A comparison of the thermal performance of roof and ceiling insulation for tropical houses

by

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Contents:

1.0 Summary

Comparisons on the levels of roof insulation for tropical houses in Darwin are made using the dynamic simulation program ESP-r (U. of Strathclyde, ESRU, UK). The purpose is to investigate how the variations in position, location and type of insulation can influence cooling loads (when air conditioning is in use) and the levels of discomfort (when natural ventilation is considered).

A typical house from the Commonwealth Department of Housing (Northern Terriroty) is used for the of simulations. The Masterbedroom ($16m^2$) is used as the base of calculations. The results are given in terms of kWh(A/C operation) and Kh (Free running operation) for one summer month only. Thermostat settings and thermal comfort band are defined. The hourly climate data for the simulations (Darwin73) is used from ACAD. The final results are given for the Master bedroom only. Additional results are also given for the roof.

Permutations varied in terms of location, position and levels of insulation. Reflective insulation (Rfoil) and Resistive insulation (bulk R1.5) are used on top of ceiling and under the roof construction. Solar absorptance levels (0.2 to 0.9) are tested for air conditioning mode and (0.2,0.4,0.6 and 0.8) are tested for free running mode. Ventilated and unventilated attic roof are also analysed. The envelope construction of the house is kept fixed (Hollow concrete block walls, concrete floor and metal deck roof) . Windows are also fixed in 20% of the floor area, facing North and East, fully shaded. Internal heat gains and an air flow network is set the same for the whole period of simulations.

2.0 Methodology adopted in the ABC study

To identify changes in the thermal performance of the A/C and free running master bedroom (MB) when different levels of roof insulation (reflective and resistive) are used the following methodology is followed. Performance measurement parameters are presented and the selected climate data file (Darwin73). The appropriate period for the simulations is described. The base case model is presented along with internal gains, air flow network (ventilation and infiltration rates) and materials and air spaces description. A list of simulated permutations for ceiling/roof, reflective/resistive insulation and ventilated/unventilated attic space are presented.

2.1 Climatic data file: simulation period for summer

The climate data file that is used for this study was provided by ACADS[1], which was selected using the TRY (Test Reference Year method). The TRY consists of a selection of a reference year based solely on temperature data. For Darwin, 1973, is the TRY file. For the purpose of assessment of performance in conditioned and free-running zones (MB), different summer months were assessed and October was chosen as the most critical in terms of DBT(Dry bulb temperature profile). Therfore it is chosen as the month for the simulation period. The simulations are carried out for the whole October month and the last 3 days of September. The results for the first 3 days (for the simulations to reach an equilibrium) are not considered in the simulation results. Appendix 4 demonstrates the climatic input for the October month. The list below gives the climatic parameters considered in ESP-r simulations.

```
# 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)
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[1] Assoc. of Computer Aided Design

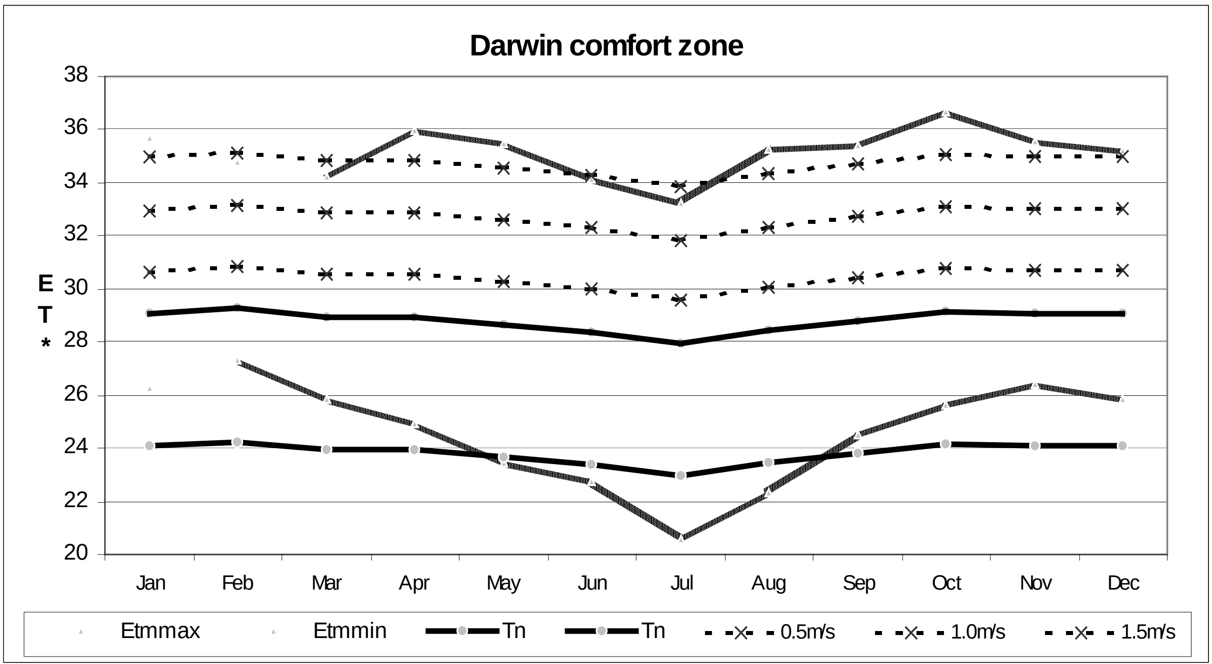


Fig 2.1. Darwin Comfort zone in terms of ET* (De Dear's equation (1997) for free-running buildings) with extensions due to different wind speed values.

During summer the high levels of thermal stress are evident from Figs. 2.1,2.2, and the data described (Appendix 4). At night, when occupants are usually at home, there is a drop in temperature but with high levels of humidity. Breezes tend to increase (3-4.5m/s) in the afternoon until 20:00, which can contribute to heat dissipation by convection. However, during sleeping time (23:00-6:00) breezes are mostly unavailable.

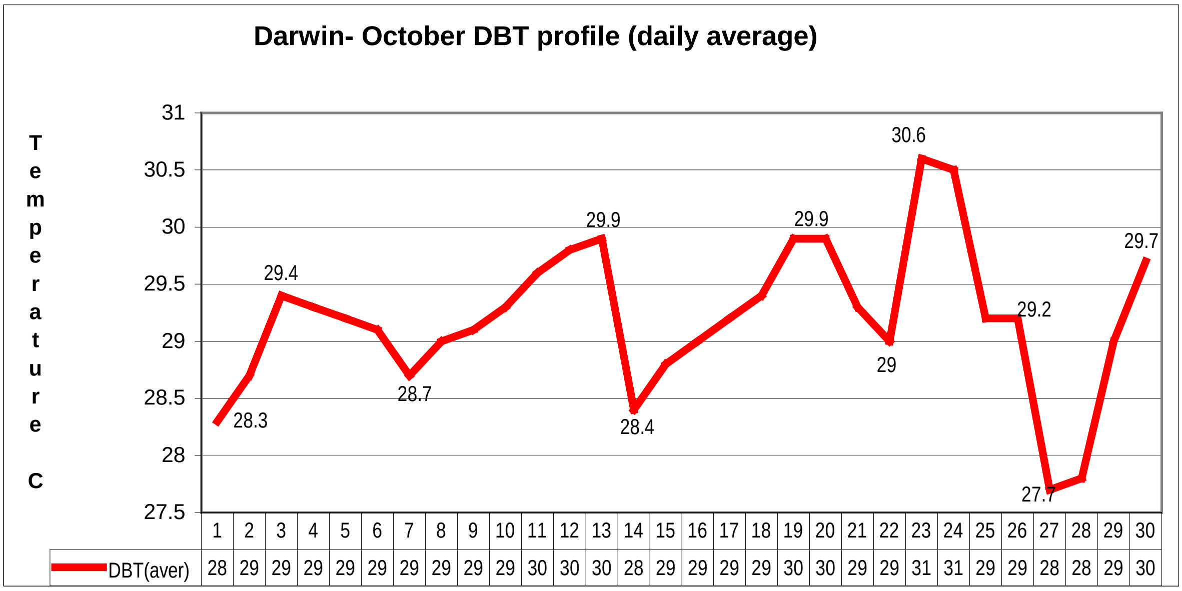


Fig. 2.2. October Dry Bulb temperature profile for Darwin (daily average DBT).

