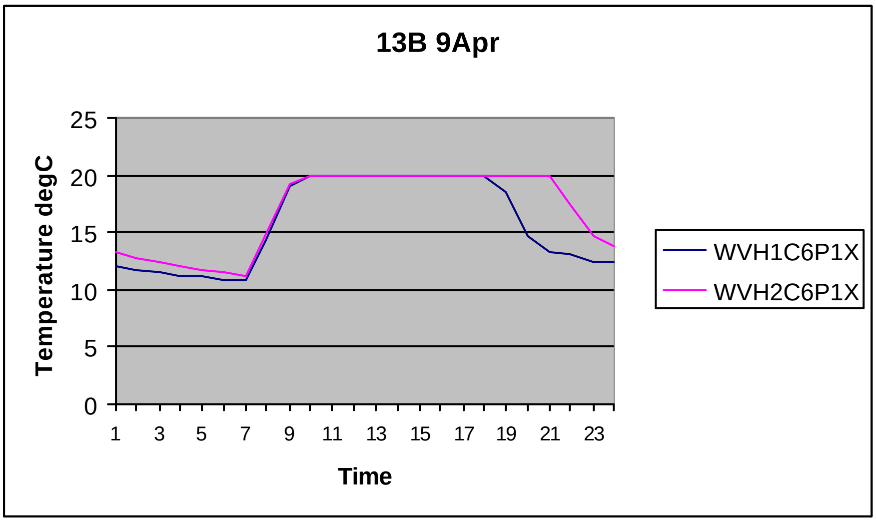
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Time
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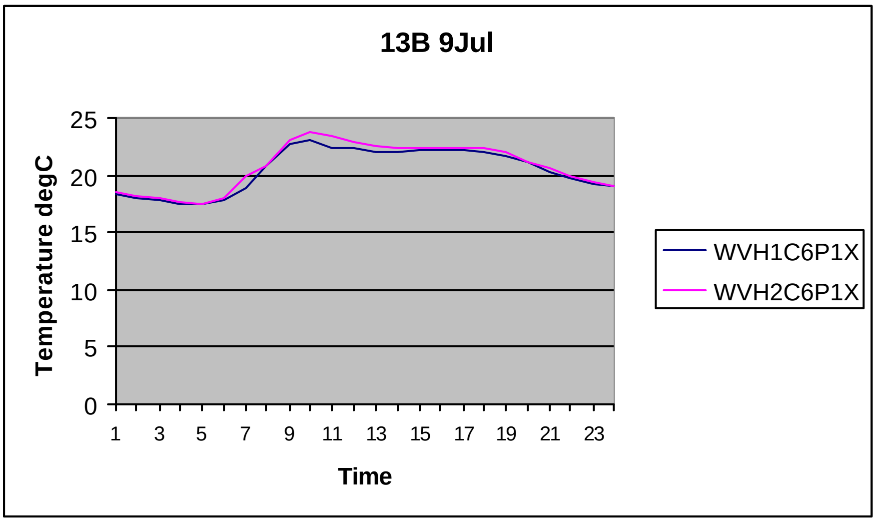
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Time
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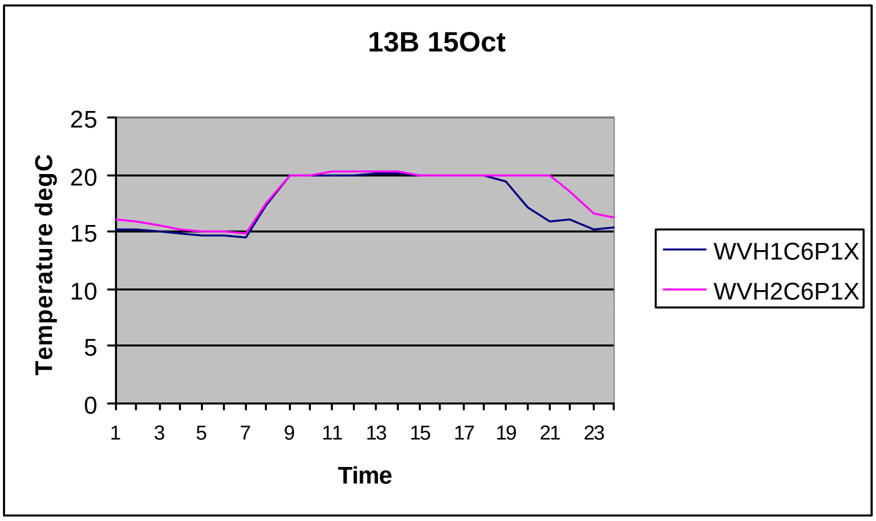
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Time
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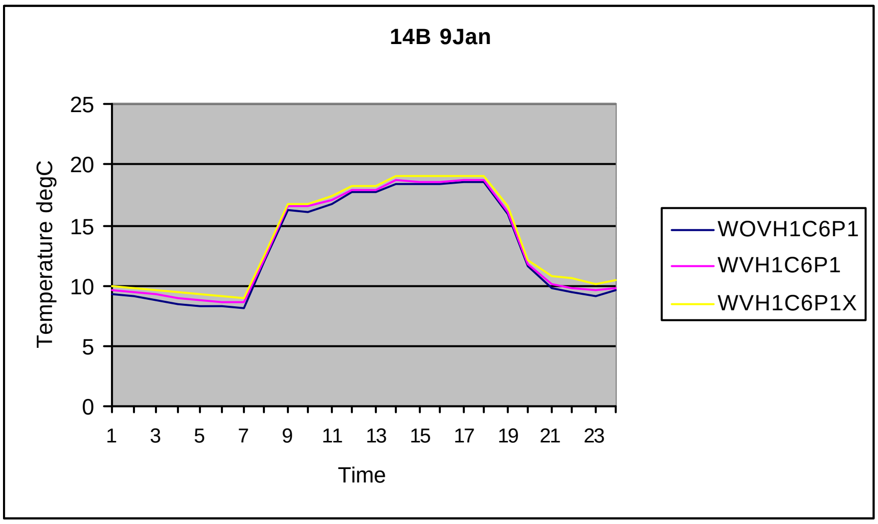
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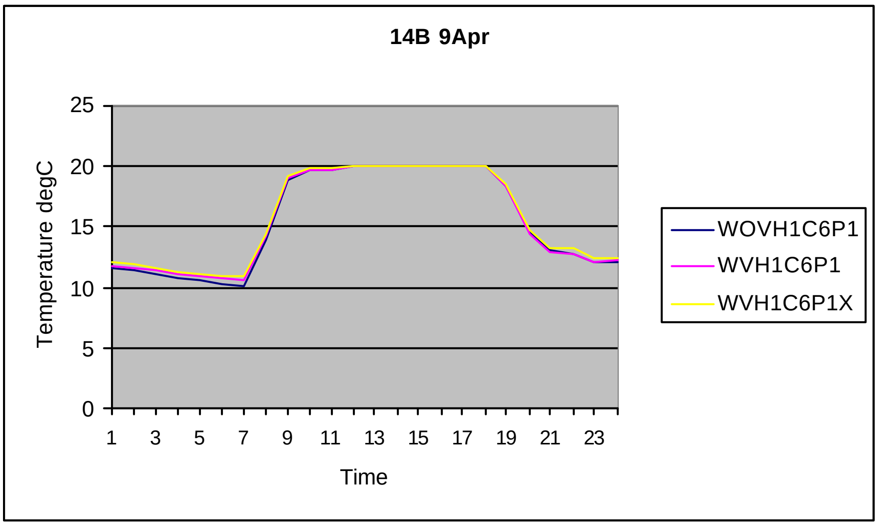
WVH1C6P1X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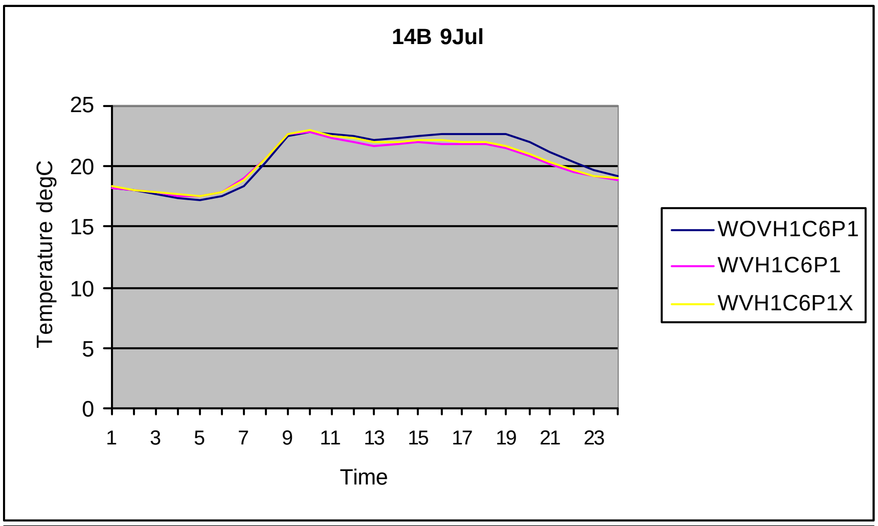
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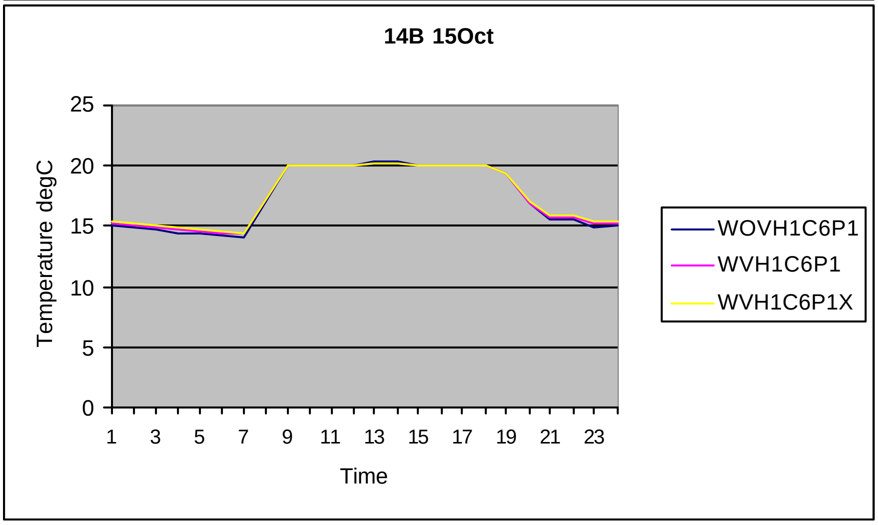
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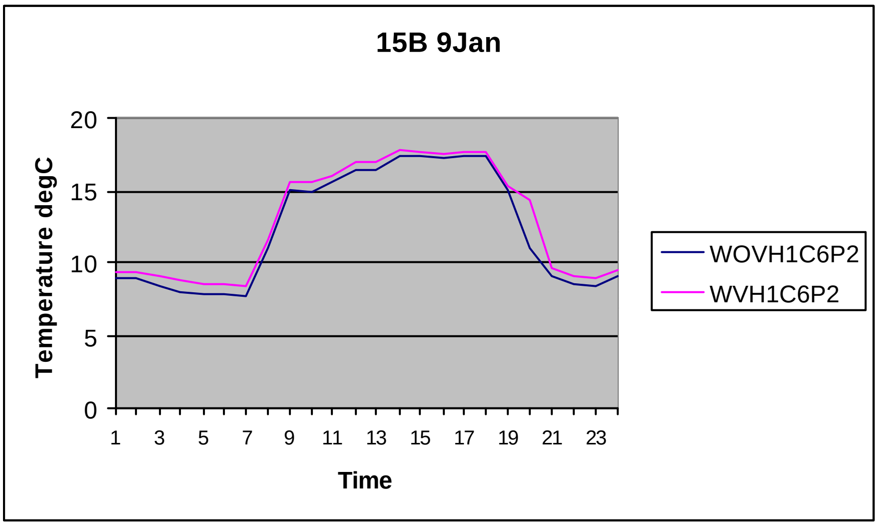
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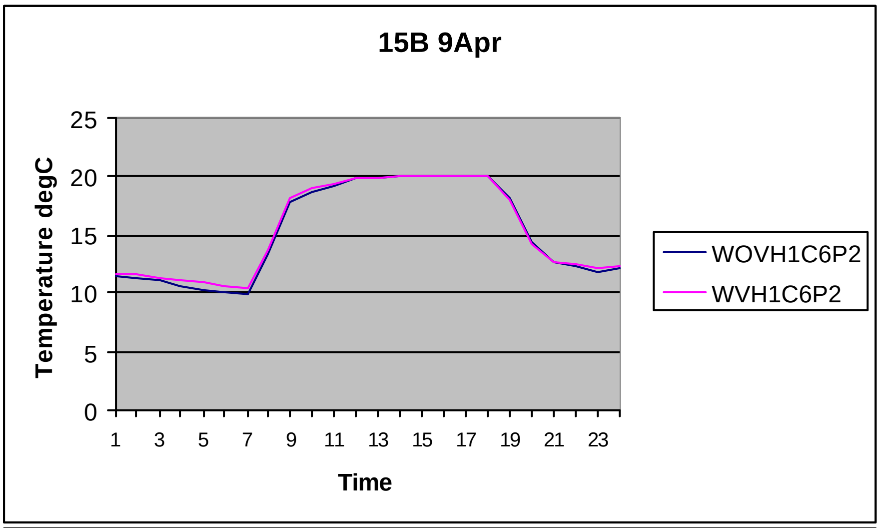
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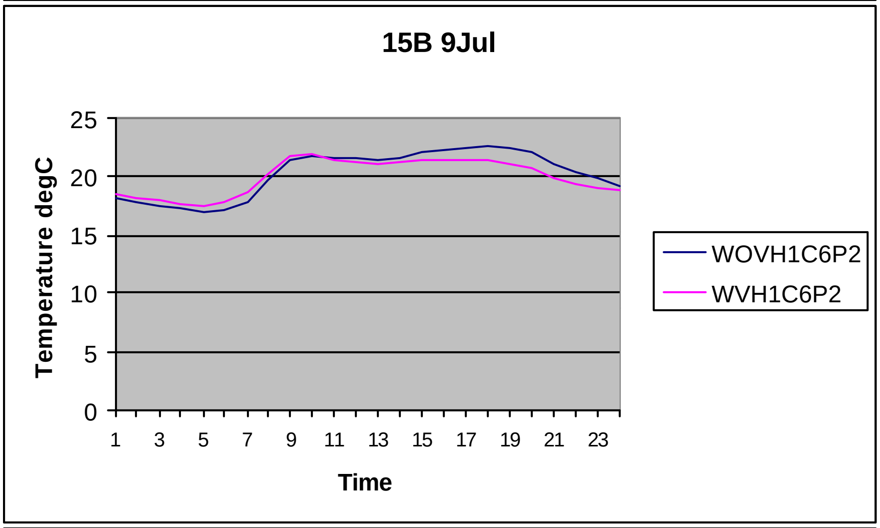
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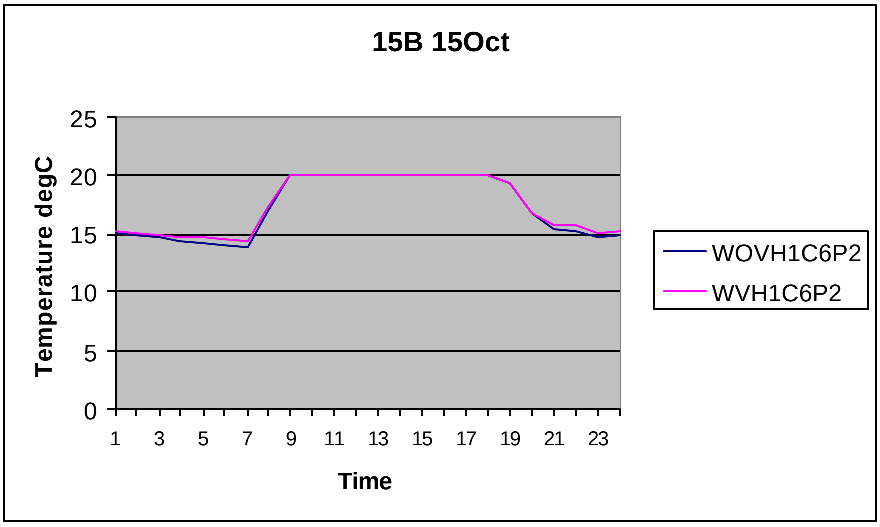
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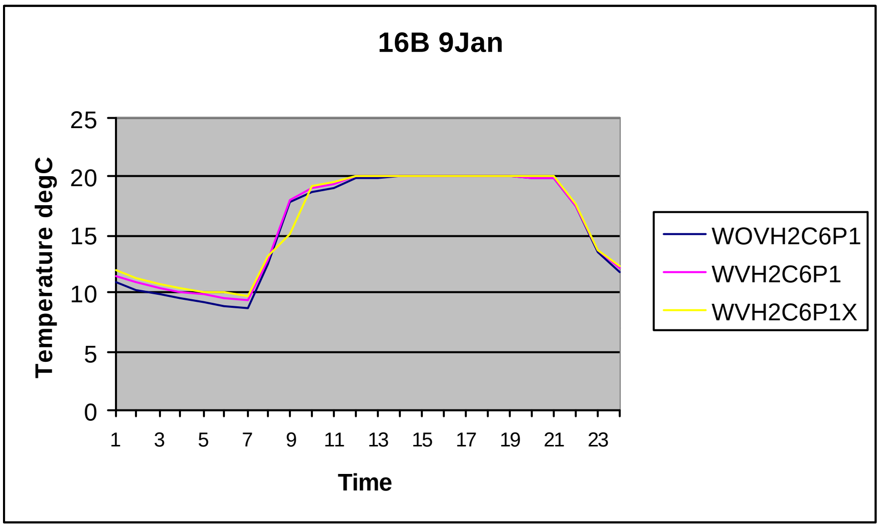
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Time
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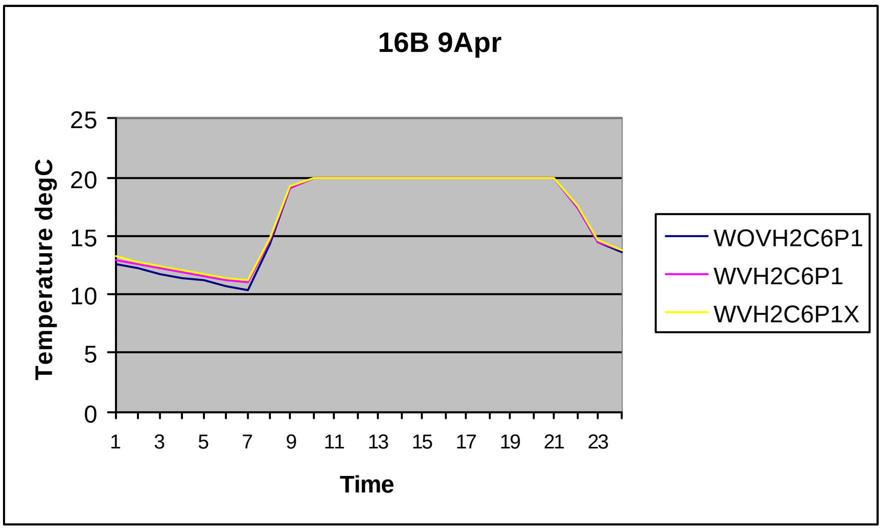
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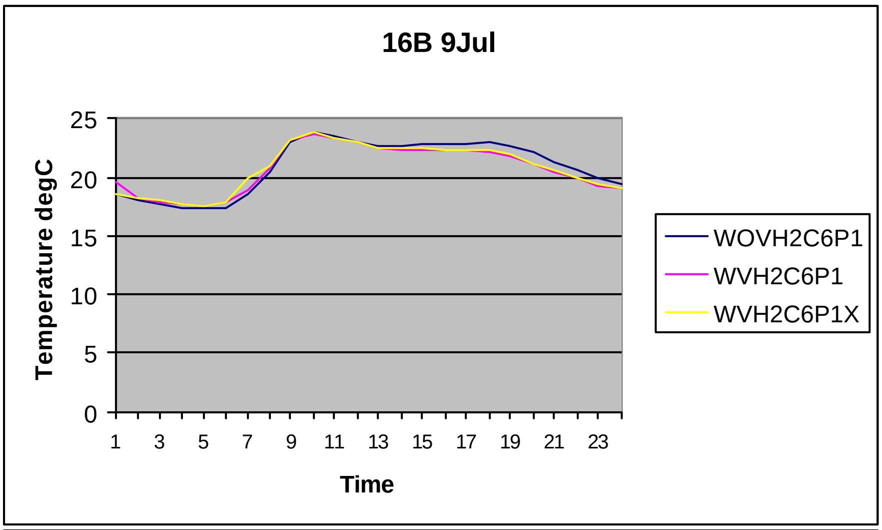
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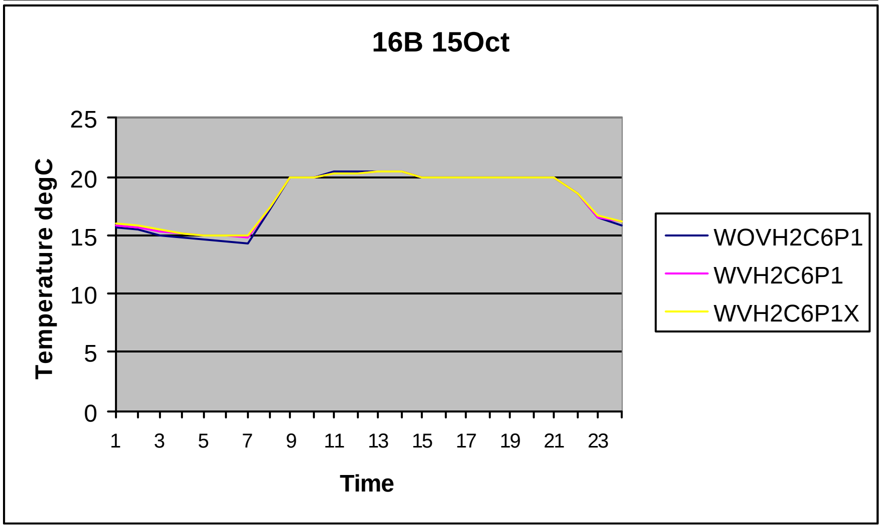
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Temperature degC