2.2 Quantifying comfort and energy: evaluation parameters

The performance of both conditioned and free-running houses are simulated. The conditioned results are presented as cooling energy requirements to maintain comfort temperatures within the Master bedroom zone, expressed in terms of kWh/month. The free-running results are presented in terms of residual discomfort, and are measured in terms of degree hours of overheating (counted above the comfort limit) (DBT), as set in Auliciems' formula as quoted by Auliciems & Szokolay (1997).

Comfort zone and Thermostat settings for OCTOBER = 24-29°C

2.3 The base case description: model set up

The base case house chosen as a vehicle for simulation is a typical house from the Commonwealth Department of Housing in the Northern Territory. The isometric as modelled in ESP-r is shown in Figure 2.3. For the purpose of this set of simulations (ABCstudy), modifications were made to the original model - masterbedroom (window opening are – 20% floor area, as well as orientation of windows – North/East). The house is a three bedroom 120m^2 house, with North/ South orientation, on ground concrete/tiles floor, with hollow concrete block walls, single glazing and metal deck roof. No insulation is provided. The data in Table 2.1 is a summary description of the base case house.

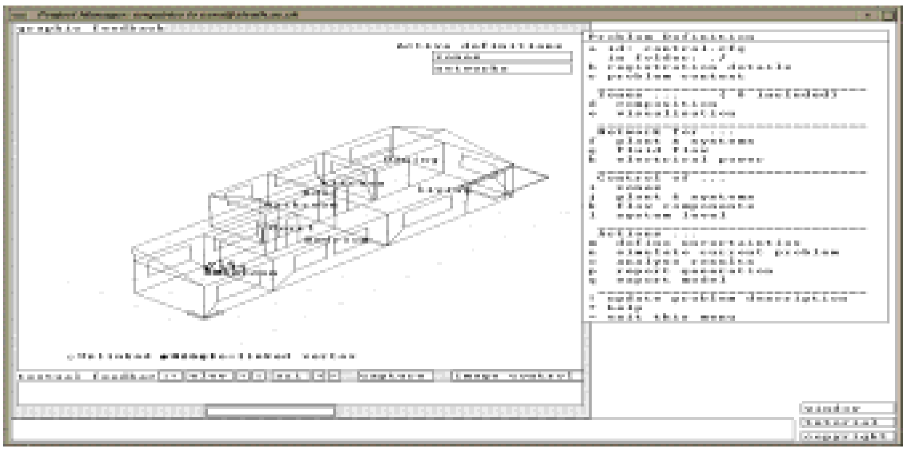


Fig. 2.3 Base case house – Darwin

Table 2.1. Description of base case house.

Roof	Metal deck roof	
Roof cavity	Ventilated as airflow network is on. Node inside attic ceiling.	
Roof pitch	20°	
Ceiling	Plasterboard with no insulation	
Ceiling height	2.4m	
External walls	Hollow concrete block walls	
Floor: Living/bedroom areas	On ground concrete floor with tiles	
Windows	Aluminium window framing + single glazing	
External doors	Hollow core timber	
Internal doors	Framed panels	
Ventilation	Airflow network on. Nodes on all zones.	
Infiltration rate	Cracks on doors and windows of 2mm	
Floor plan	Rectangular, 18m x 6m, excluding stairways	
Floor area	Total	120.5m^2
	Livinzone	28m^2
	Diningzone	13.5m^2
	Masterbedroom(MB)	**16m^2**
	Bedroomzone	21m^2
	Servicezone (bath + kitchen + corridor + veranda)	42m^2
Orientation	North/South	
Window opening area (MB)	North : 2.2m^2 – fully shaded	
(20% floor area)	East: 1.0m^2 – shaded (6:00-8:00am no shading)	
Internal heat gains	2 occupants (24hrs) – 180W sensible/100W latent	
	Equipment: (1 computer & 1 TV) 200W	
	Lights on: 17:00 – 23:00 (6.25W.m2)	

The materials listed in Table 2.2, are used in the construction of the building elements. Code numbers and thermal properties are based on the ESP-r Data model summary: ESP-r Version 9 Series (1998) and some were added for new combination of constructions. Table 2.3, 2.4 and 2.5 give details of material and air space layers, which make up the building elements forming the boundaries of zones. They are constructed from the exterior inwards. Tables 3.5 and 3.6, give the thermal resistance of air spaces, for either normal or low emittance air gaps, according to ASHRAE (1985).

Table 2.2. Conductivity, density, specific heat, emissivity, solar absorptivity of materials used to make up building elements.

Material	**Conductivity**	**Density**	**Specific**	**Emittance**	**Solar absorptance**
	W/m°K	*kg/m³*	*J/kg°K*		
HollowConcrete block	0.64	700	1000	0.90	0.65
Heavy concrete	1.40	2100	653	0.90	0.65
Cement screed	0.41	1200	840	0.90	0.65
Clay tile	0.85	1900	837	0.90	0.60
EPS (Exp. Polysterene)	0.03	25	1000	0.90	0.30
Plasterboard	0.16	950	840	0.91	0.50
Corrugat metal sheet	50	7800	480	0.40	0.20
Weatherboard	0.14	650	2000	0.91	0.65
Hardboard	0.13	900	2000	0.91	0.70

Tables 2.3 and 2.4 give thermal resistance values for air spaces. These values apply for enclosed air spaces, and were found through average on direction of heat flow, up and down, as stated by ASHRAE (1985).

Table 2.3. Resistance of normal emittance air gaps (unventilated) as used in the simulations. (m^2 K/W)

Dir heat flow	**10mm**	**20mm**	**40mm**	**90mm & up**
Horizontal (walls)	0.14	0.15	0.15	0.15
45° Sloped	0.14	0.15	0.15	0.15
Vertical (roofs)	0.14	0.15	0.15	0.16

Table 2.4. Resistance of low emittance air gaps (unventilated) as used in the simulations.

Dir heat flow	**10mm**	**20mm**	**40mm**	**90mm & up**
Horizontal (walls)	0.41	0.57	0.64	0.60
45° Sloped	0.41	0.54	0.64	0.64
Vertical (roofs)	0.39	0.49	0.68	0.96

Table 2.5. The construction of building elements

WALL TYPE	**U-VALUE (W/m^2K)**	**CONSTRUCTION**
Hollow concrete block (HCB)	2.04	Hollow CB (200mm)
Concrete floor with tiles	3.50	Heavy concrete mix (100mm) Cement screed (10mm) Clay tiles (10mm)
Plasterboard ceiling	4.16	Plasterboard ceiling (10mm)
Metal deck roof (no insulation)	5.62	Corrugated metal sheet (1mm)

2.4 Ventilation and Infiltration rates: Airflow network

Depending on the type of construction of a building, the outdoor air enters into interior spaces through its various openings (i.e. windows, doors) or cracks. Fluid flow analysis is an important aspect of building simulation, because knowledge of the results is necessary for the calculation of heating/cooling load as well as for the thermal comfort assessment of a building. Three approaches for fluid flow simulation have been developed: the computational fluid dynamics modelling (CFD); the mass balance/flow network approach (zonal method) and the infiltration rates ach/h input. This study is based on the concept of airflow network.

The zonal method is based on the concept that each zone of a building can be represented by a pressure node. Boundary nodes are also used to represent the environment outside the building. Nodes are interconnected by flow paths, such as cracks, windows or doors to form a network. Pressure at boundary nodes is known and it has to be determined for internal nodes. Flow characteristics of zones, in kg/s, ac/h, between internal and external openings can be provided. For the purpose of this study, an air flow network was set up to run integrated thermal and air flow simulations, according to the data provided by the climatic file (wind speed and direction/pressure coefficients database). No assumptions are therefore made for the levels of ventilation or infiltration, as it can be seen on the infiltration rates method.

In the free running mode, windows are not controlled and therefore opened all day and night. In the conditioned mode, windows are closed when heating or cooling is required. Infiltration by windows or door cracks is considered during the conditioned running mode. Cracks aree set as 2mm. In between the thermostat settings, (24-29 summer) windows are fully opened.

2.5 The insulation and permutations

To reduce the undesirable heat gains through building elements insulation is used. The effectiveness of insulation increases as the difference in temperature between the interior of the building and the outdoors increases. Thermal insulation will control the heat flow through the three types of insulation: resistive, reflective and capacitive. In this study it was required the comparisons of reflective and resistive insulation for the Master bedroom only. The two locations considered were on top of ceiling and underneath the corrugated metal sheet roof.

The following parameters were considered:

- No insulation.
- R1.5 EPS (Expanded polystyrene. 45mm) only
- R1.5 EPS + Reflective Foil (Rfoil)
- Unventilated attic roof space
- Ventilated attic roof space
- Location: top of ceiling & underneath roof
- All the above permutations for α0.2 to 0.9 (air conditioned mode) and α0.2, 0.4, 0.6 and 0.8 (free running operation).

The following combinations are described in the final results and are permuations of the parameters above (both simulated for free running and conditioned operation):

1) Basecase
2) Basecase*
3) Ceiling EPS only
4) Ceiling EPS only*
5) Ceiling EPS + Rfoil
6) Ceiling EPS + Rfoil*
7) Ceiling EPS + Roof Rfoil
8) Ceiling EPS + Roof Rfoil*
9) Roof EPS only
10) Roof EPS only*
11) Roof EPS + Rfoil
12) Roof EPS + Rfoil*
13) Roof Rfoil only
14) Roof Rfoil only*
15) Roof EPS + Ceiling Rfoil
16) Roof EPS + Ceiling Rfoil*
17) Ceiling Rfoil only
18) Ceiling Rfoil only*

A total of 144 simulation runs (air conditioned mode) and 72 simulation runs (free running operation) are demonstrated in the final results.

unventilated attic roof space

3.0 Thermal modelling using ESP-r program

Esp-r has been developed by the Energy Systems Research Unit (ESRU), at the University of Strathclyde, Glasgow, UK. It is a dynamic energy simulation system, which is capable of modeling the energy and fluid flows within combined building and plant systems when constrained to conform to some distributed control action. The package comprises a number of interrelating program modules addressing project management, simulation, results recovery and display, database management and report writing.

In terms of research potential, ESP-r can be characterized by:

- It is a research oriented environment, with the objective to simulate the real world as rigorously as possible to a level which is dictated by international research efforts/ results.

- It sets out to take fully into account all building & plant energy flows and their interconnections. It also offers the possibility to assess building & plant performance in terms of thermal comfort. Thus it is specifically suited to do research on subjects in which interweaving of energy and mass flows plays an important role, as in warm-humid climatic conditions. However, in terms of direct thermal comfort analysis, it provides access only to constancy models (Fanger 1970) and the 2-node model (Gagge 1970).

- The system is now in use by various research groups worldwide.

- The system has been, and still is, the subject of various international validation programs (see e.g. SERC 1988).

- The system offers extensive graphics facilities.

The development of the system dates back to the 1970's (Clarke 1985) at the UK. Since than, it has been refined, reorganized and validated against various simulation tools in Europe and USA. Esp-r requires a UNIX workstation offering X-Windows and with at least 8 Mbytes RAM. Implementation exists for SUN and Silicon Graphics platforms and more recently for PC Linux systems.

A building's indoor environment is determined by a number of forces acting via various energy and mass transfer paths. The main sources may be identified as:

- Outdoor climate which, in the present context, the main variables are: air temperature, radiant temperature, humidity, solar radiation, wind speed, and wind direction.

- Occupants who cause casual heat gains by their metabolism, usage of various household or office appliances, lighting, etc.

- Auxiliary system, which may perform heating, cooling, and/ or ventilating duties.

These sources act upon the indoor climate via various energy and mass transfer processes:

- Conduction through the building envelope and partition walls

- Radiation in the form of solar transmission through transparent parts of the building envelope, and in the form of long wave radiation exchange between surfaces

- Convection causing heat exchange between surfaces and the air, and for instance heat exchange inside plant components

- Air flow through the building envelope, inside the building, and within the heating, cooling and/ or ventilating system

- Flow of fluids encapsulated within the plant system

The indoor climate may be controlled by the occupants basically via two mechanisms:

- Altering the building envelope or inner partitions by for example opening doors, windows, or vents, or by closing curtains, lowering blinds, etc.

- Scheduling or adjusting the set point of some controller device which may act upon the auxiliary system or upon the building by automating tasks exemplified above.

The cycle periods of the excitations acting upon the systems are also highly diverse. They range from something in the order of seconds for the plant, via say minutes in case of the occupants, to hours, days and years for the outdoor climate. From the above it will be apparent that we are indeed addressing a very complicated dynamic system.

3.1 Theoretical basis of ESP-r

Esp-r considers a building and its plant as a collection of small finite volumes - perhaps numbering 5-10K for a medium-sized building and HVAC system. These finite volumes represent the various regions of the building and plant within and between which energy and mass can flow. Throughout a simulation, these energy and mass flows are tracked as they evolve under the influence of the climatic boundary conditions and the constraints imposed by any control action and by the potentially time-dependent inter-volume links. The technique ensures that all regions of the building are correctly connected across space and time so that any excitation will have the correct causal effect. For each finite volume and at each computational time-step, a conservation equation is generated and fed to a central numerical solver where the equations are integrated simultaneously. The coefficients of these equations are developed as a function of the various heat transfers associated with short-wave and long-wave radiation, surface convection, casual gains, leakage behavior and so on.