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Time
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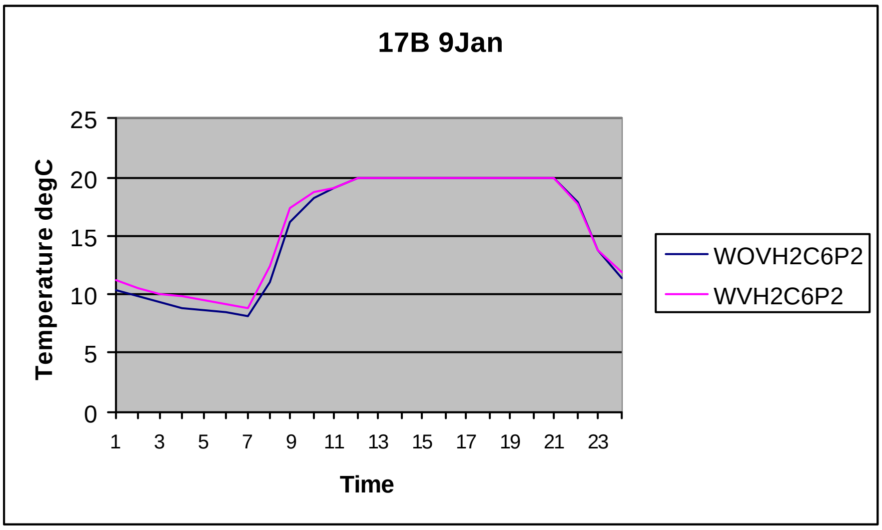
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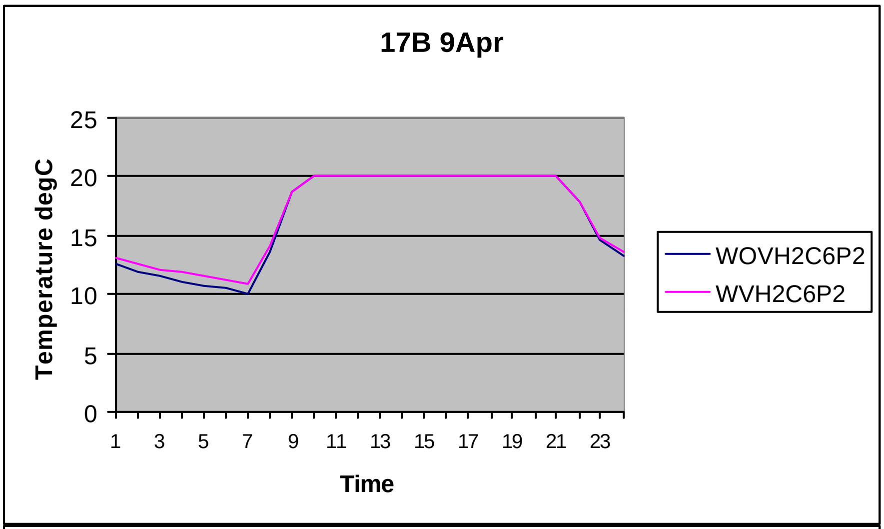
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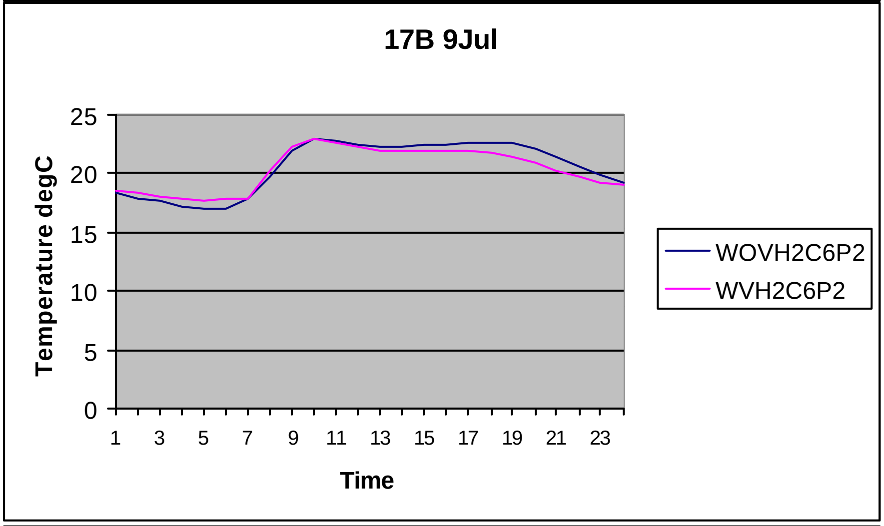
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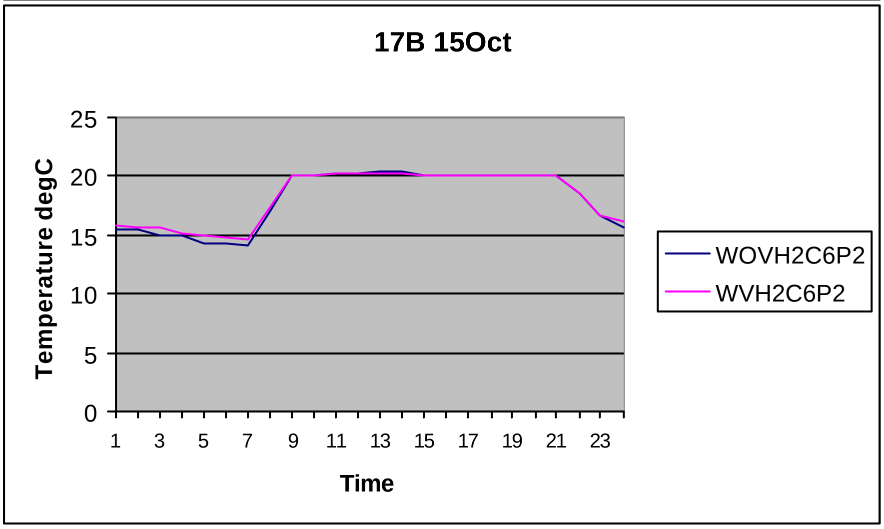
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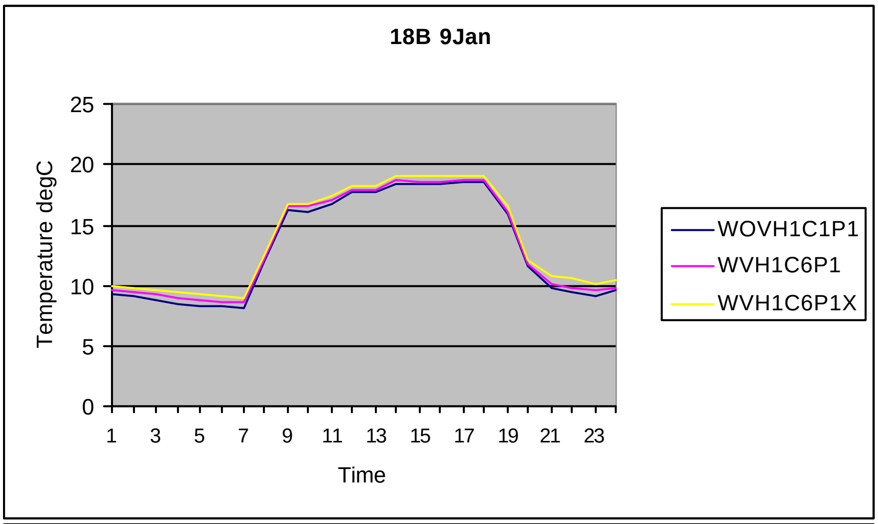
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Temperature degC
Time
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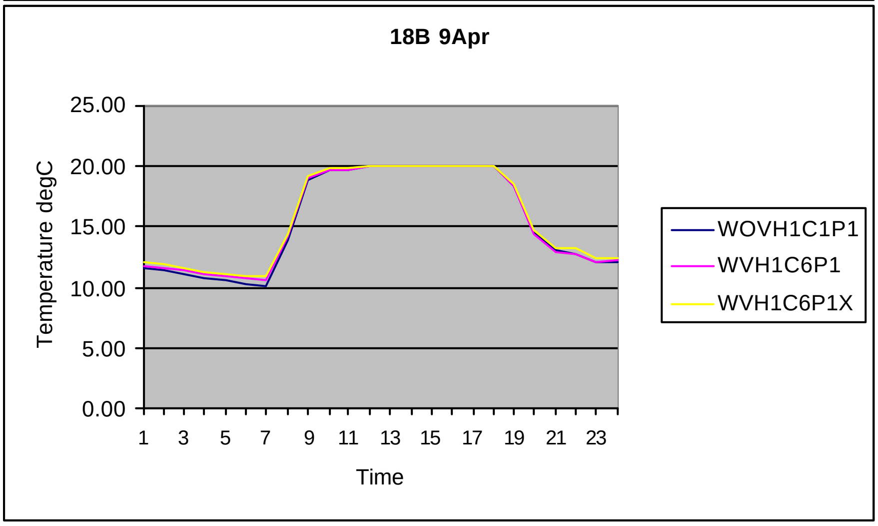
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Temperature degC
Time
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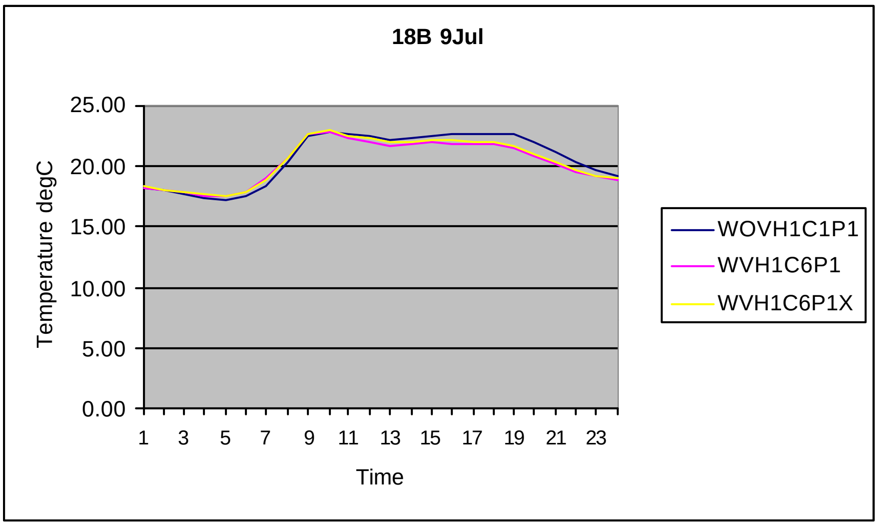
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Temperature degC
Time
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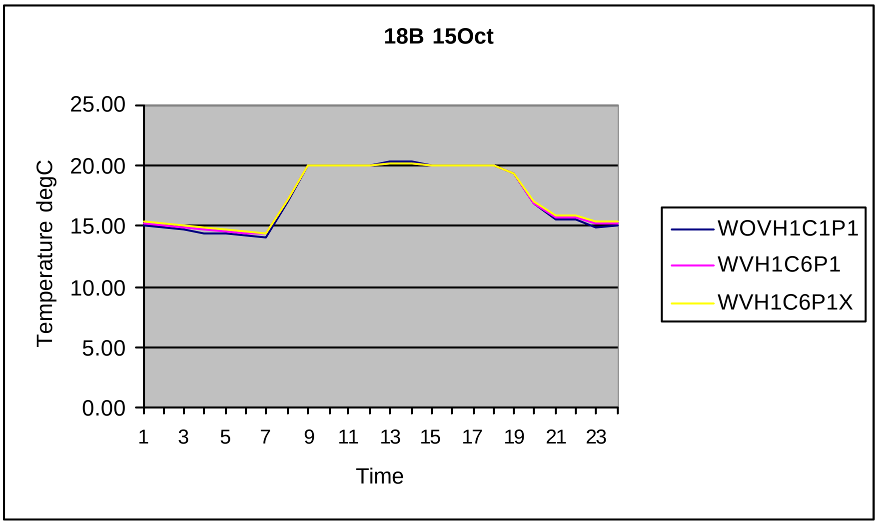
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Temperature degC
Time
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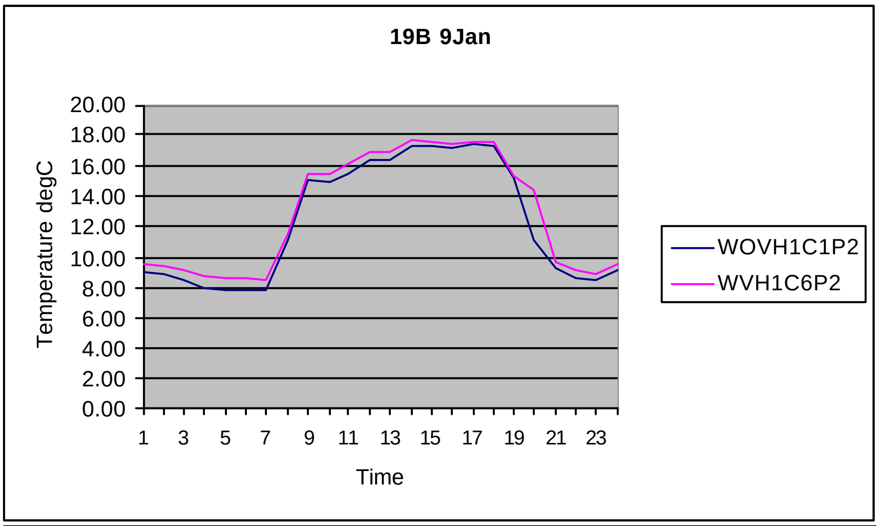
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18.00
16.00
14.00
12.00
10.00
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2.00
0.00
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Time
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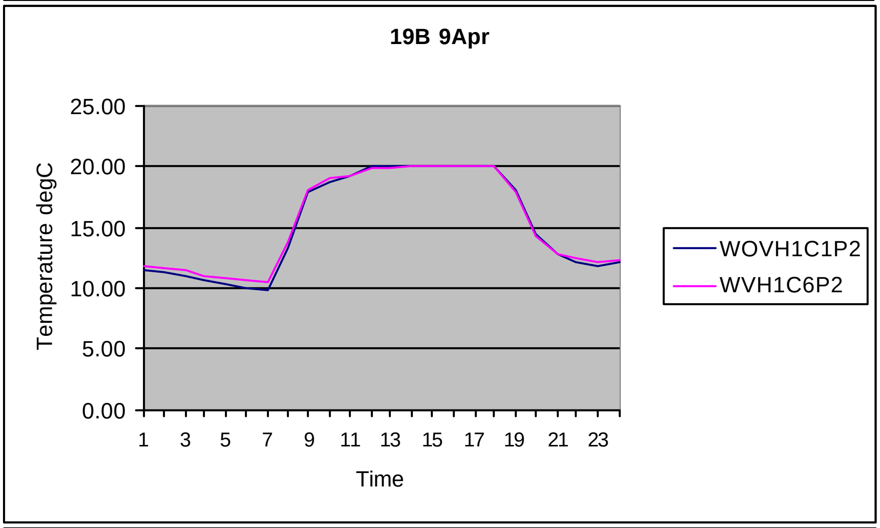
WVH1C6P2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Time