- *Climatic file*: ESP-r requires dry bulb temperature (°C), direct normal (or alternatively global horizontal) solar irradiance (W/m^2), diffuse horizontal solar irradiance (W/m^2) wind speed (m/s) wind direction (clockwise from North) and relative humidity (%). These data are required on an hourly basis.

- *External Surface Convection*: convection coefficients at external surfaces are computed as a function of the prevailing wind speed and direction. This is achieved by resolving the free stream wind component onto the plane of each external surface. The local wind speed is then used as the input to an exposure dependent correlation. ESP-r also offers a facility whereby user-specified values for any surface (s) and time can be imposed on a simulation.

- *External Surface Long wave Radiatio*n: At each time step, ESP invokes an algorithm to determine, for each external surface, the equivalent ambient temperature to which the surface will communicate long wave flux. This equivalent temperature has three components – for the sky, ground and surroundings – with the proportion of each depending on the site exposure.

Evaluation of the sky component involves estimation of the cloud condition from the prevailing direct and diffuse irradiance. During the night hours, the cloud cover level is held constant. Ground temperatures are found by surface energy balance and the temperature of a surrounding building surface is assumed to be the same as the corresponding surface of the target buildings.

The final flux exchange is therefore a function of: direct and diffuse solar irradiance (W/m^2), dry and wet bulb air temperatures (°C), surface, ground and sky emissivities, scene view factors, and the monthly variation in ground temperature.

- *Short-wave radiation:* ESP-r employs an anisotropic model by Klycher (1979) to determine the sky diffuse radiation on an inclined surface, and an isotropic model to represent the short-wave reflection from the ground and surroundings. The direct beam is determined by straightforward trigonometric manipulation. The shading of the direct beam by surrounding and/or facade obstruction is determined by projecting these obstructions onto the facades of the target building.

Alternatively it is possible to utilize user-specified fixed or time varying shading schemes.

The apportionment to internal surfaces of the direct and diffuse flux after window transmission is determined by projecting each window onto the internal surfaces as a function of the prevailing angle of incidence. The technique employed is to project a finite element representation of each window onto the plane of the surfaces, which comprise the zone. Alternatively, as with the shading time-series, it is possible to impose some user-specified internal surface insolation scheme on a simulation.

ESP-r offers two ways to model the short-wave response of window systems. In the first, the window is modeled as a zero capacity entity with no finite volumes (and therefore nodes) used in this representation. This means that the conductive flux, including the inward transmitted component of the absorbed short-wave flux, is applied at the corresponding zone air node, with the transmitted short-wave flux applied at internal surfaces. This treatment, while of acceptable accuracy when used to model traditional buildings, was often inadequate in the case of passive solar buildings with high glazed areas and asymmetric heating. A second more accurate approach is therefore offered by ESP-r: now windows are treated as transparent multi-layered construction so that the transient conduction and the element short-wave response and surface convective and long-wave exchanges, are modeled in detail.

In the former case ESP-r requires the direct and total (direct + inward retransmitted absorbed) transmission curves to determine the direct and diffuse short-wave transmission both radiatively and convectively. In the latter case the absorption curve of the individual elements is required in addition to the direct transmission curve. Typically these data are available from manufacturer's catalogues. If not, ESP-r offers spectral analysis so that these data can be calculated for any glazing system incorporating thin film technology. In any event these transmission data are specified to ESP as discrete data values corresponding to angles of incidence of 0, 40, 55, 70 and 80. Linear interpolation is then used to determine the values appropriate for the incidence angles prevailing at simulation time.

The short-wave flux passing the window plane is now processed through an internal distribution algorithm, which includes the effects of re-transmission through to another zone or back to the outside. The transmitted diffuse irradiance is applied to each internal surface except the window wall. The transmitted direct beam is applied to those surface(s) indicated by the window projection or by the user-specified instruction. Both the direct and diffuse flux transmissions are tracked to their first reflection. All reflected flux is then accumulated and subsequently apportioned to all zone surfaces, including windows, on an area-weighted basis with a bias against the window wall. Any diffuse flux incident on a zone window at its inner side is then processed using the window short-wave response data.

- *Conduction*: In ESP-r conduction within solid regions such as multi-layered constructions (opaque and transparent) and zone contents is a function of the region's thermo physical properties: conductivity (W/m K), density (kg/m^3) specific heat (J/kgK) dimensions (m), and any internal excitations associated with short-wave absorptions, internal heat generation from plant, cavity ventilation and long-wave exchange and the like. While all conductive flow-paths are essentially one-dimensional, it is possible to model two- and three-dimensional effects by representing a construction as a number of small volumes, thick-walled contiguous zones.

Ground slabs are treated in the same manner as other multi-layered constructions but, in addition, require the specification of annual ground temperature profiles. ESP offers a number of geographically typical profiles or will accept user-defined data. Thermal bridges and other small (but thermally significant) entities such as window frames can also be modeled as distinct multi-layered constructions or, alternatively, they can be lumped together and treated as resistance only areas.

- *Internal Surface Convection*: The time varying convection coefficients at internal surfaces are computed from data correlations which express the convection coefficient as a function of: surface temperature (°C) adjacent air temperature (°C), surface aspect, direction of heat flow, and surface characteristic dimension (m). In addition ESP-r offers the possibility to substitute user-specified values for any surface(s) at any time within a simulation.

- *Air flow processes*: ESP-r allows a traditional approach to the modeling of airflow by accepting prescribed (and possibly time dependent) air change rate information to represent zone infiltration and zone-coupled airflow. Alternatively, it is possible to specify a leakage network to represent the distributed air flow paths.

This is done in terms of characteristic equations, which represent the volume flow rates as a function of pressure difference and opening characteristics. The network can be time dependent to allow the modeling of occupant interaction and mass can be taken at any node. Within the ESP-r system a pressure coefficients database exists to store sets of representative pressure coefficients, which can be associated with network nodes to generate surface pressure as a function of the prevailing wind speed and direction. Airflow simulations can be performed via ESPair (pressure and fixed buoyancy driven flows) or ESPsim (pressure and variable buoyancy driven flows with combined heat transfer). The mass balance solution algorithm employs a Newton-Raphson iterative technique with a number of convergence devices imposed.

Stratification is handled by introducing more than one vertical zone and defining the flow connections between these zones and adjacent internal or external spaces. The inter-volume surfaces are fictitious, allowing the transmission of short-wave radiation.

- *Internal surface Long-wave radiation*: This heat flow mechanism depends on: surface temperature (°C), surface emissivity and the inter-surface view factors. Within ESPsim linearised radiation coefficients are employed to evaluate the longwave flux exchanges. These, in turn, are based on inter-surface view factors established prior to the simulation. These coefficients are then inserted in the system energy balance matrix equation to influence the overall simultaneous solution. If the zone geometry is precisely known then the view factors can be calculated by ESPvwf.

For a zone of arbitrary complexity, ESPvwf uses finite elements, ray tracing technique to determine the angular relationship between surface pairings. If no view factors are passed to Espsim, then a simple area weighting technique is employed to estimate the view factors.

- *Casual gains*: These gains, from people, lights and equipment are represented as profiles of time varying power with associated convective/radiant splits. The convective part is applied directly to the corresponding zone air and the radiant part is apportioned to the zone surfaces on an area-weighted basis. All casual gains are identified by source so that it is possible to schedule each gain type independently on the basis of time, temperature or illuminance.