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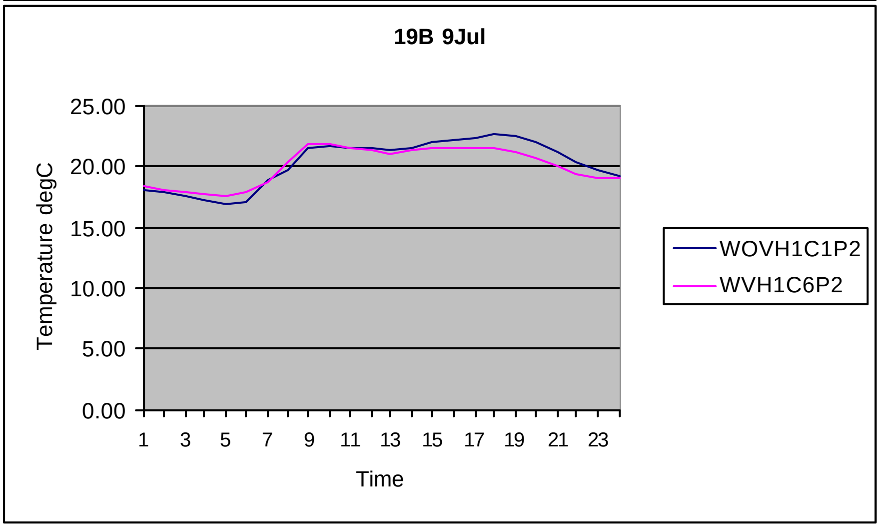
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Time
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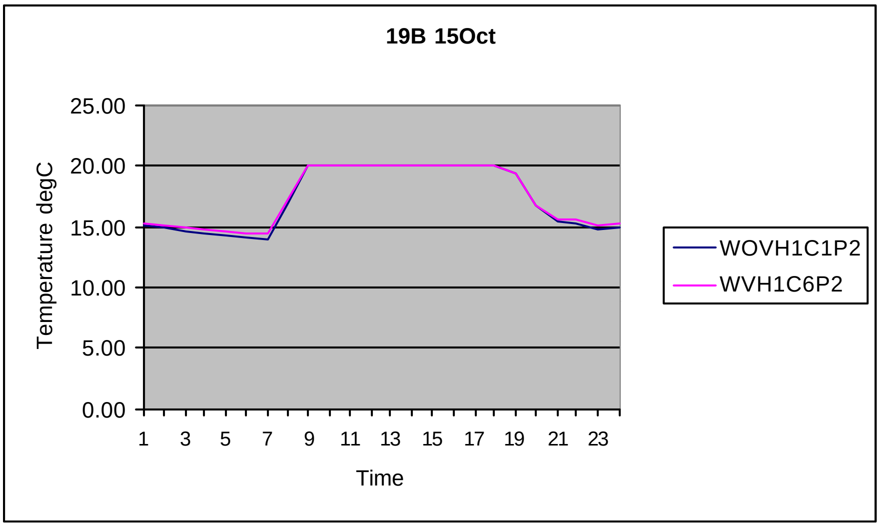
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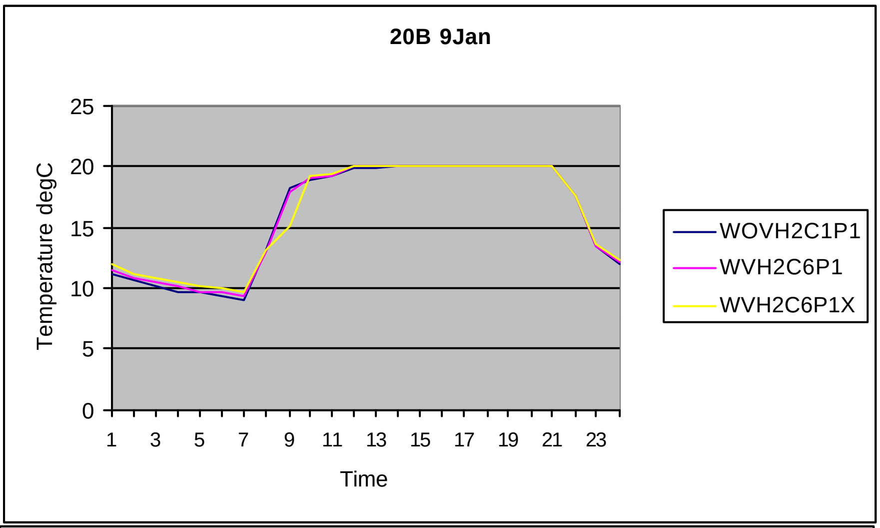
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Time
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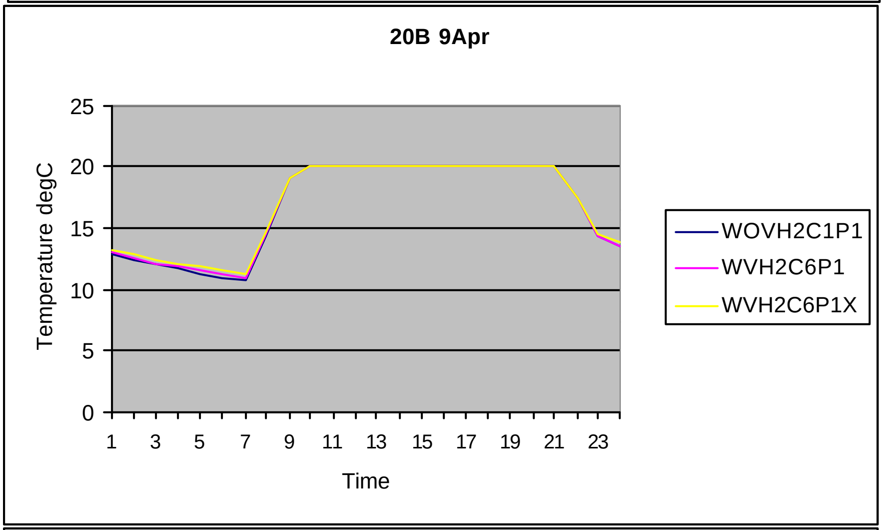
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Time
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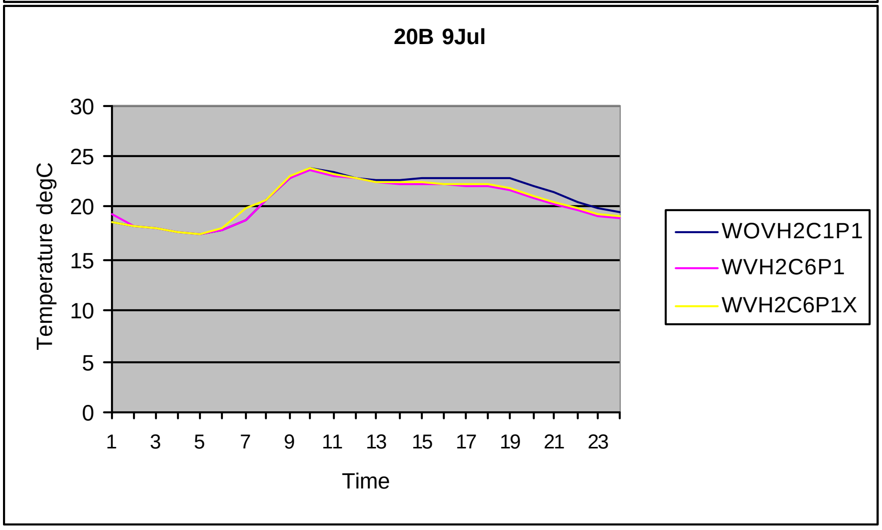
20B 9Jul
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Time
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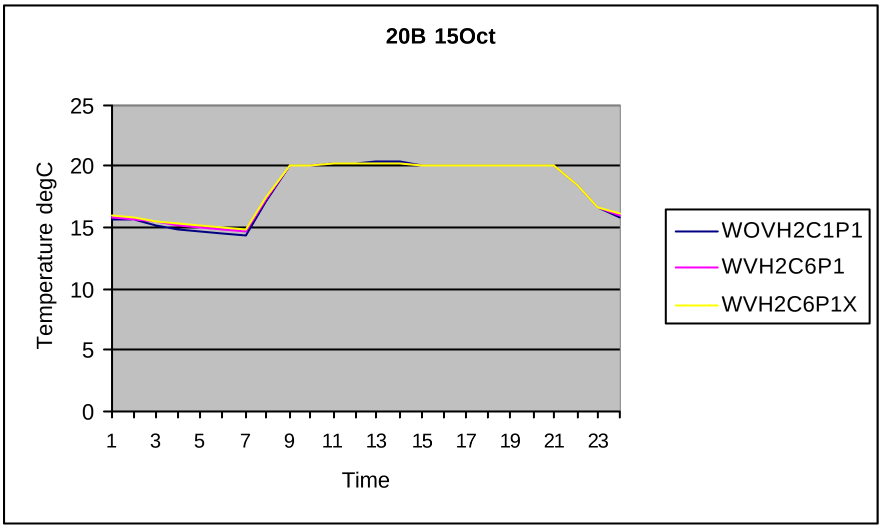
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Time
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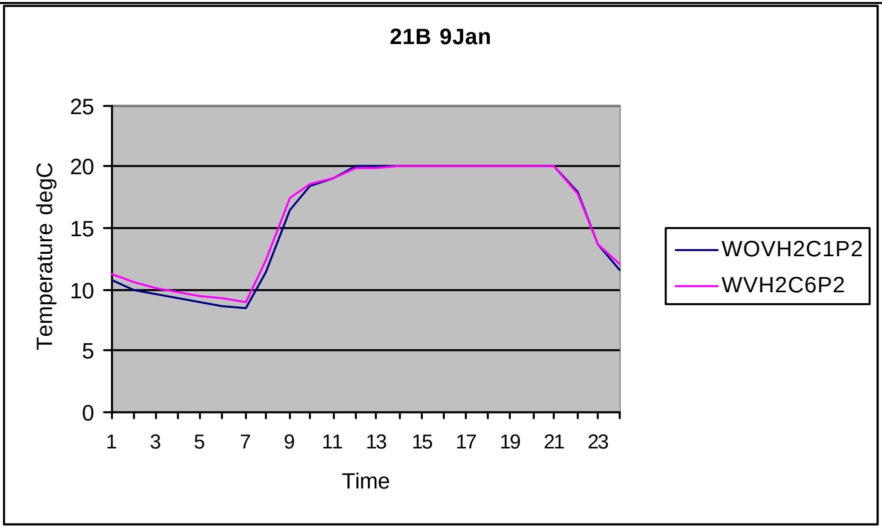
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Temperature degC
Time
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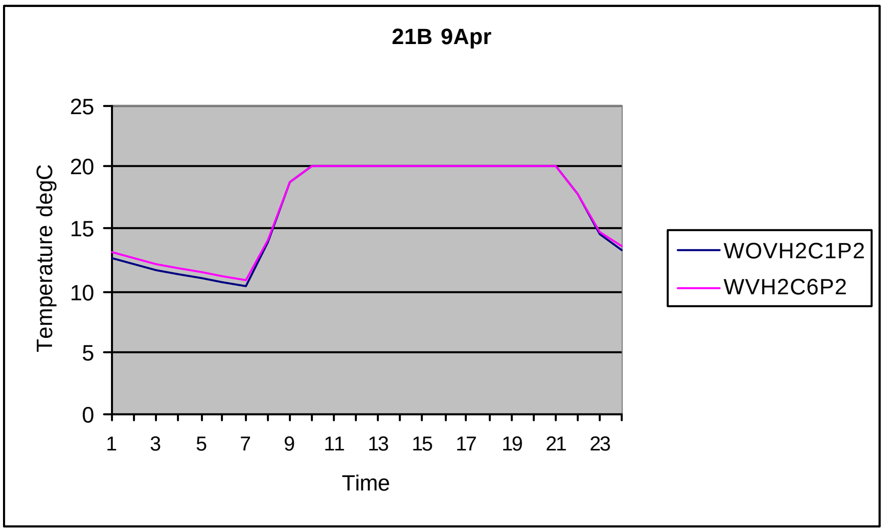
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Temperature degC
Time
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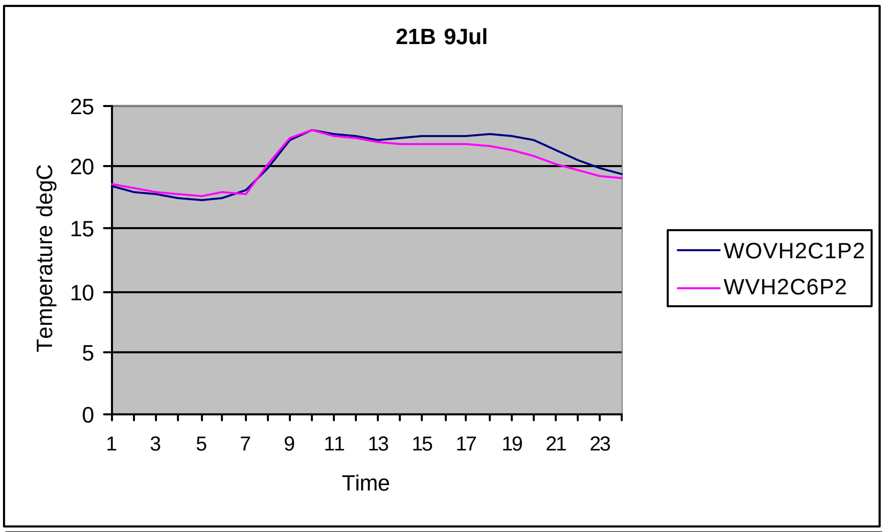
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Temperature degC
Time
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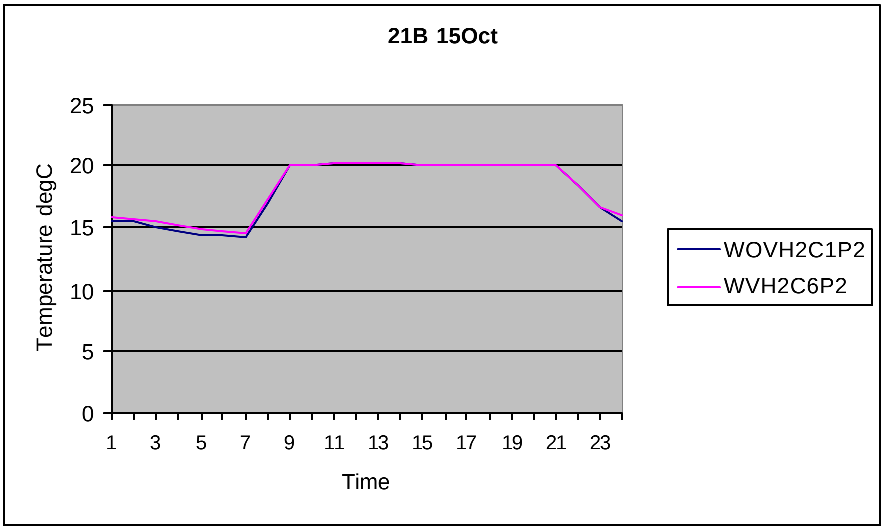
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Temperature degC
Time
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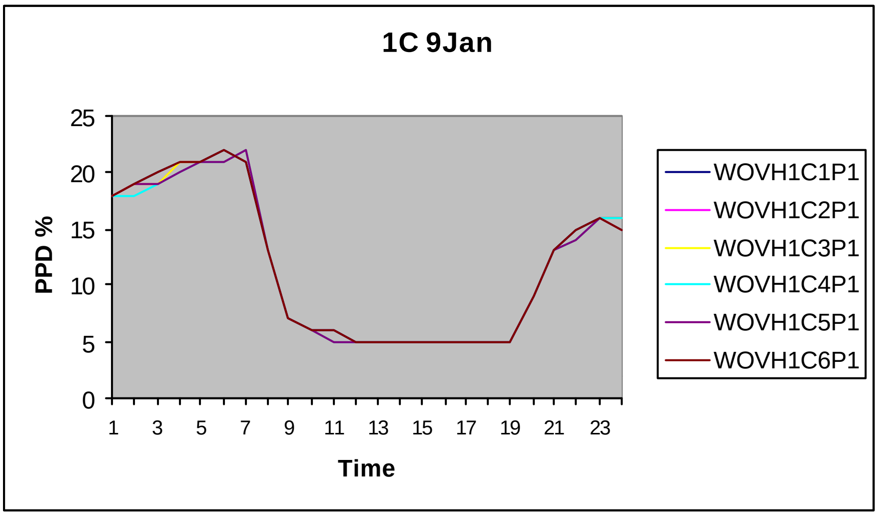
1C 9Jan
PPD %
Time