- *Thermal comfort*: ESP-r has a comfort assessment capability, which is based on occupant activity and clothing levels. Three comfort indices are evaluated on a time-step basis: SET – Standard Effective Temperature, Predicted Mean Vote and Predicted Percentage Dissatisfied.

- *Plant*: Using ESP-r it is possible to simulate the thermodynamic processes found within plant systems. In the approach plant components are represented by state-space equations, which represent the energy and (up to two-phase) mass flows within and between each plant component.

Another approach to plant modeling, which does not entail the explicit description and simulation of the plant network, is also available within ESP-r. in the approach the building is subjected to a number of control loops which not only have knowledge of the desired environmental conditions but can emulate the plant operational characteristics in terms of factors such as flux availability, point of application, and convective/radiant split.

- *Control*: A generalized control facility is offered in which a number of control loops can be established and imposed on the building and/or plant systems. These loops then act at each simulation time-step to influence matrix equation construction and solution. Each control loop comprises a sensor, an actuator and time-dependent control laws.

A sensor is defined in terms of its location, the condition it senses (temperature, enthalpy, flowrate, etc,) and its characteristics (dead-band for example). An actuator is similarly defined and exists to set any nodal variable as a function of the output from a control law. Note that in ESP it is possible to actuate quantities like flux and temperature as well as the more usual ones such as valve position. The control laws define the mapping from the sensed condition to the actuated state. A number of standard laws are offered and specials can be developed and entered by a user.

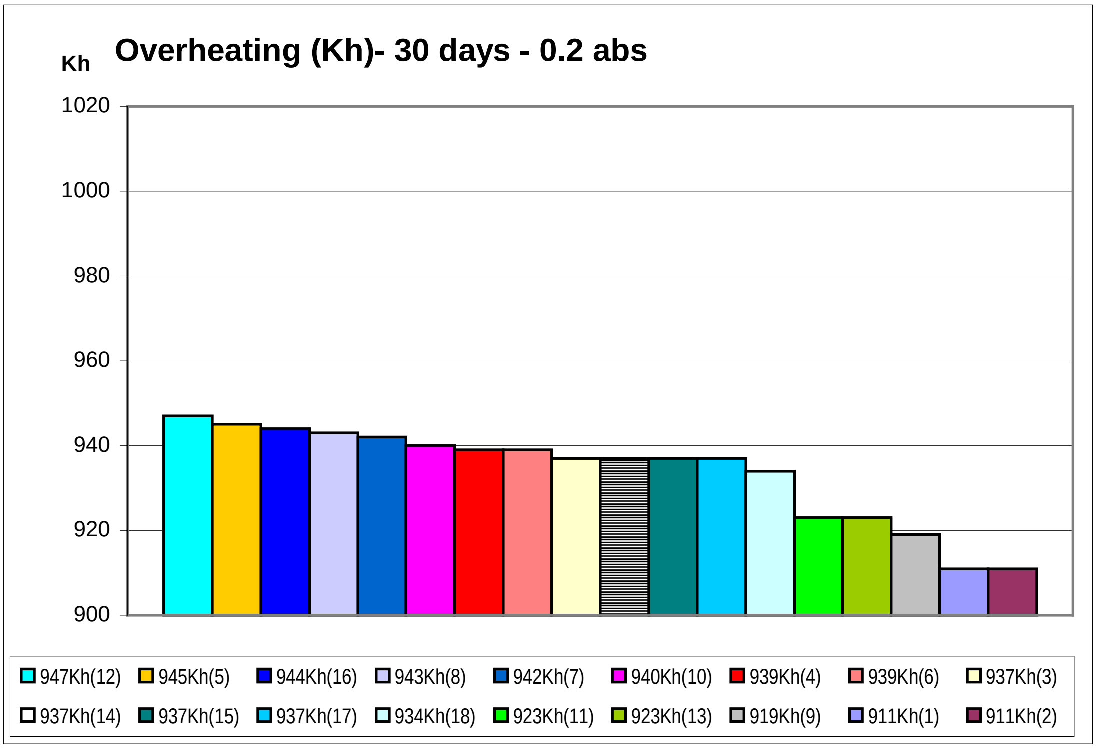
4.0 Results presentation

Graphs 4.1-4.4 show the results for the permutations defined on section 2.5 and repeated below, for free running operation (α0.2, 0.4, 0.6 and 0.8) . Graphs 4.7-4.14 show the results for A/C operation (α0.2-0.9). Both are compared from highest to lowest degree hours of overheating (free running) and cooling loads (A/C). The Dry bulb temperature profiles for the Master bedroom (for each case) with free running operation are presented from graphs 4.13 on. (a total of 72 graphs). From the simulation period (30 days October), day 24/10 was chosen as one of the highest average DBT day during the simulation period and therefore is the day presented for all the 72 graphs on DBT profile.

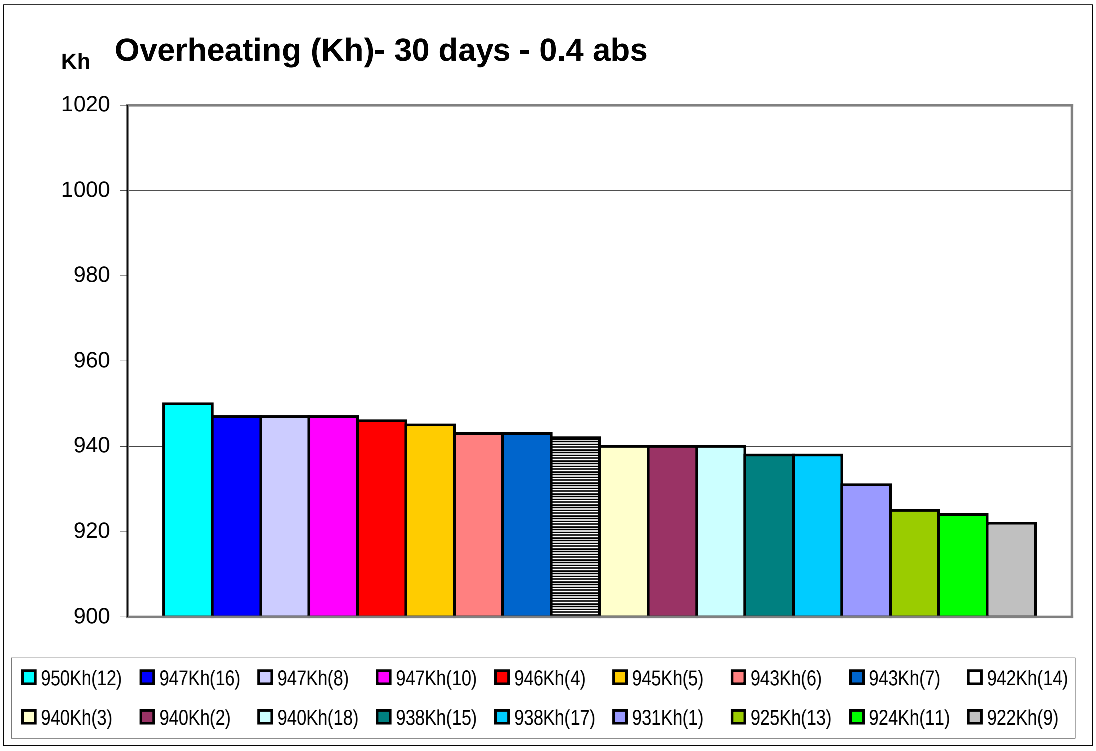
List of permutations:

1) Basecase
2) Basecase*
3) Ceiling EPS only
4) Ceiling EPS only*
5) Ceiling EPS + Rfoil
6) Ceiling EPS + Rfoil*
7) Ceiling EPS + Roof Rfoil
8) Ceiling EPS + Roof Rfoil *
9) Roof EPS only
10) Roof EPS only*
11) Roof EPS + Rfoil
12) Roof EPS + Rfoil*
13) Roof Rfoil only
14) Roof Rfoil only*