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WOVH1C3P1
WOVH1C4P1
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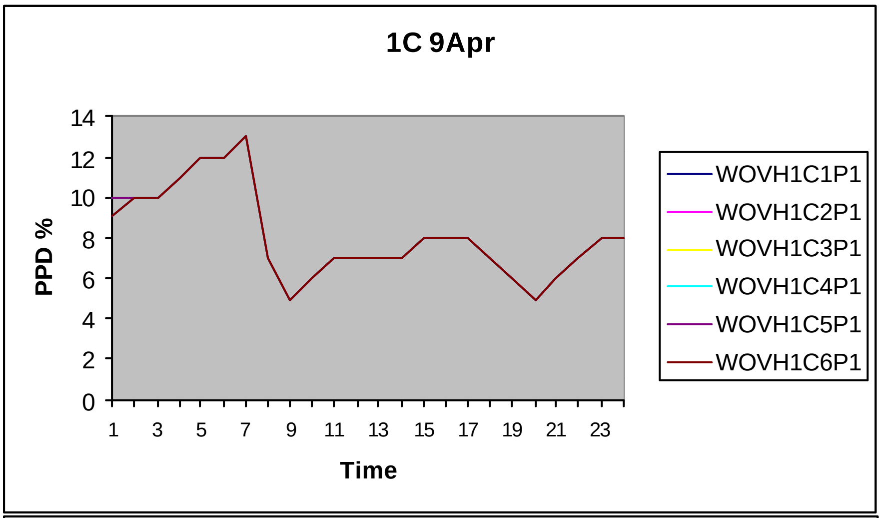
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PPD %
Time
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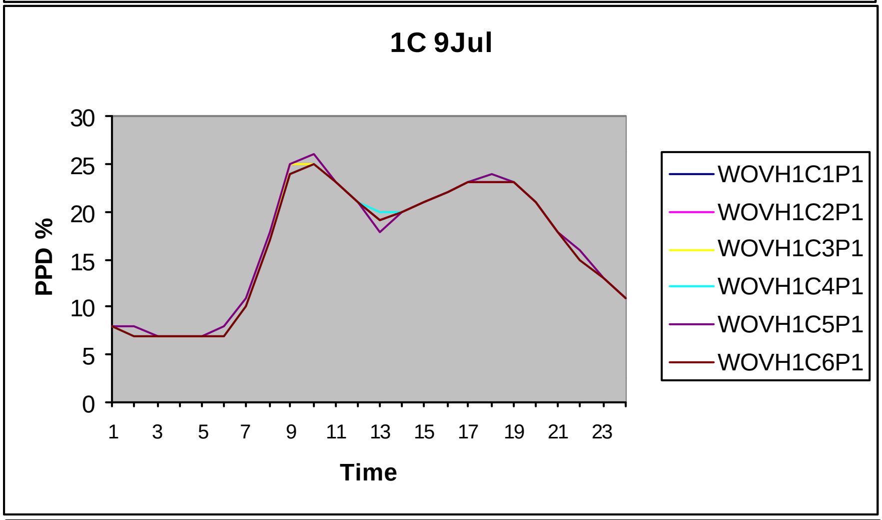
1C 9Jul
PPD %
Time
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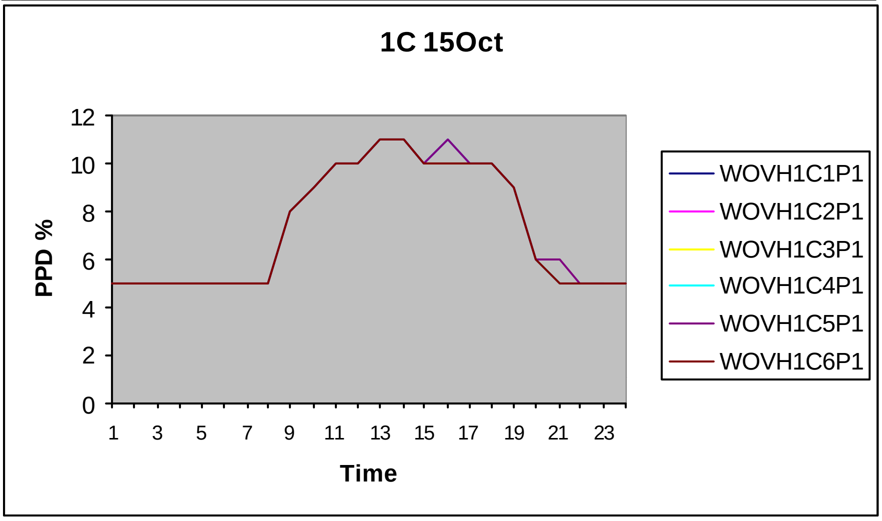
1C 15Oct
PPD %
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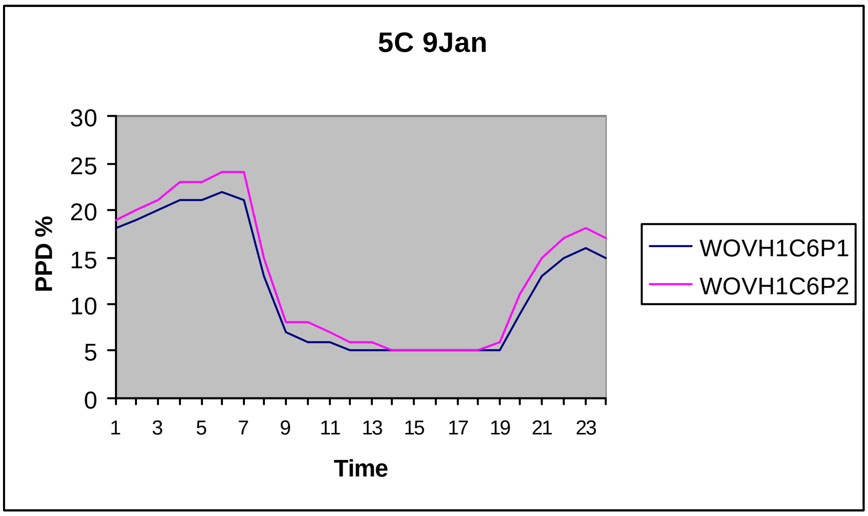
5C 9Jan
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PPD %
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23
Time
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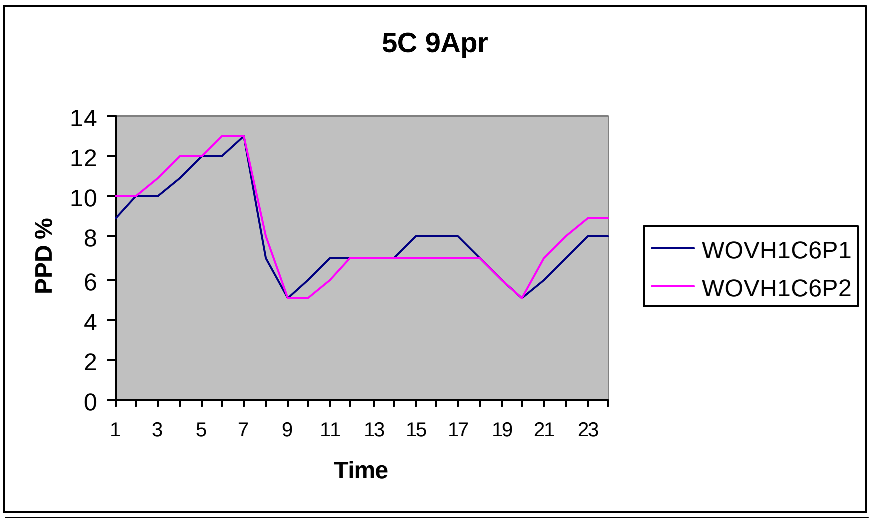
WOVH1C6P2


5C 9Apr
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PPD %
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Time
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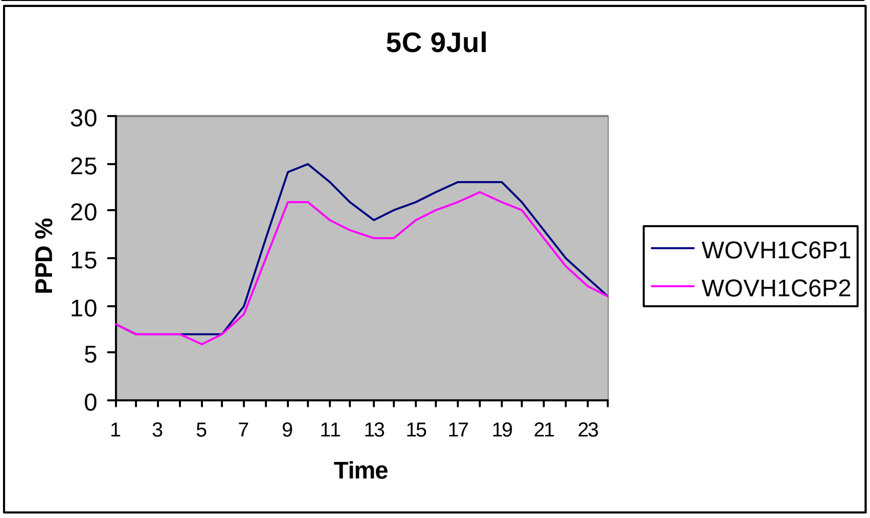
5C 9Jul
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PPD %
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Time
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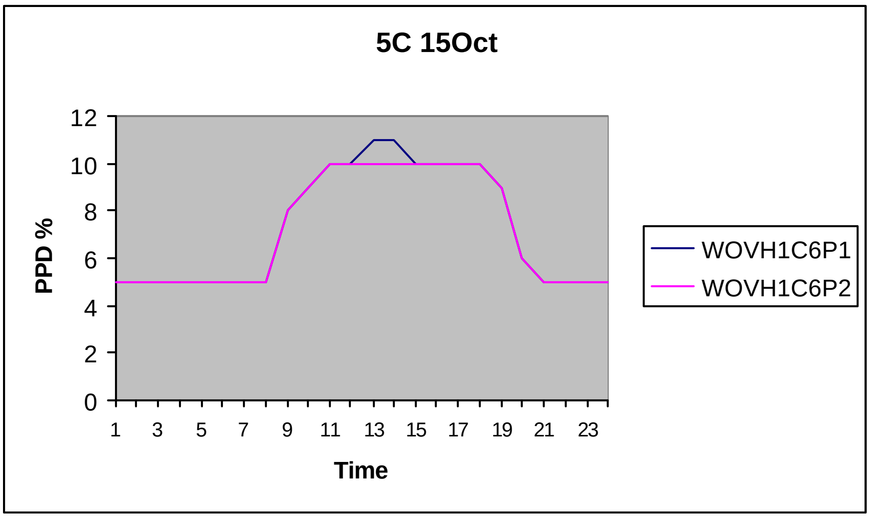
5C 15Oct
12
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PPD %
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Time
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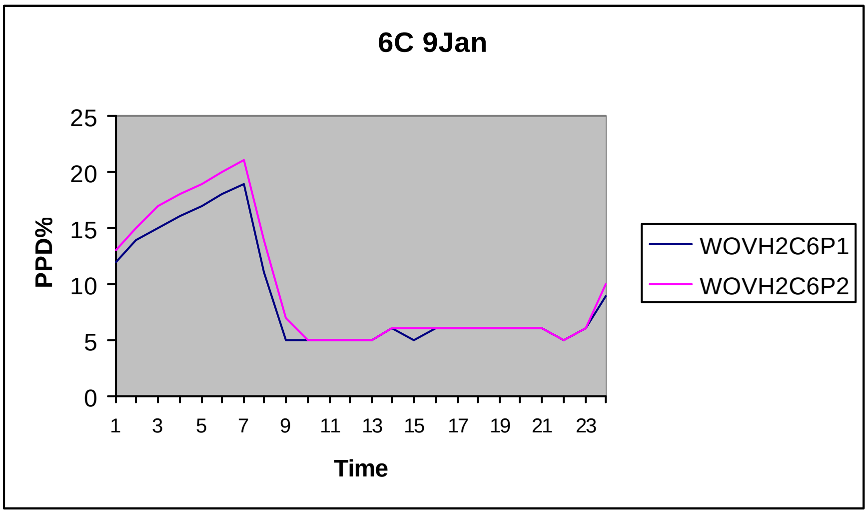
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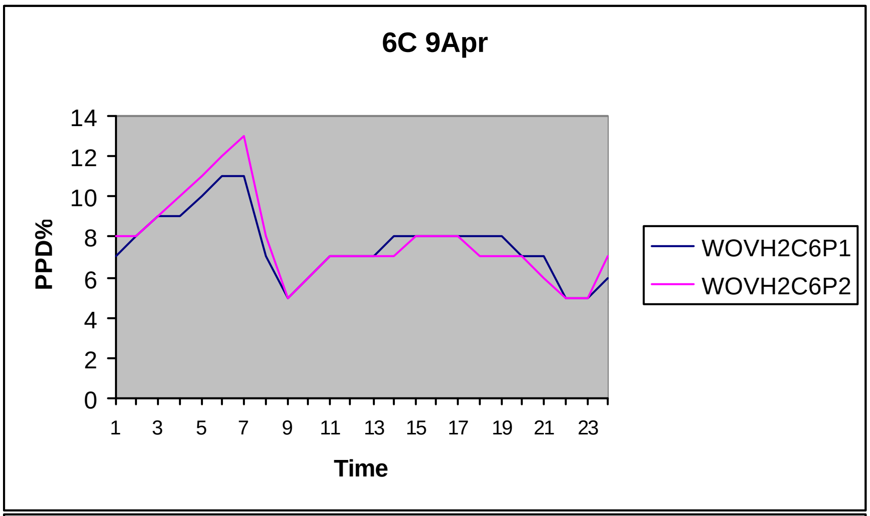
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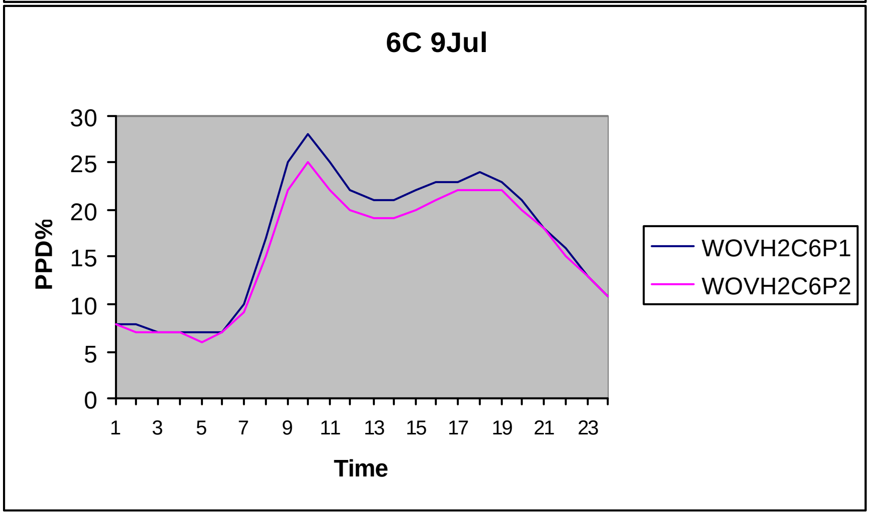
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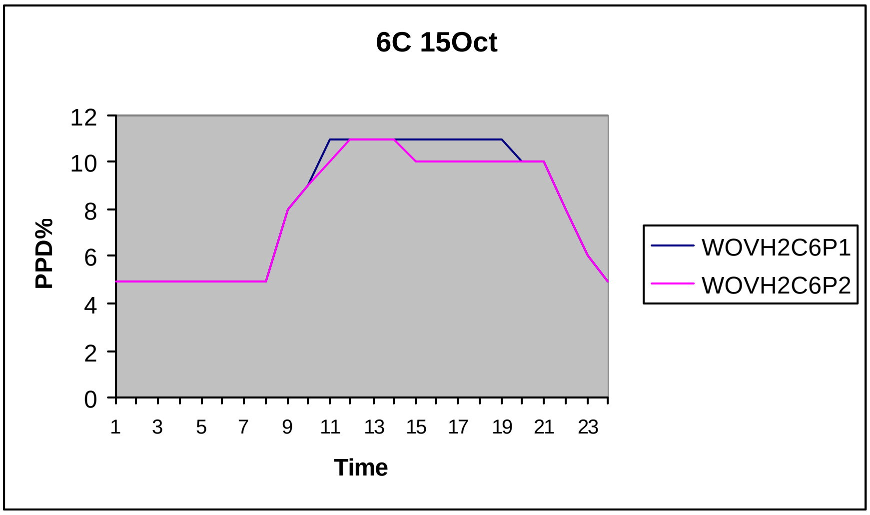
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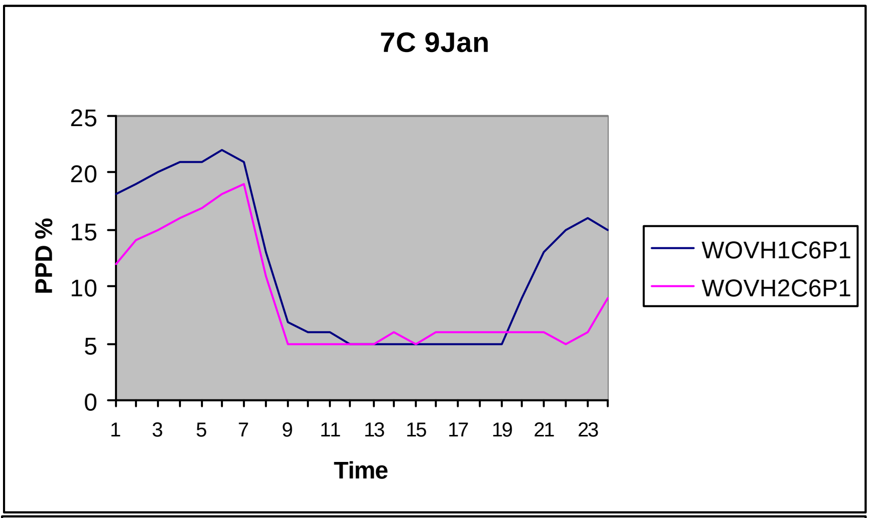
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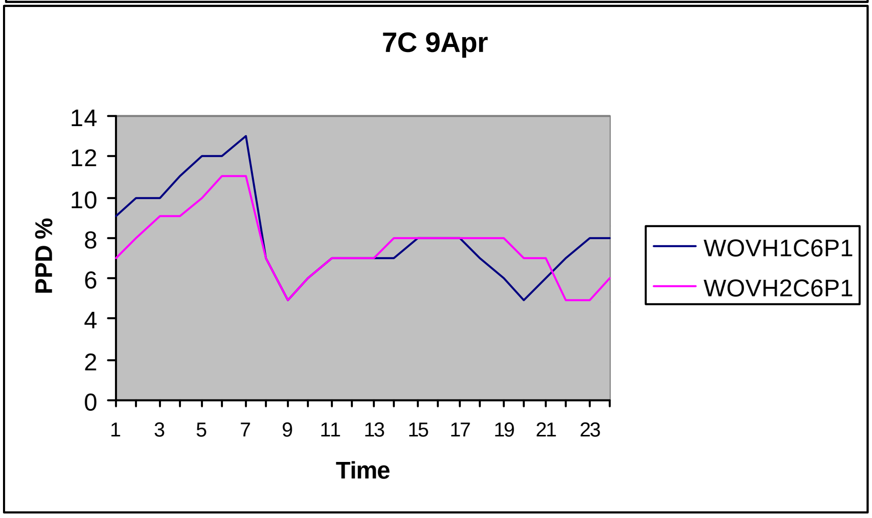
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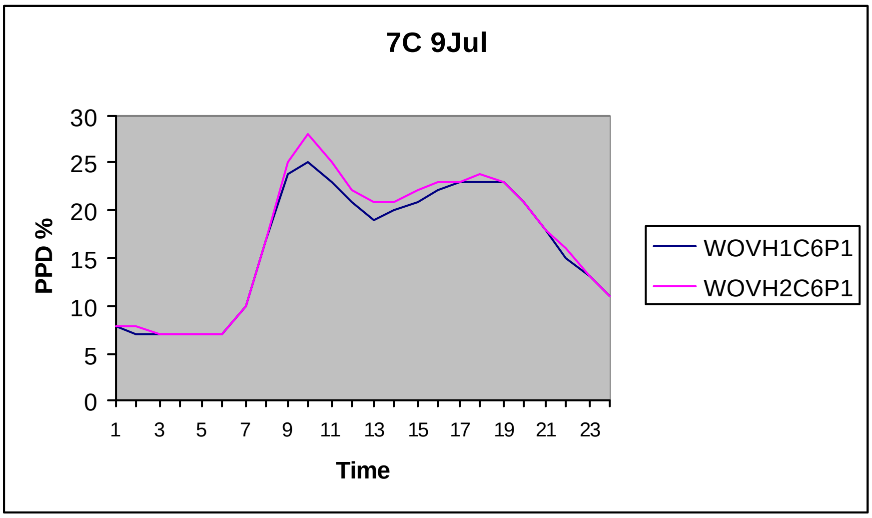
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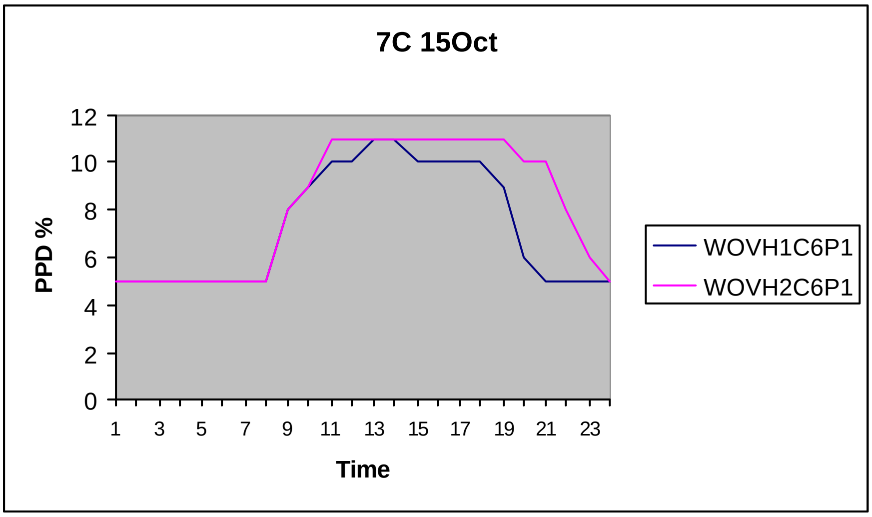
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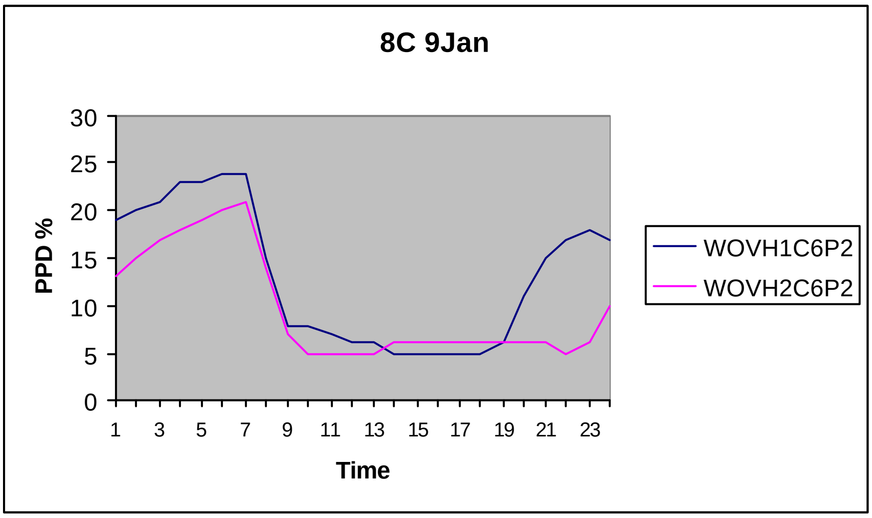
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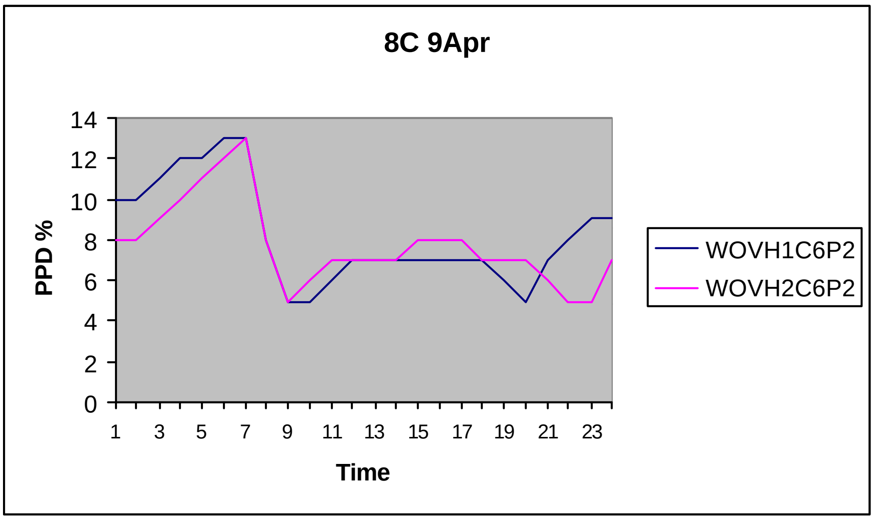
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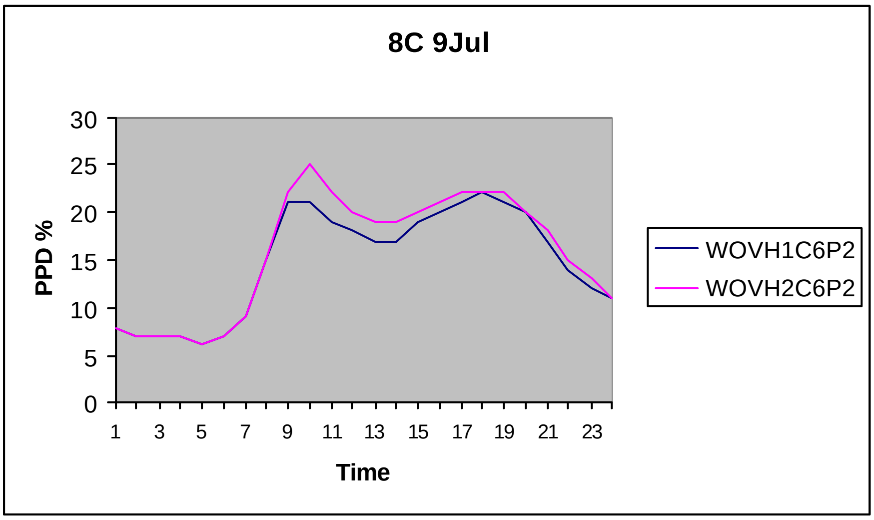
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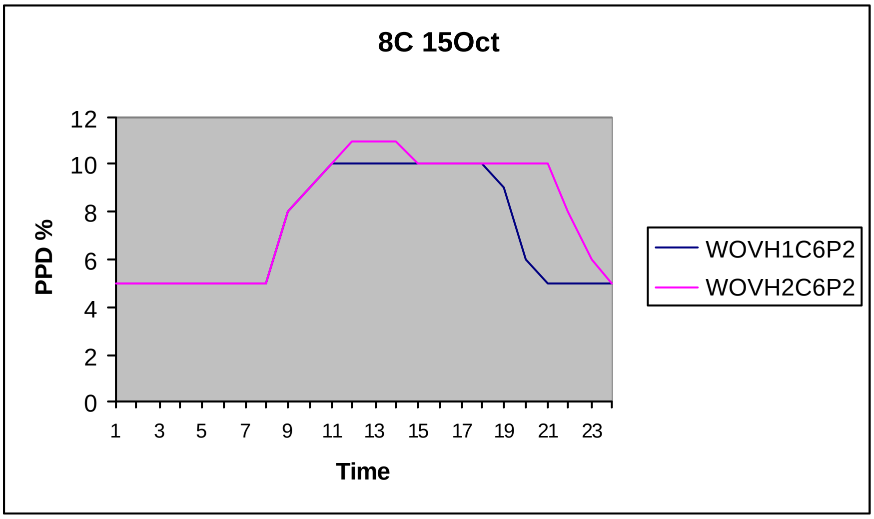
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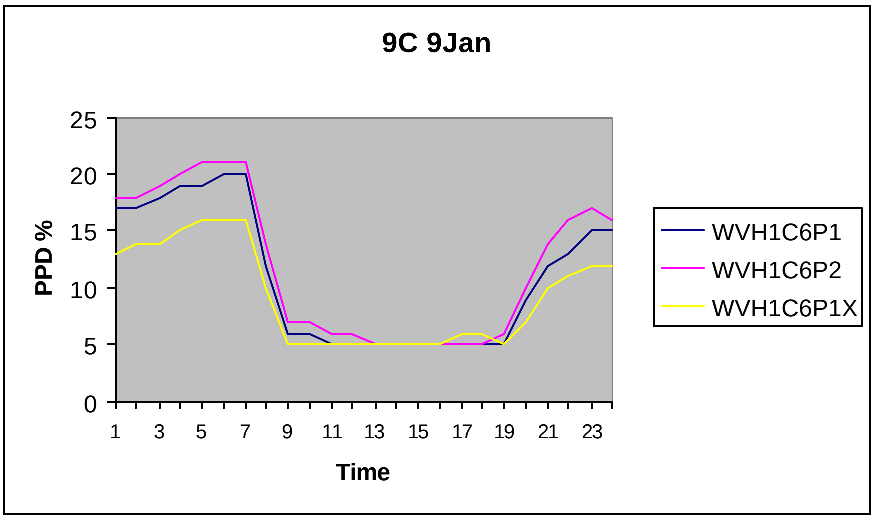
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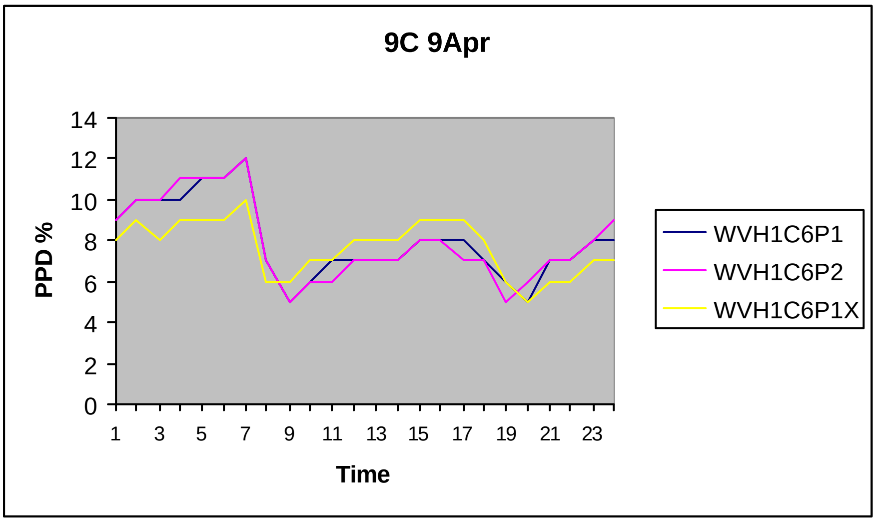
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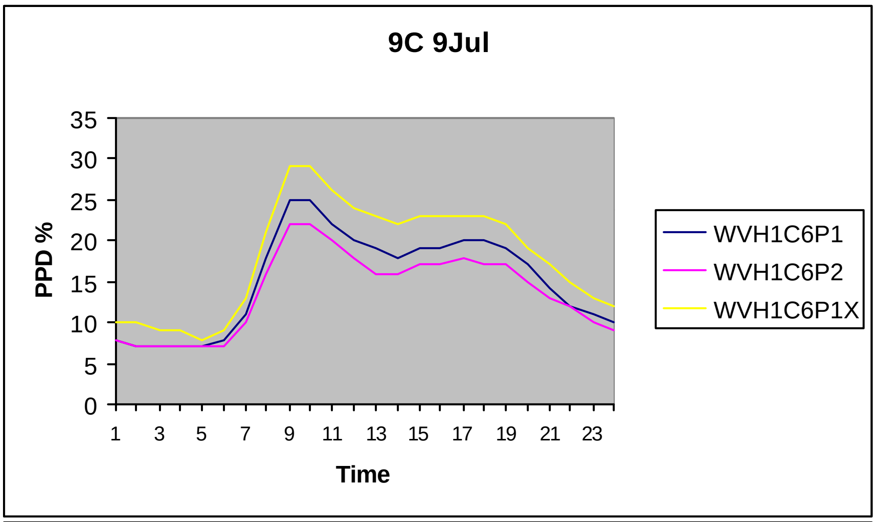
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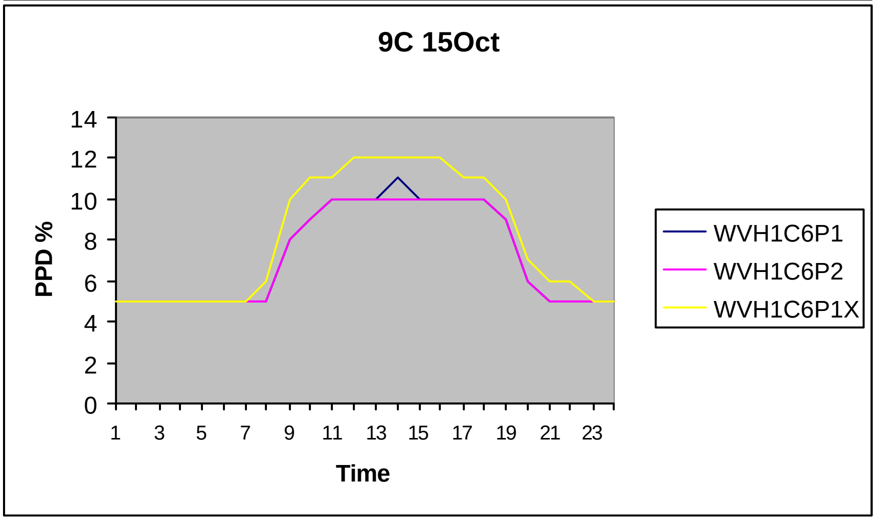
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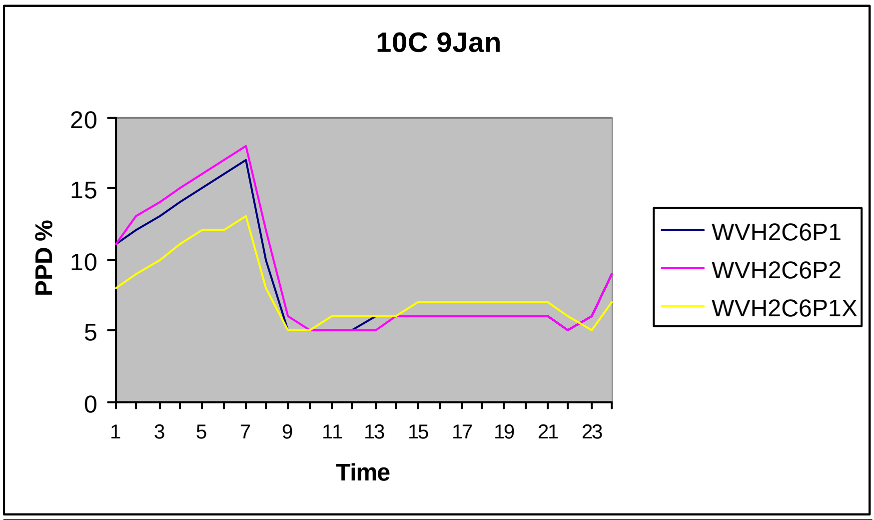
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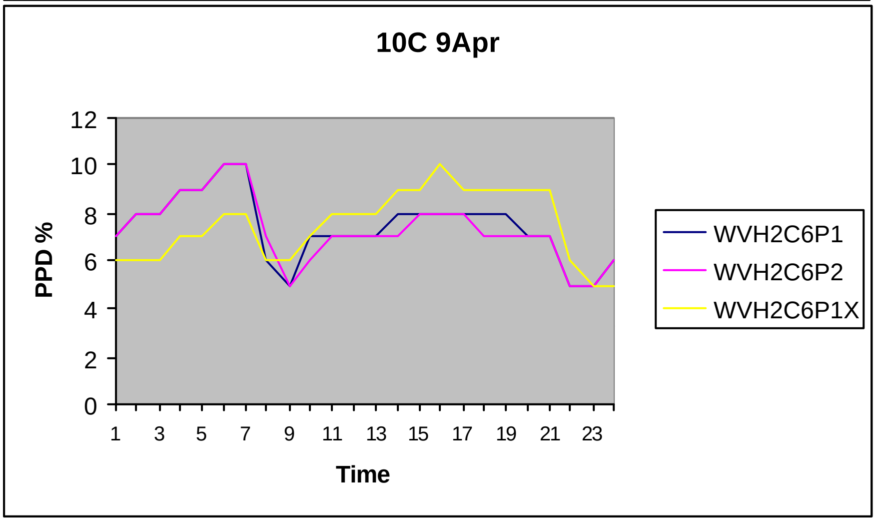
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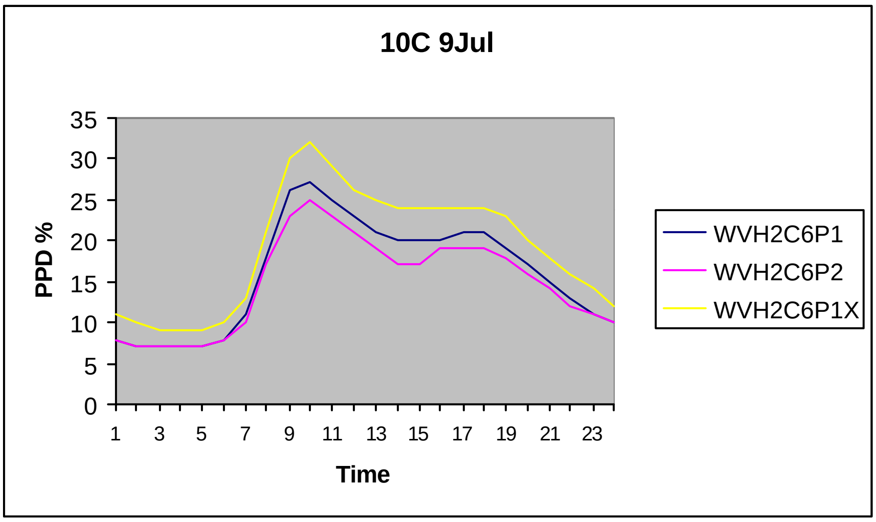
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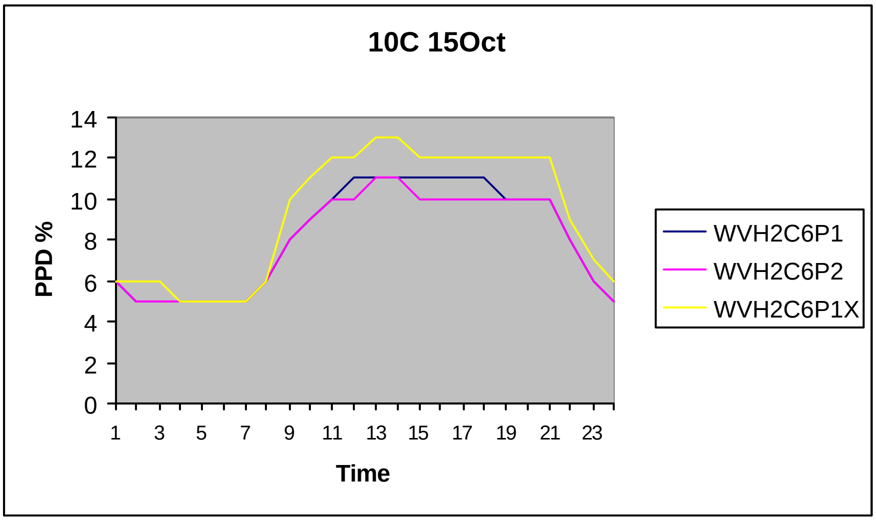
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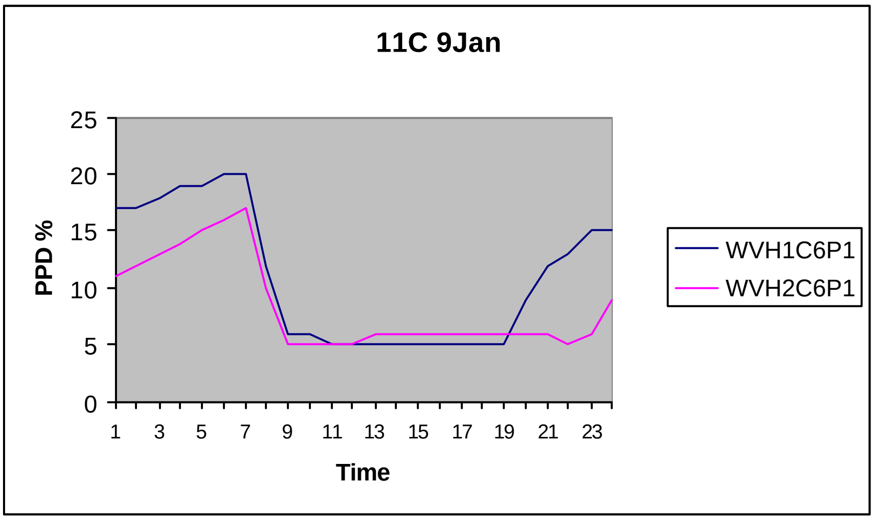