15) Roof EPS + Ceiling Rfoil
16) Roof EPS + Ceiling Rfoil*
17) Ceiling Rfoil only
18) Ceiling Rfoil only

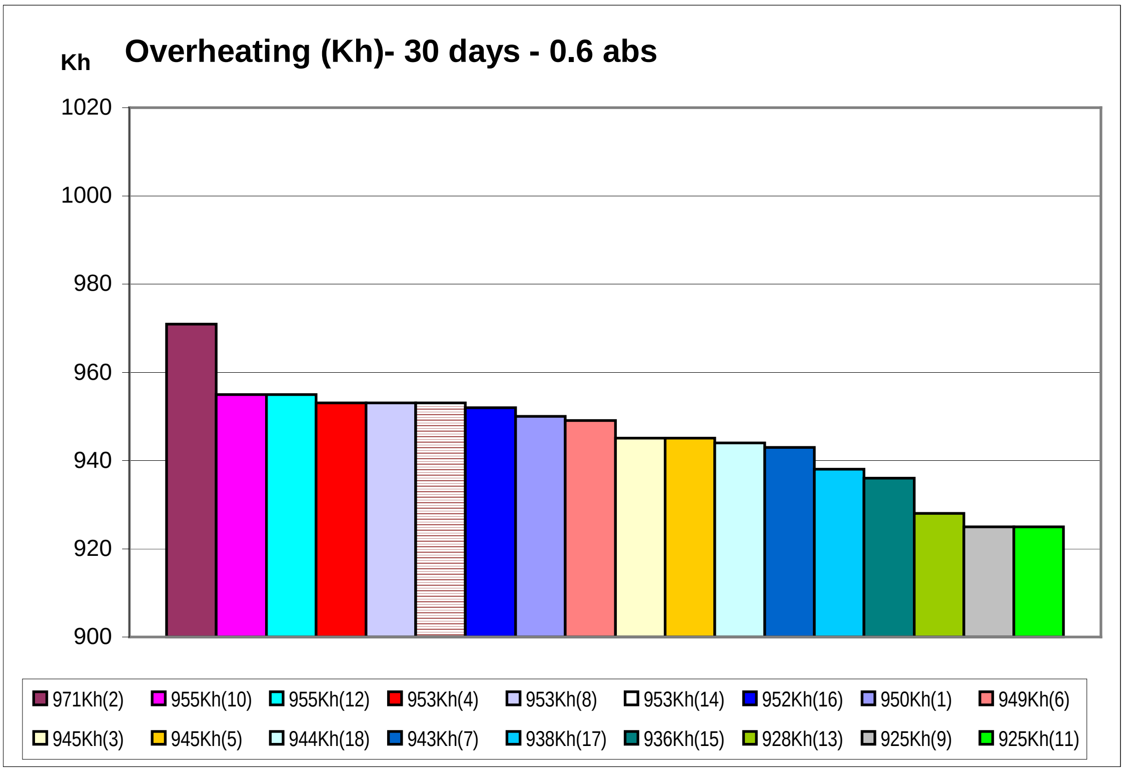
4.1 Results for free running mode



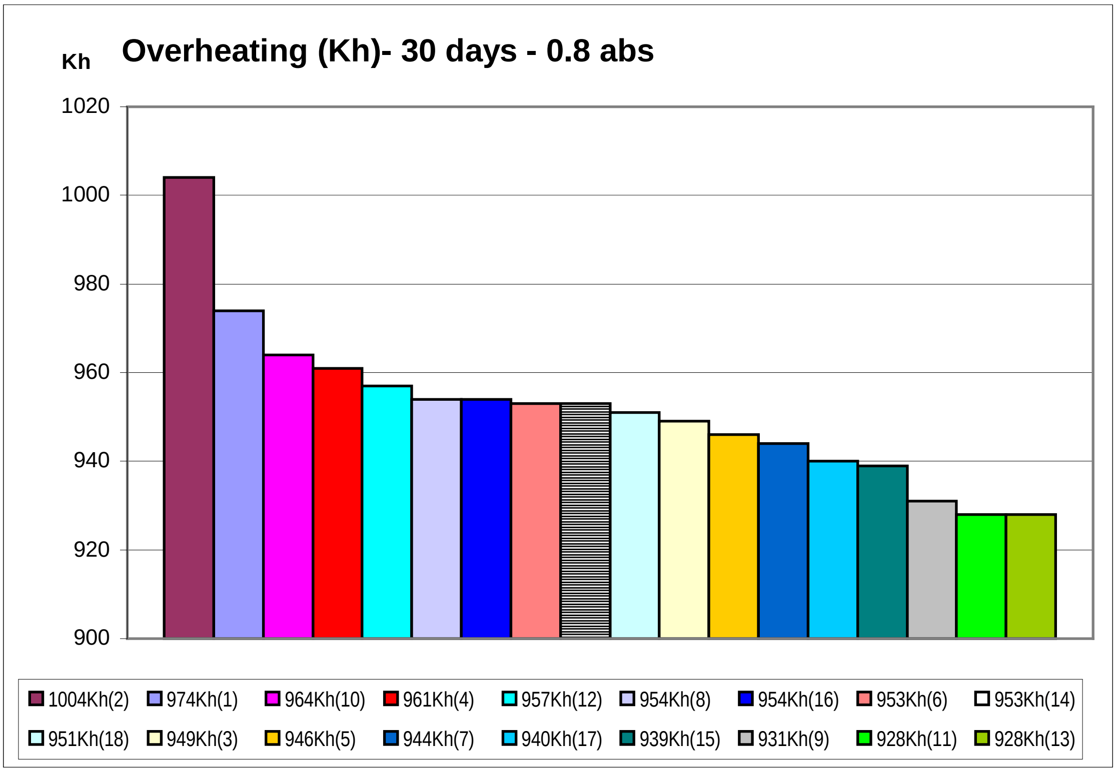
Graph. 4.1. Degree hours of overheating for ABC study. Master bedroom (Kh). (α 0.2)



Graph. 4.2. Degree hours of overheating for ABC study. Master bedroom (Kh). (α 0.4)

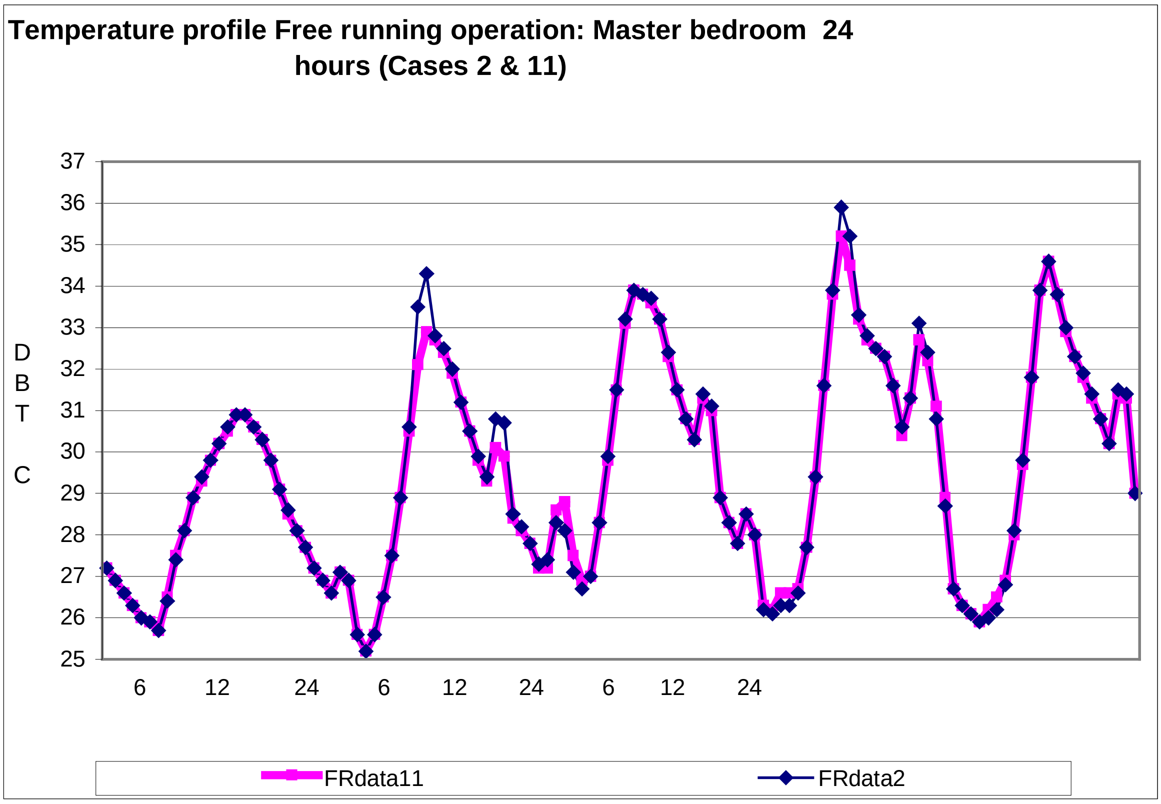


Graph. 4.3. Degree hours of overheating for ABC study. Master bedroom (Kh). (α 0.6)

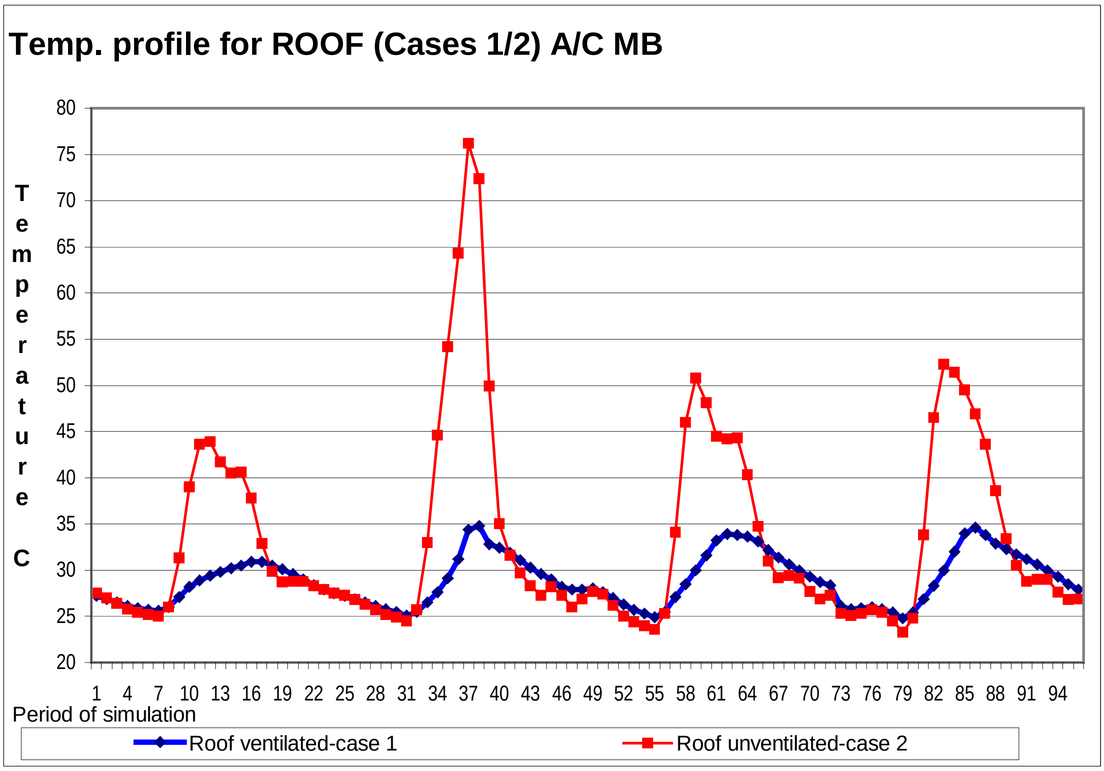


Graph. 4.4. Degree hours of overheating for ABC study. Master bedroom (Kh). (α 0.8).

Graphs. 4.5, 4.6 are demonstrative figs. of cases 2 and 11 (α0.6), for free running operation. It compares the DBT profiles. The range differences for free running operation is much smaller when compared to the A/C operation. The thermal response is very similar as the differences in thermal performance are 5% only. From the overall results, the free running operation demonstrated less sensitivity to the parametric changes when compared to the A/C parametric permutations. Graph 4.6 compares the temperature profile of ventilated and unventilated attic roofs when there is A/C on MB. As expected most of the unventilated attic roof profiles had better performance, unless lower values of solar absorptance are used.



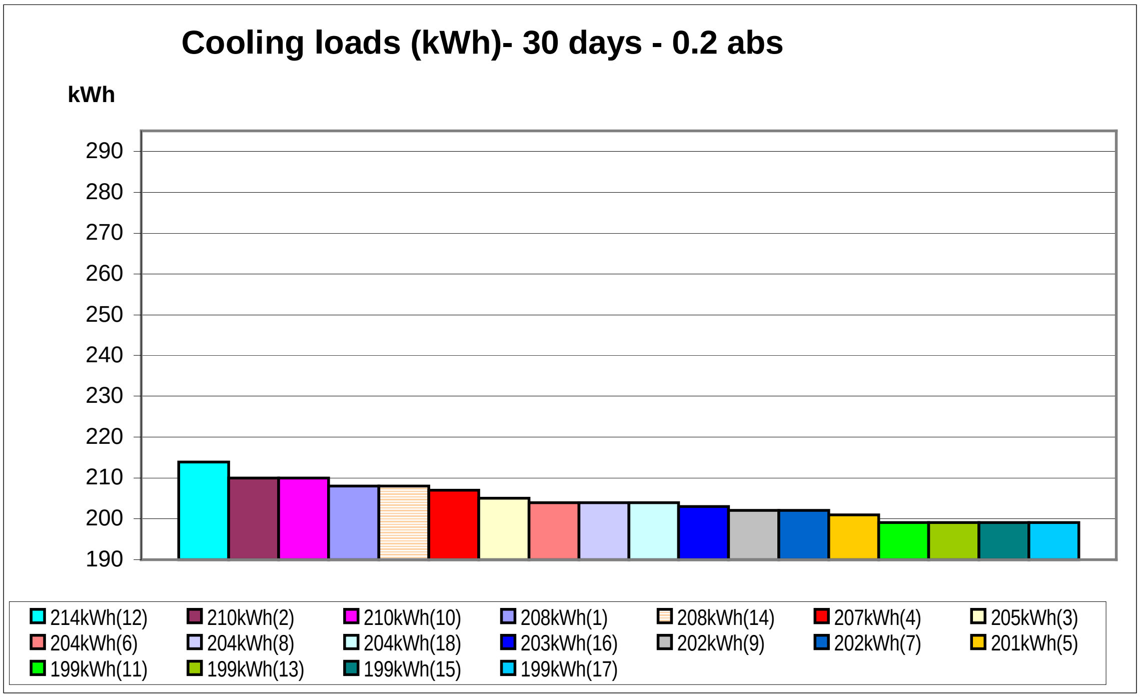
Graph 4.5. Comparisons of temperature profile (DBT) for cases 2 and 11 (MB) on free running operation (α 0.6).