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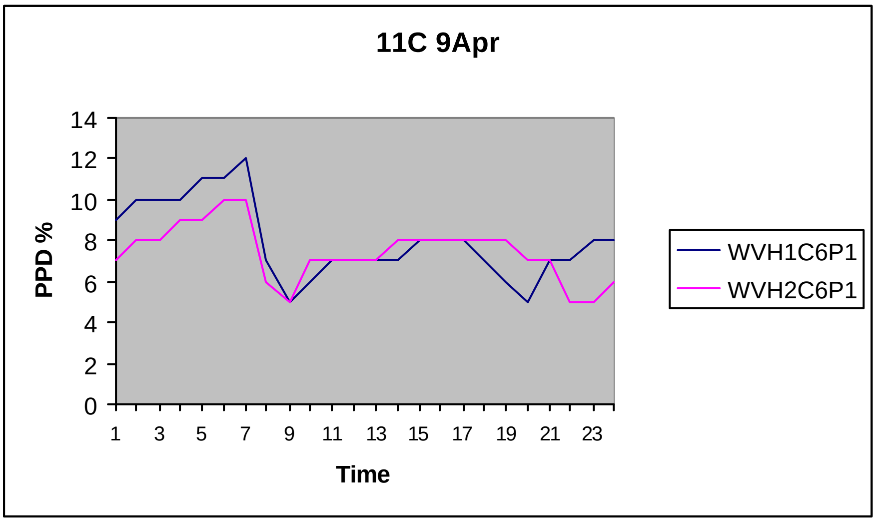
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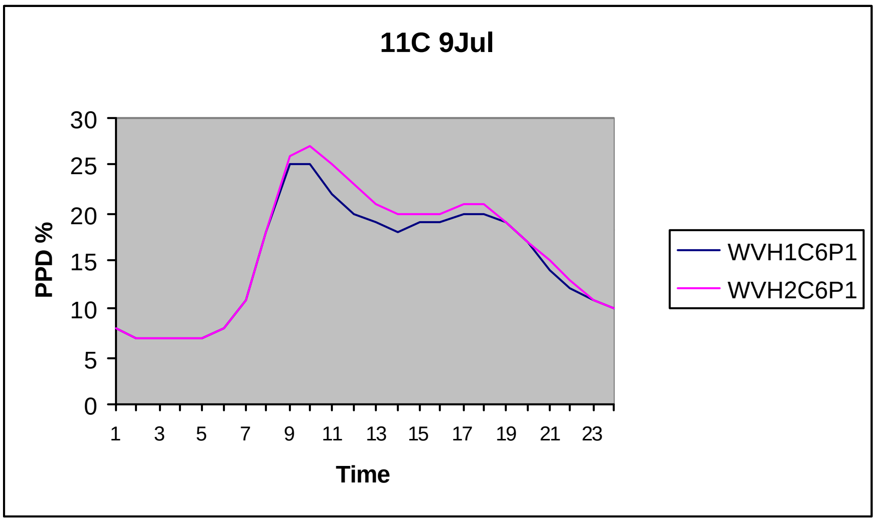
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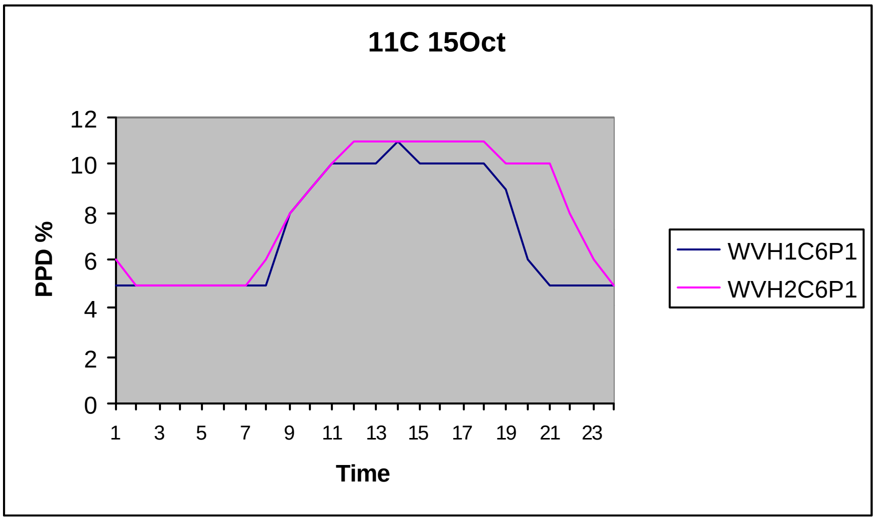
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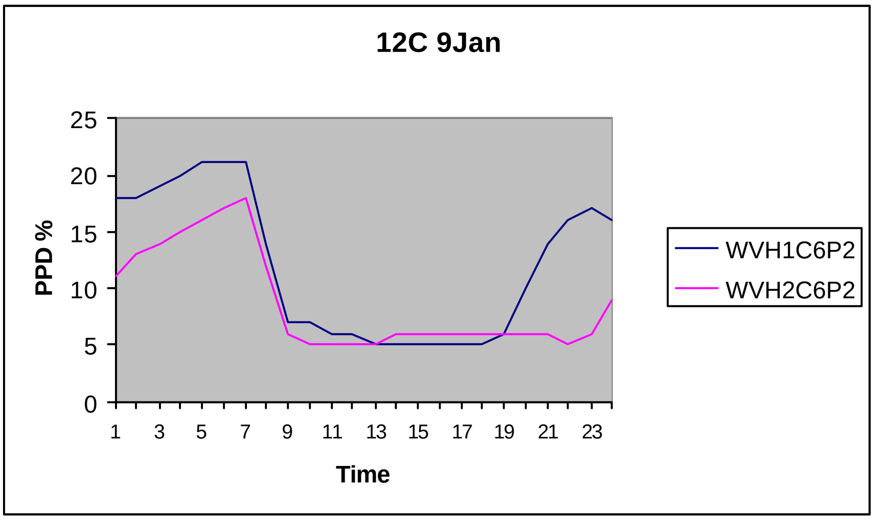
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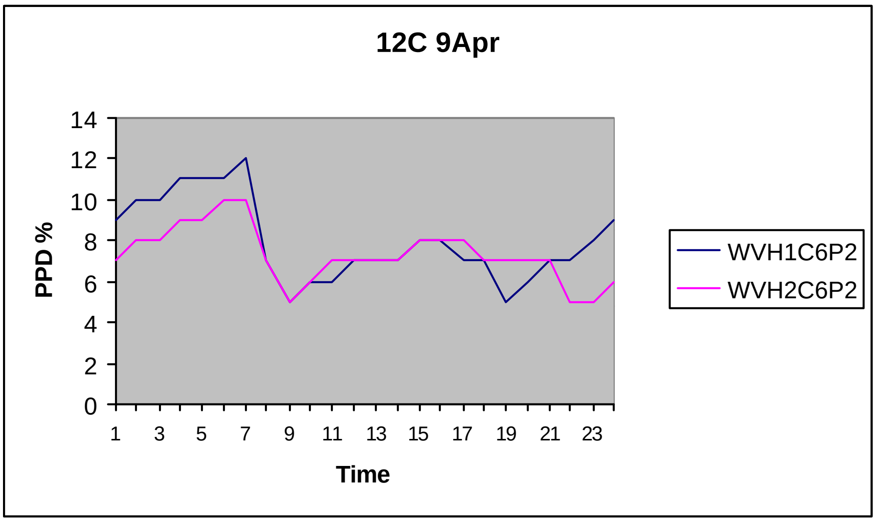
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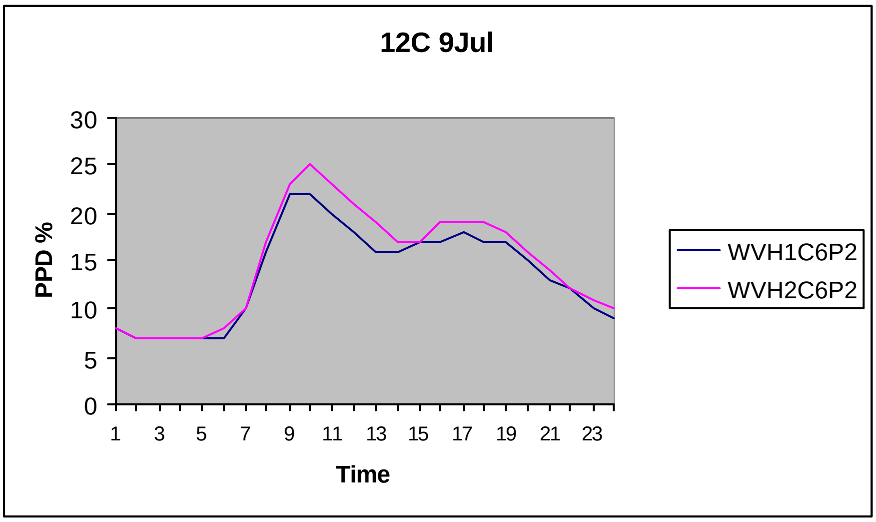
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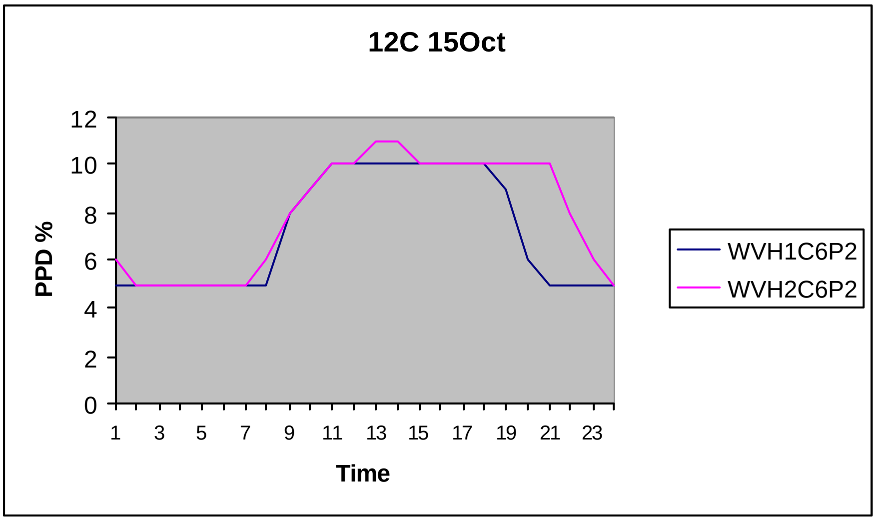
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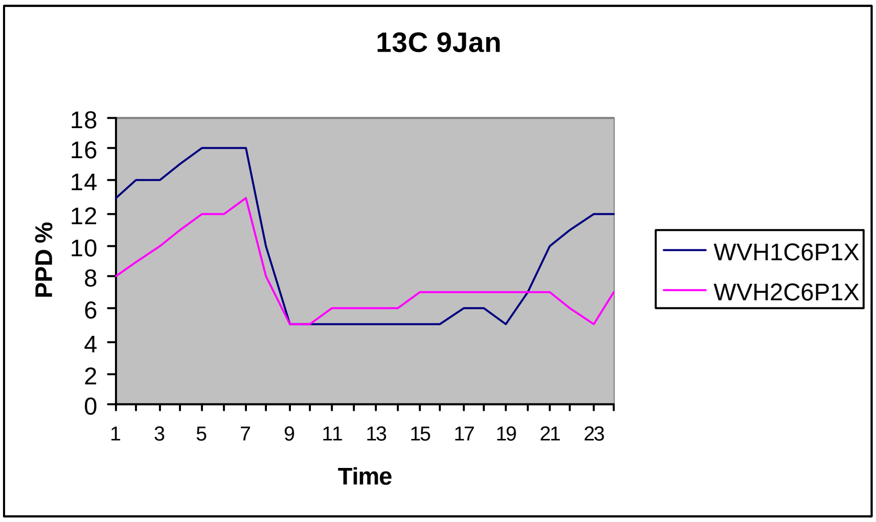
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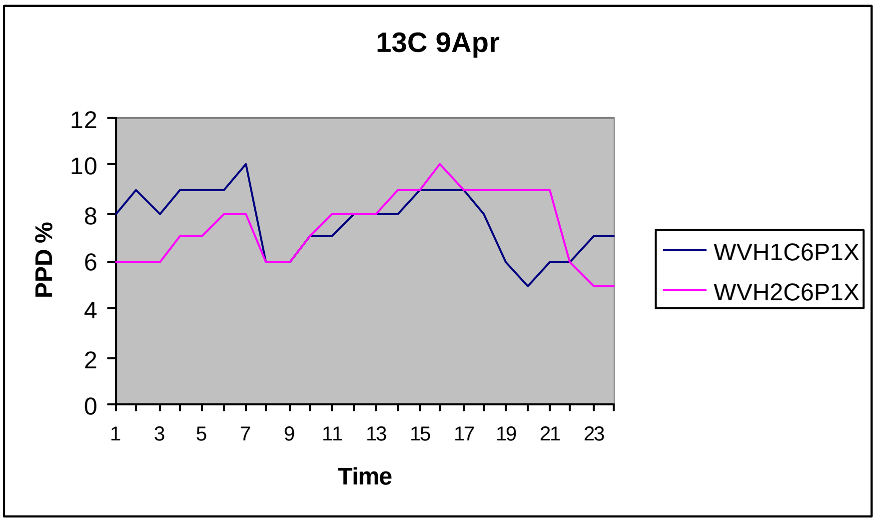
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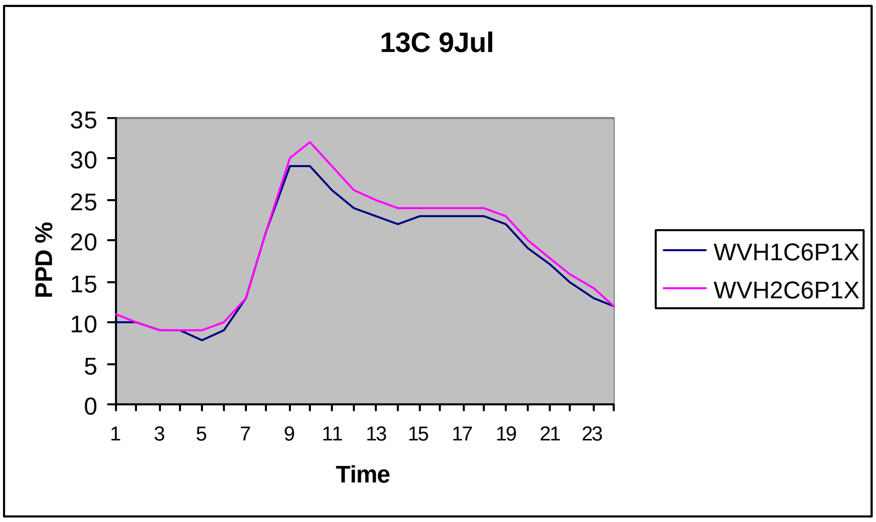
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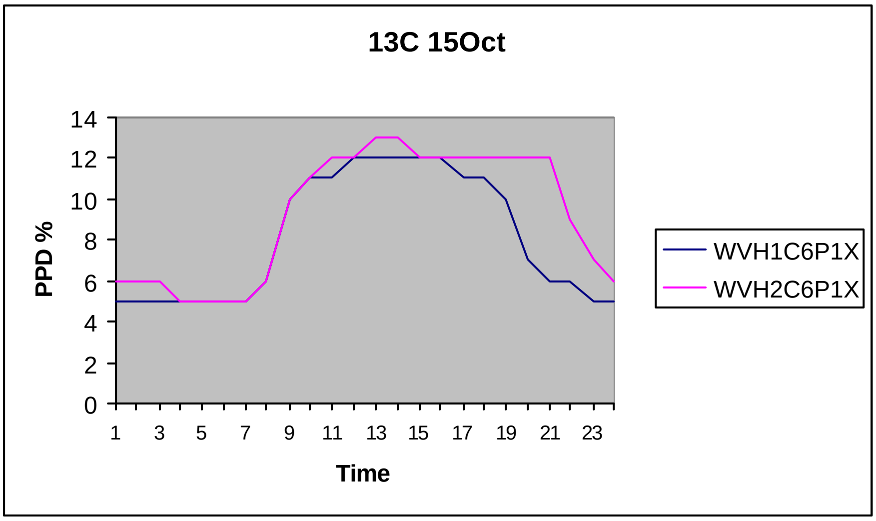
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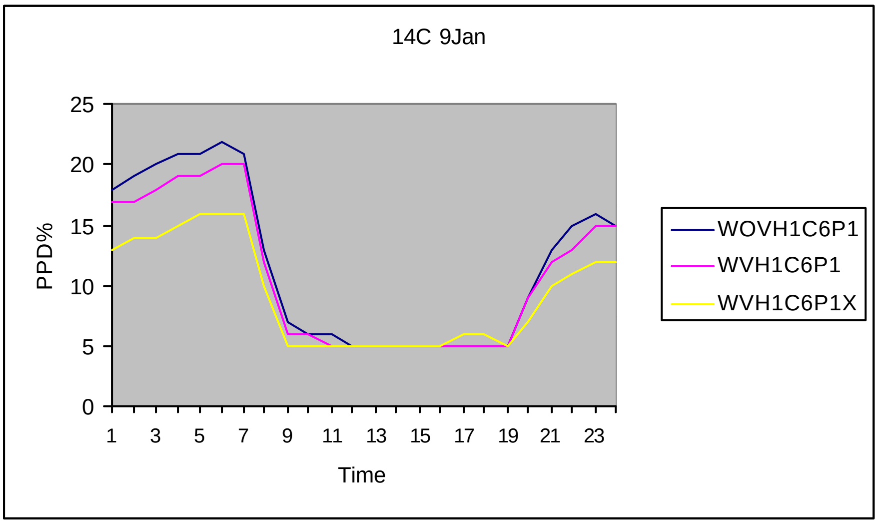
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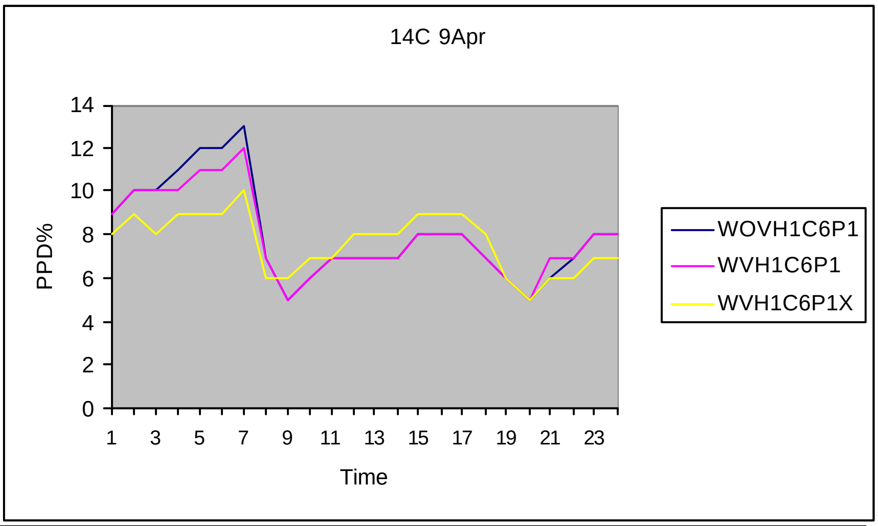
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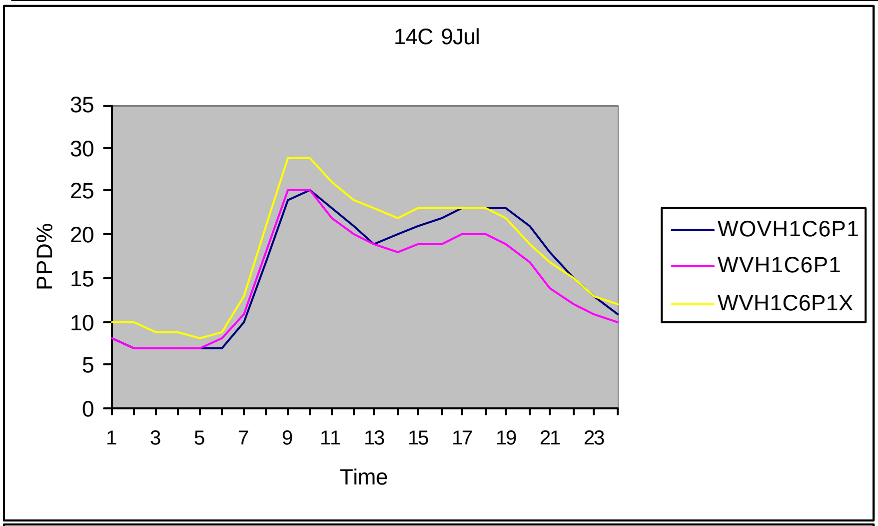
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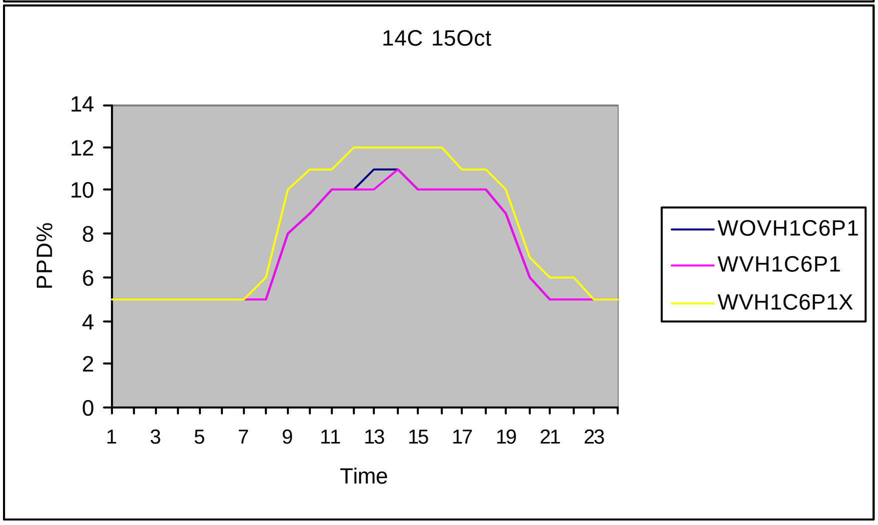
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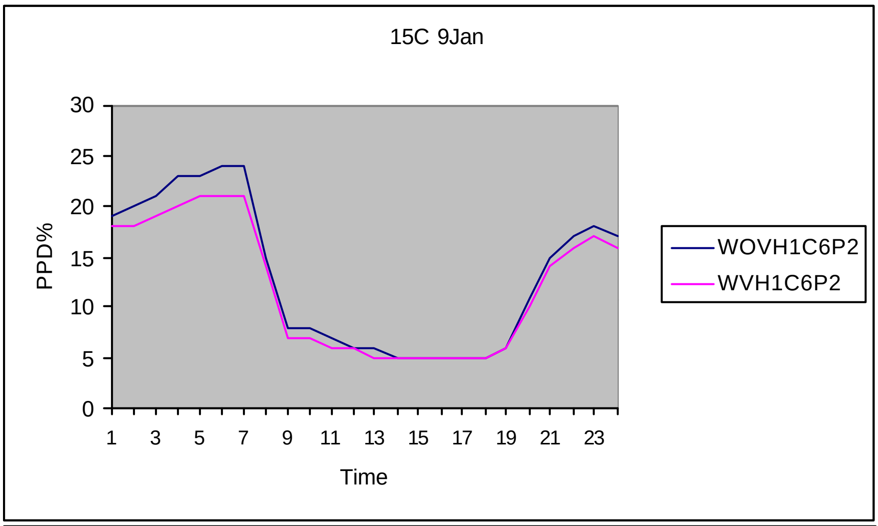
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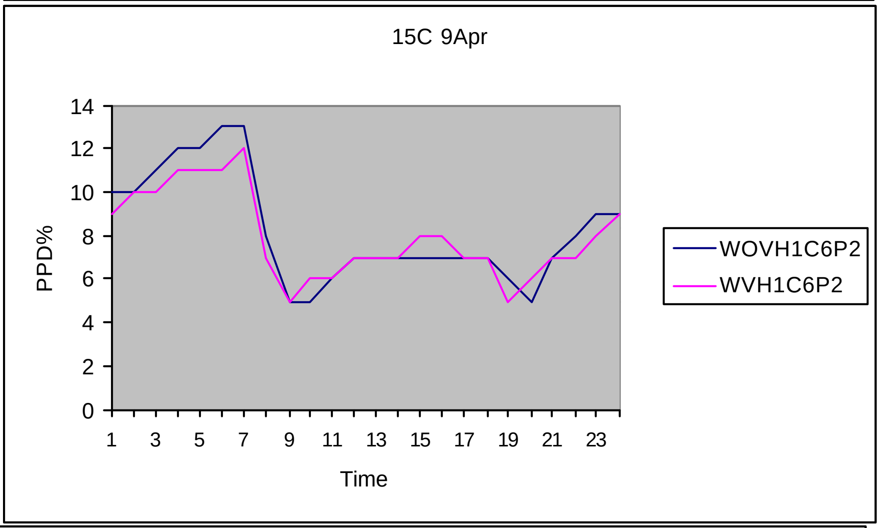
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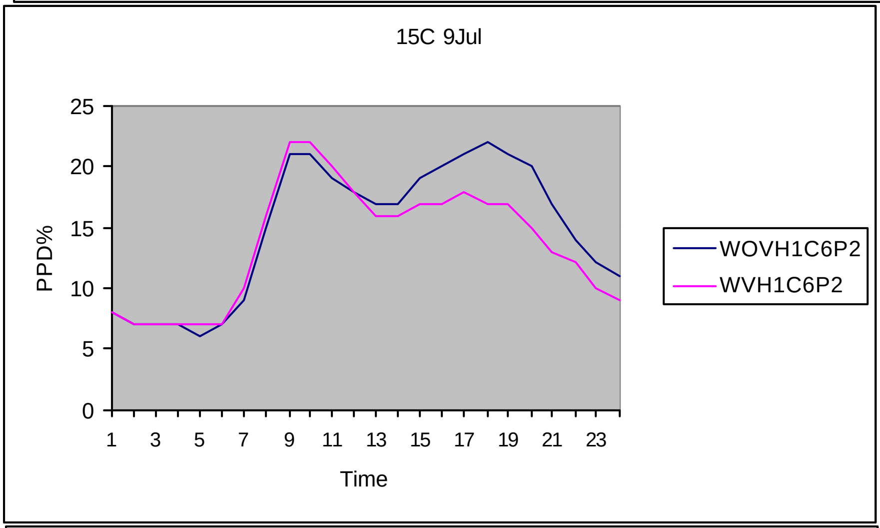
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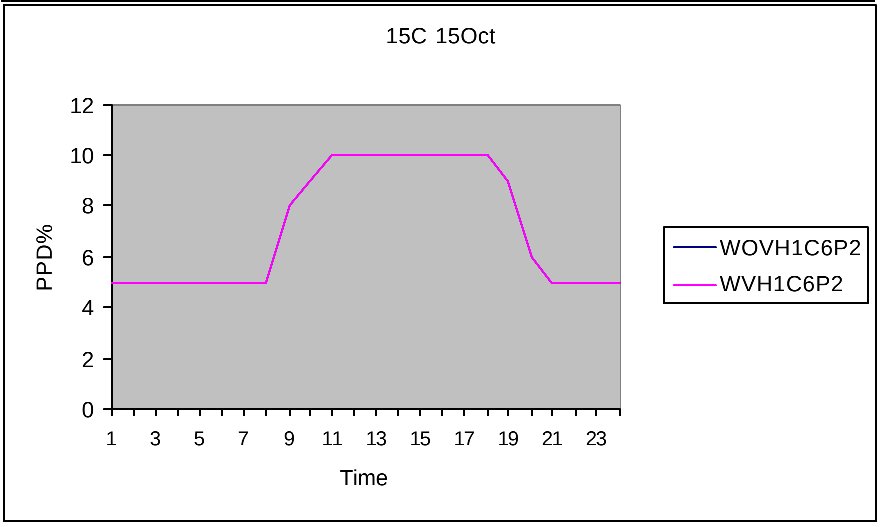
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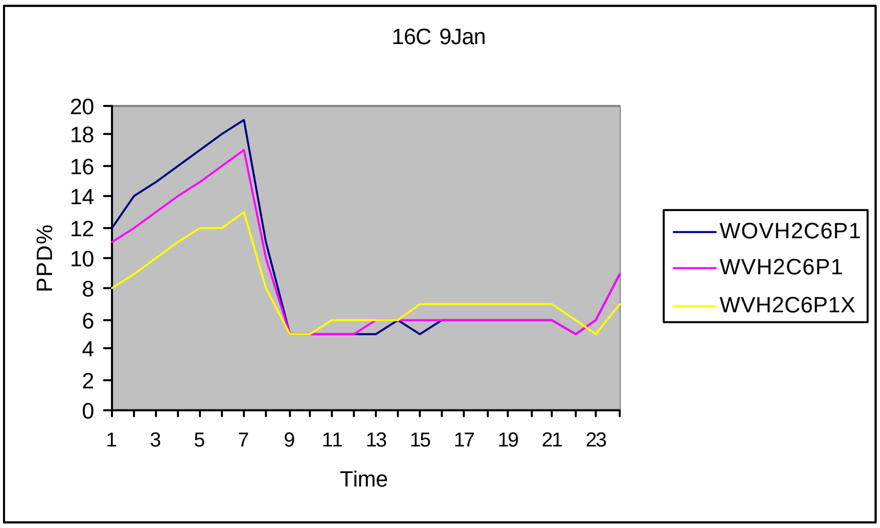
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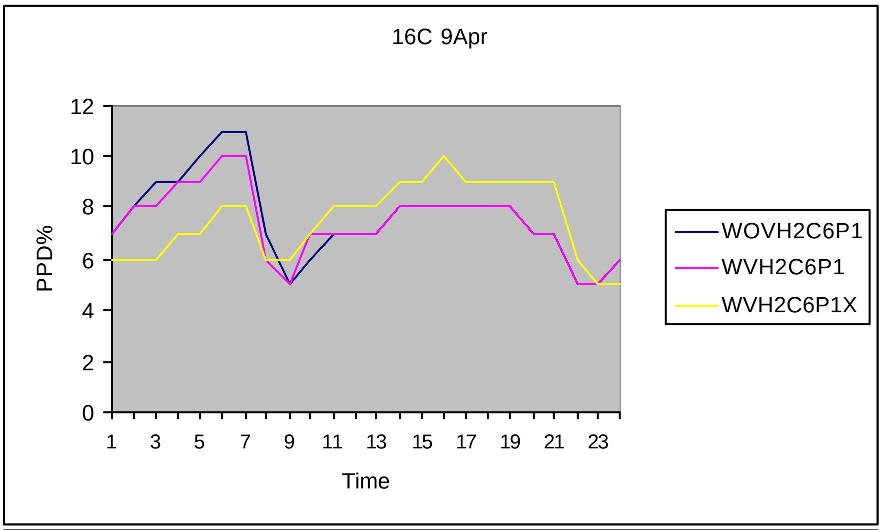
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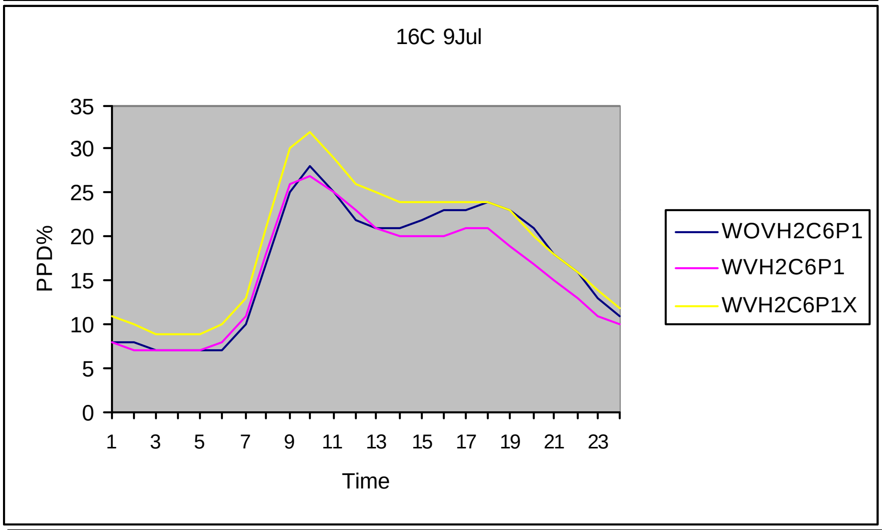
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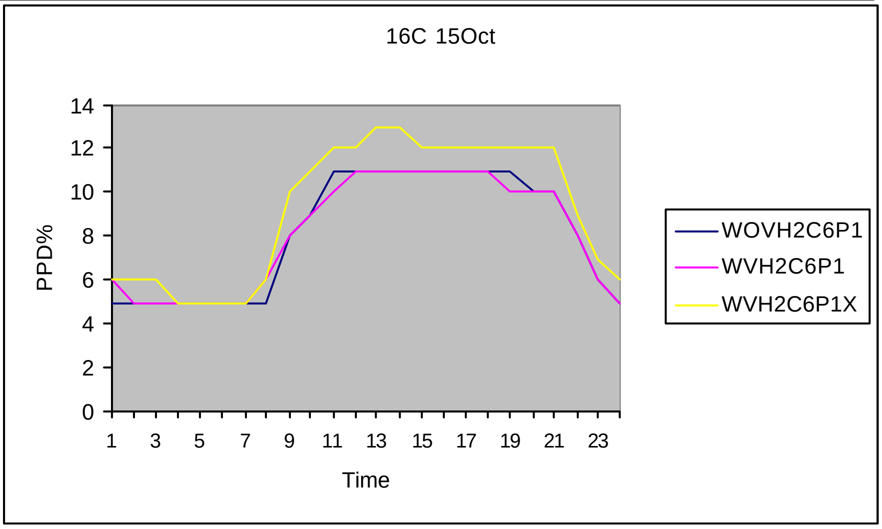
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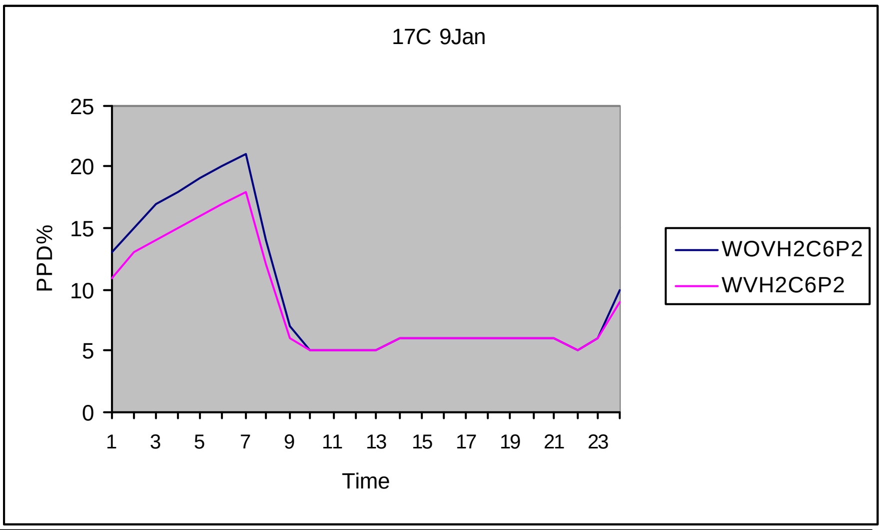
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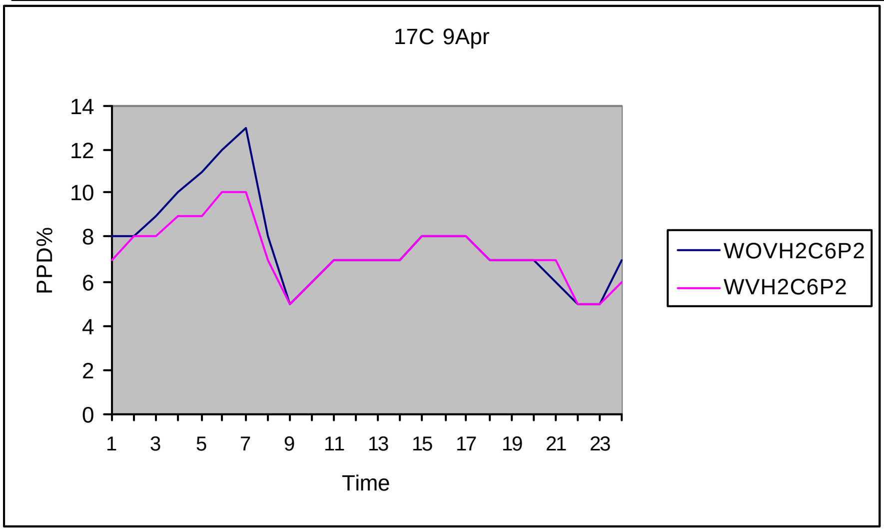
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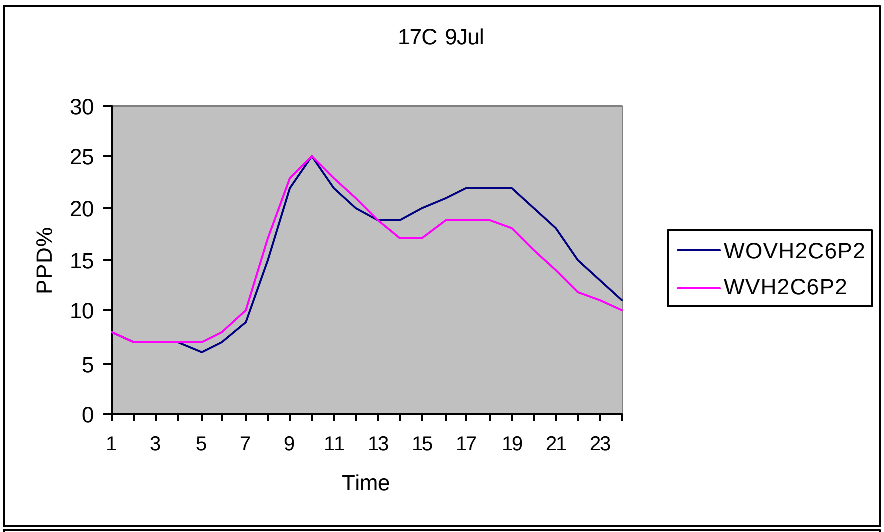
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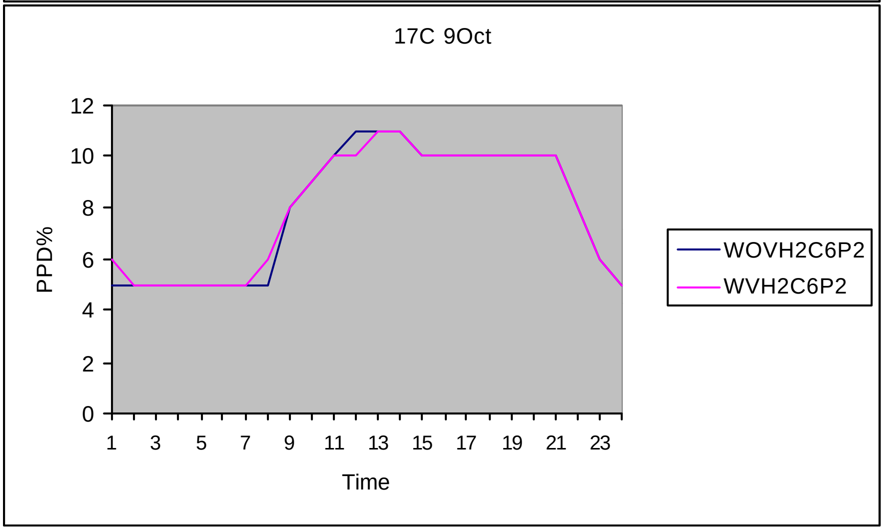
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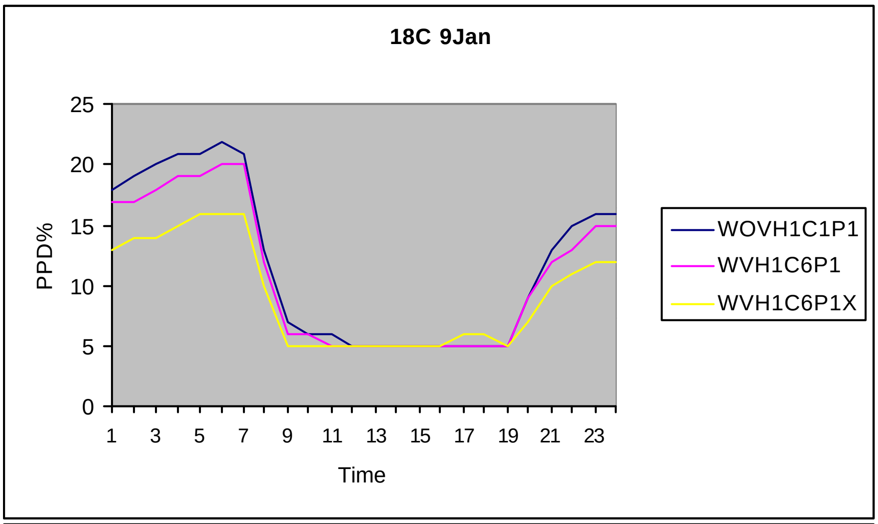
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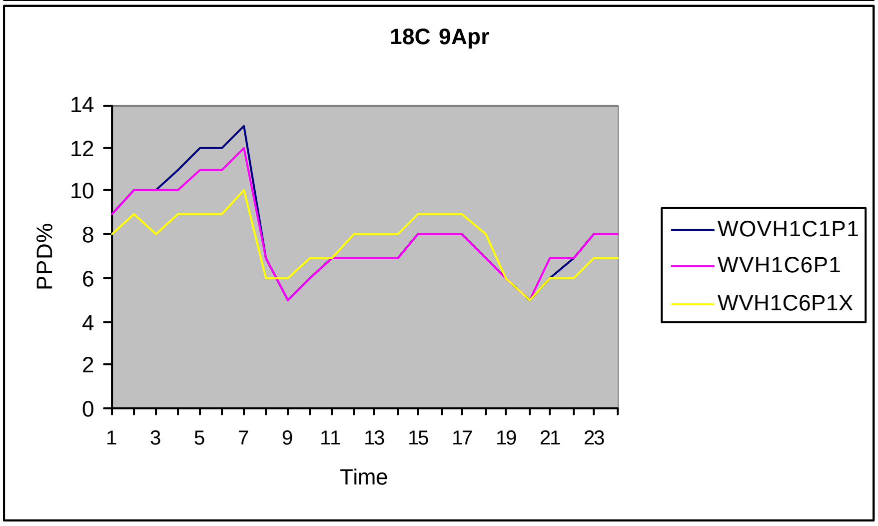
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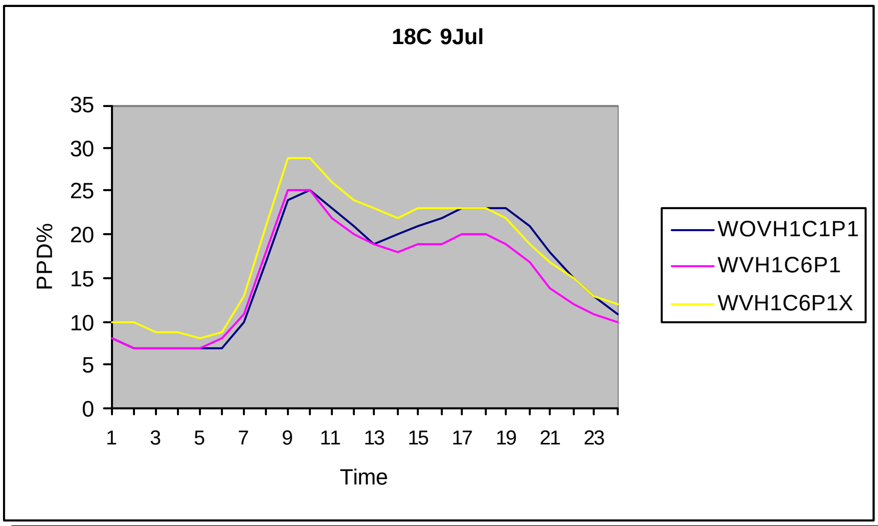
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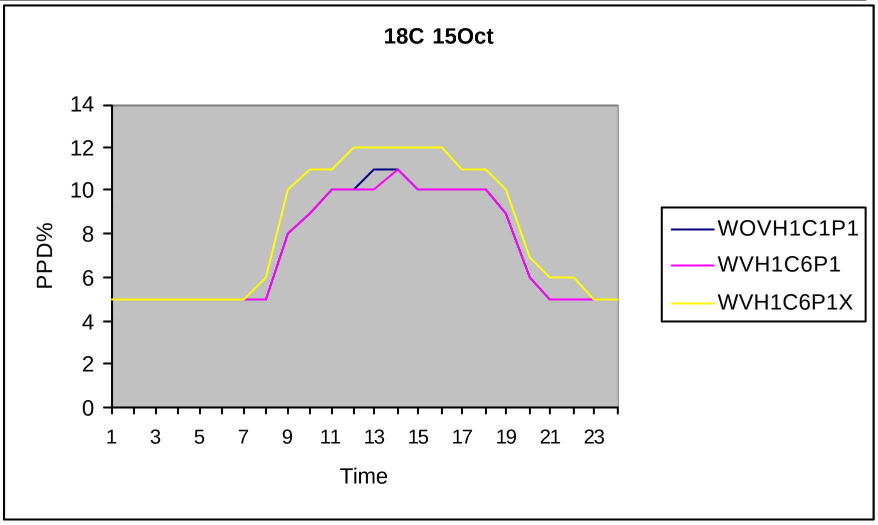
18C 15Oct
PPD%
Time
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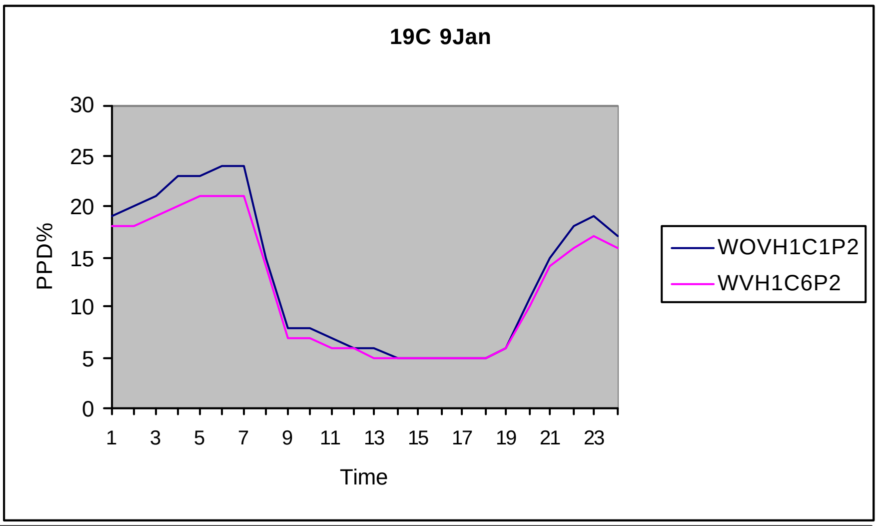
19C 9Jan
PPD%
30
25
20
15
10
5
0
1
3
5
7
9
11
13
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17
19
21
23
Time
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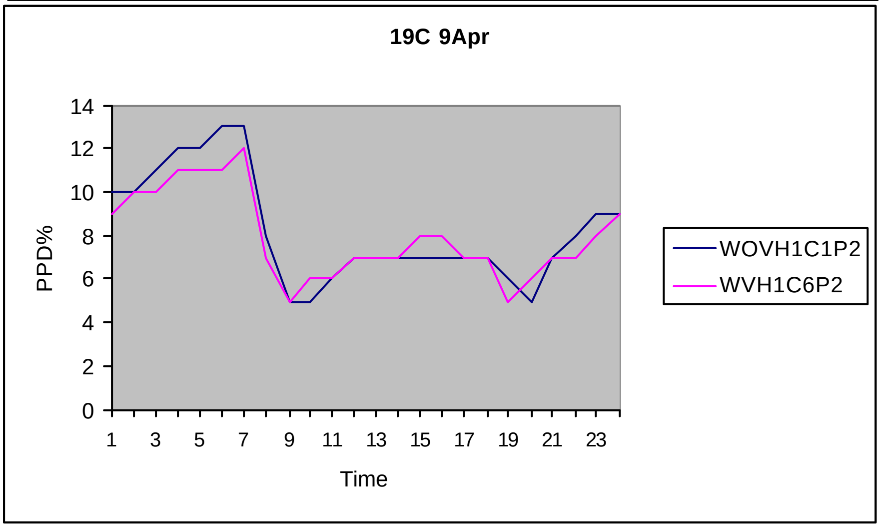
19C 9Apr
PPD%
14
12
10
8
6
4
2
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1
3
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7
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19
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23
Time
WOVH1C1P2
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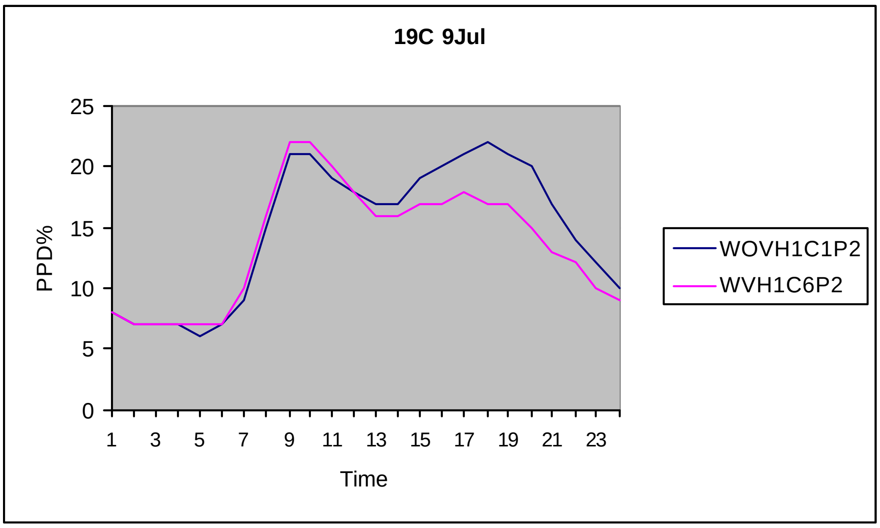
19C 9Jul
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25
20
15
10
5
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1
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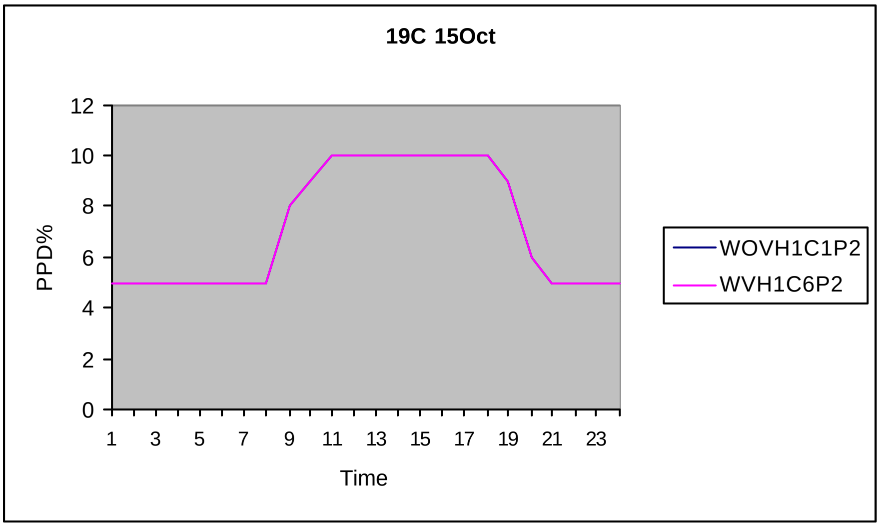
23
Time
WOVH1C1P2
WVH1C6P2


19C 15Oct
PPD%
12
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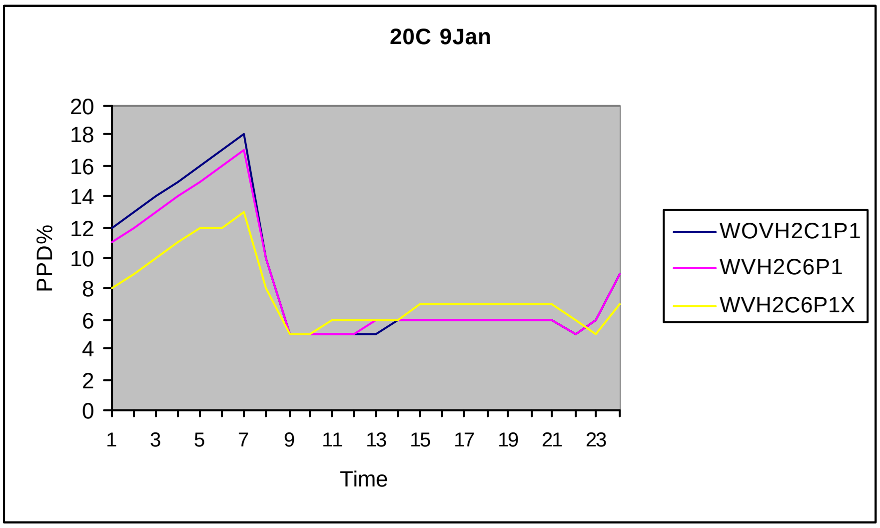
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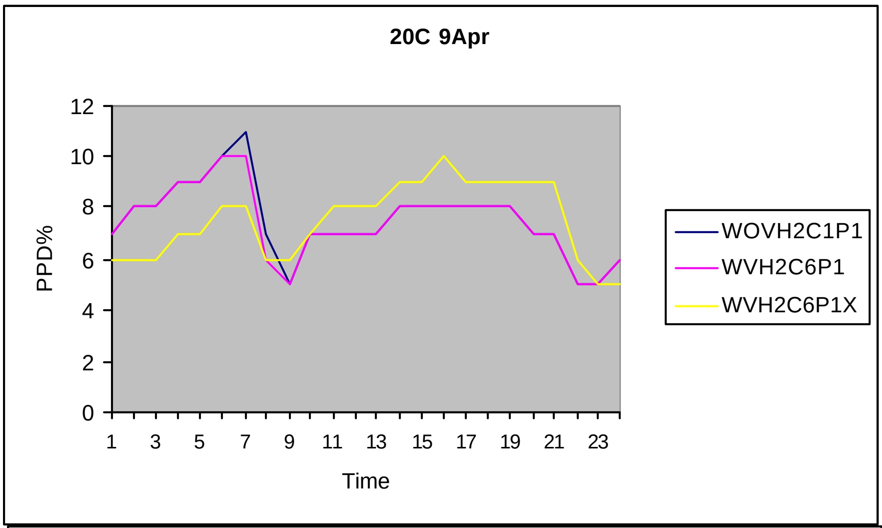
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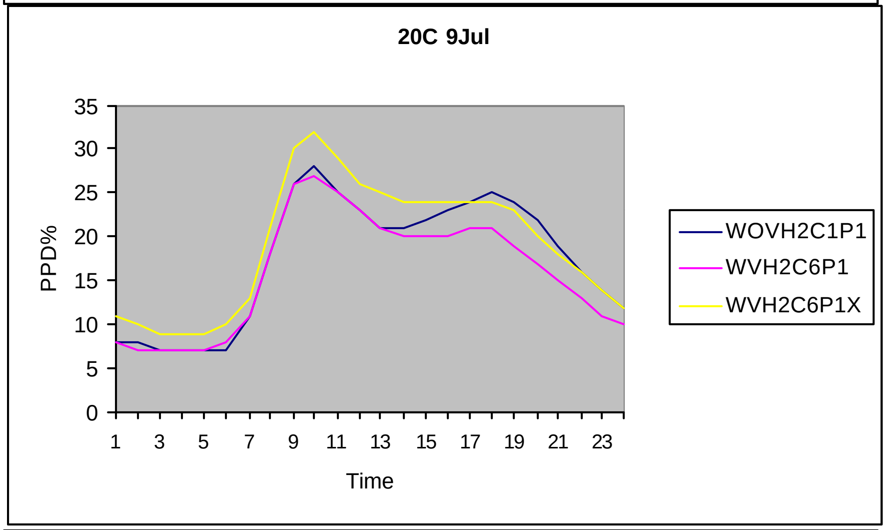
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PPD%
Time
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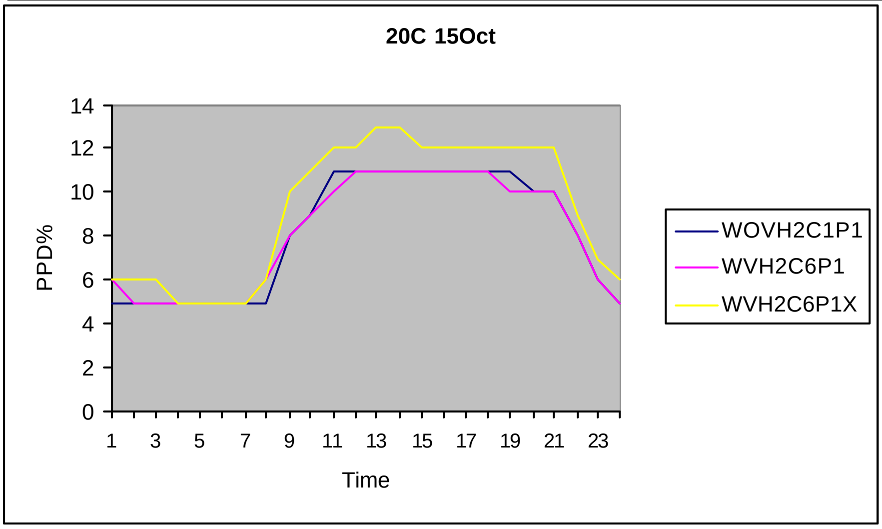
20C 15Oct
PPD%
Time
WOVH2C1P1
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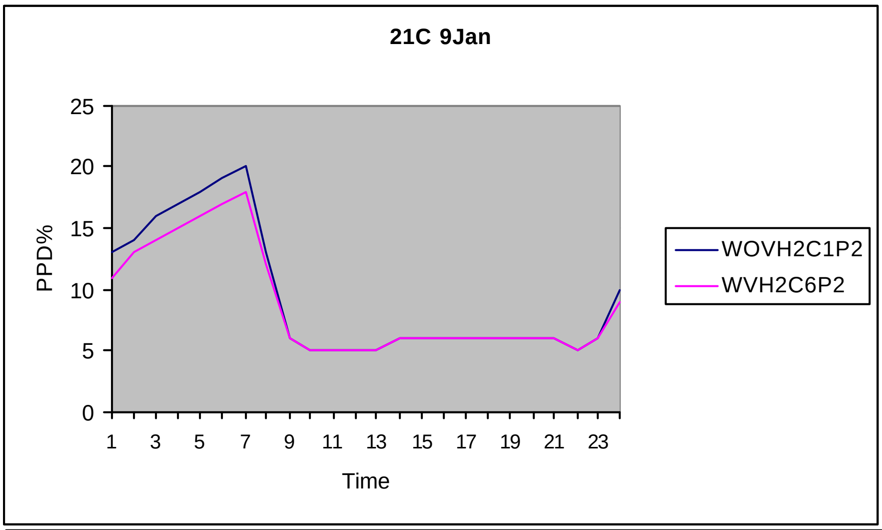
21C 9Jan
PPD%
Time
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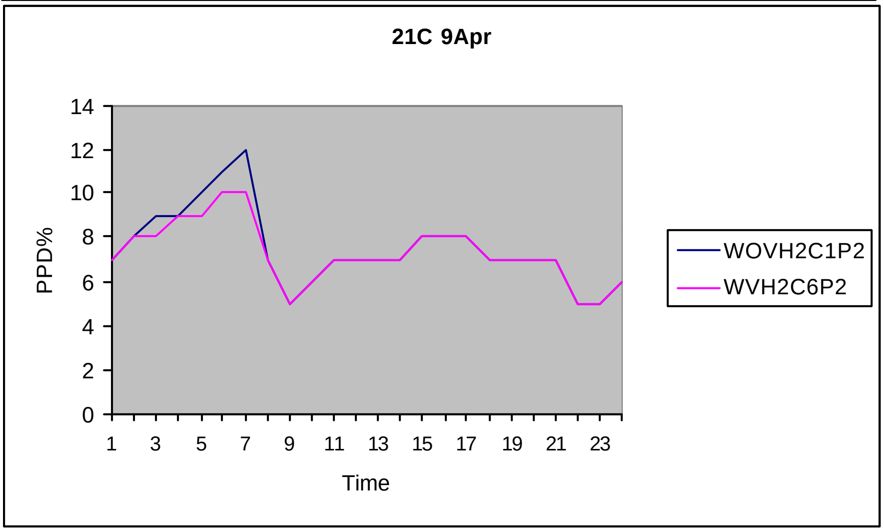
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PPD%
Time
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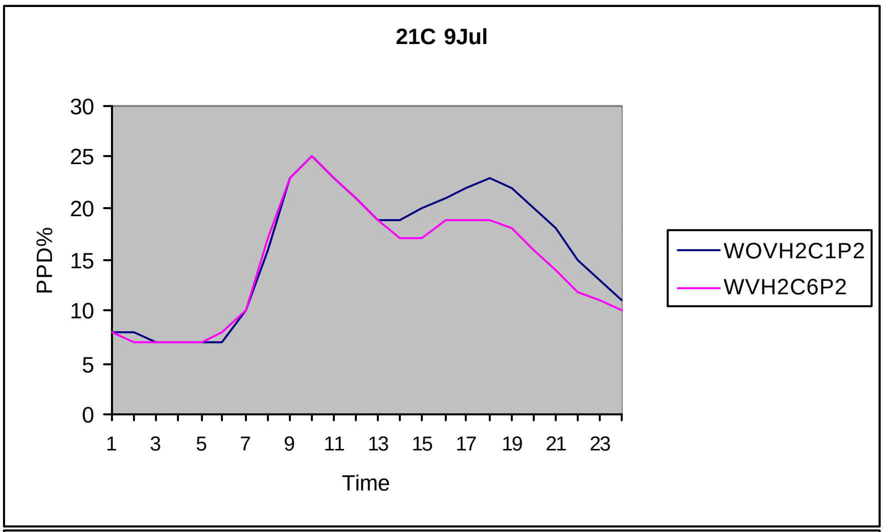
21C 9Jul
PPD%
Time
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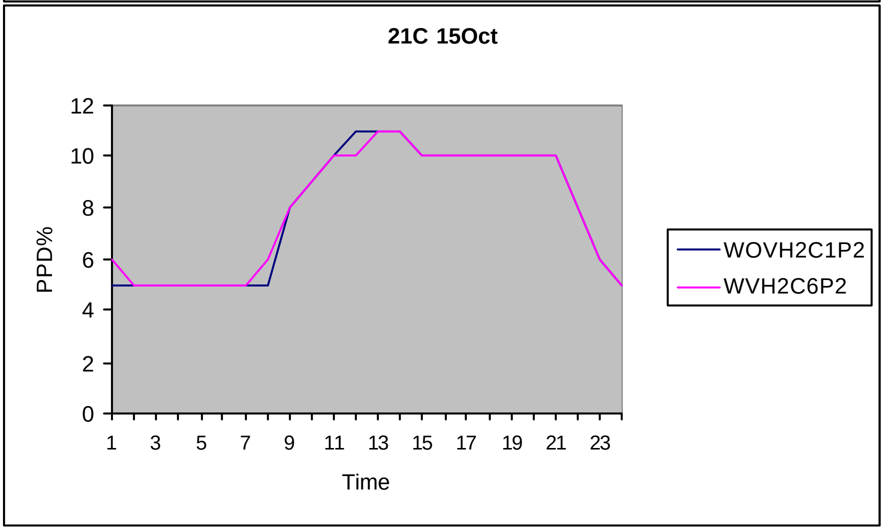
21C 15Oct
PPD%
Time
WOVH2C1P2
WVH2C6P2