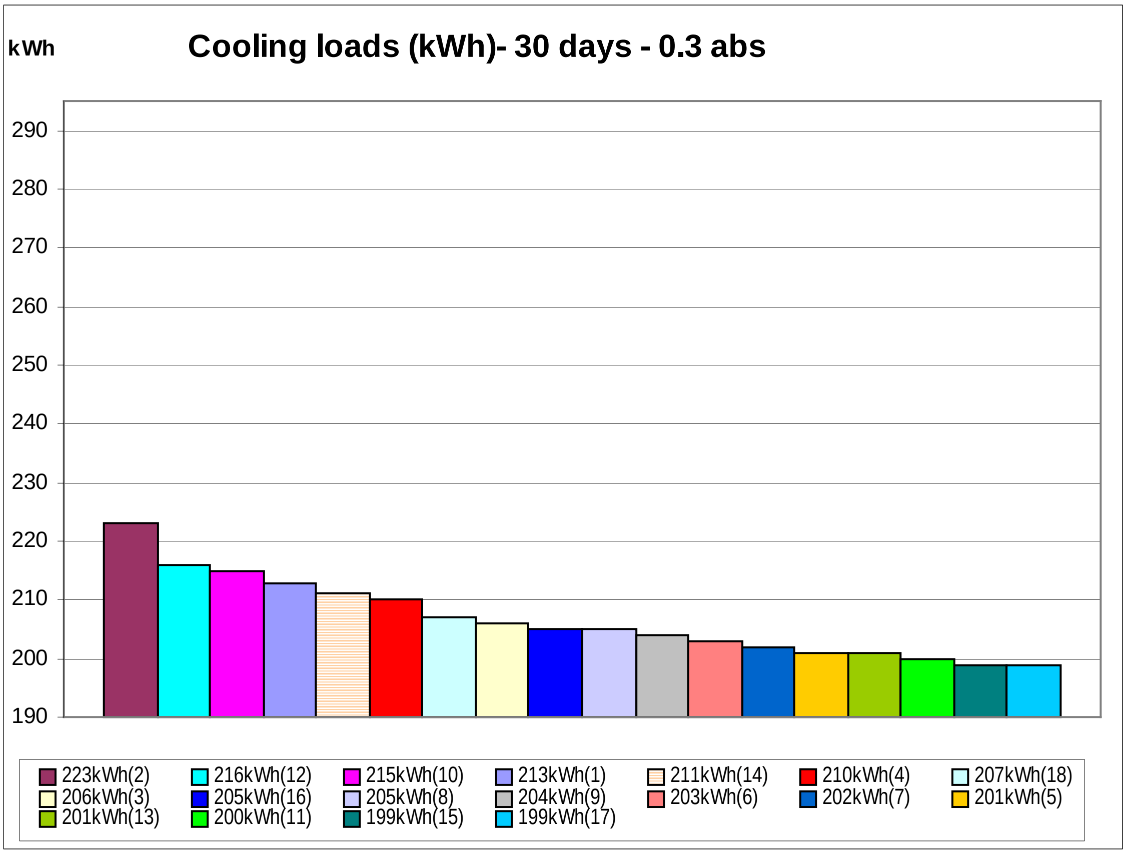
Graph 4.6. Comparisons of temperature profile of roof attic spaces –ventilated and unventilated (MB), when air conditioning is in use on Master bedroom. (α 0.6)

4.2. Results for Air Conditioned mode

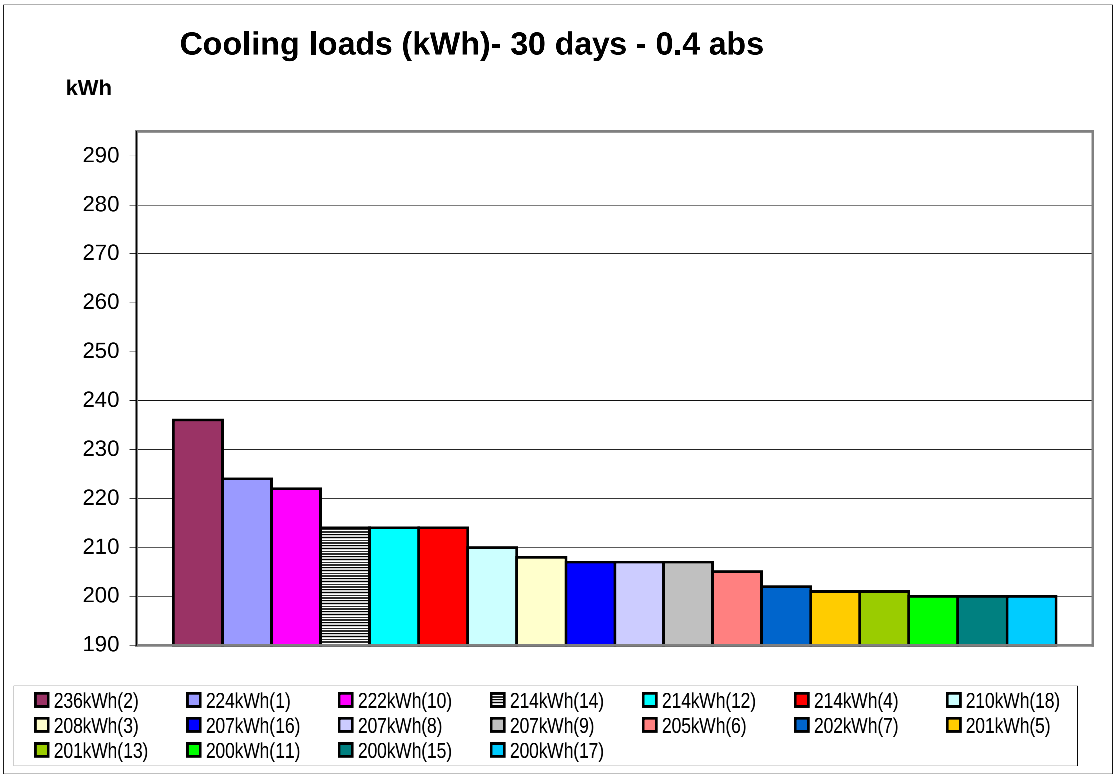
The following graphs (4.7-4.14) show the results for the A/C operation in terms of cooling loads (kWh)



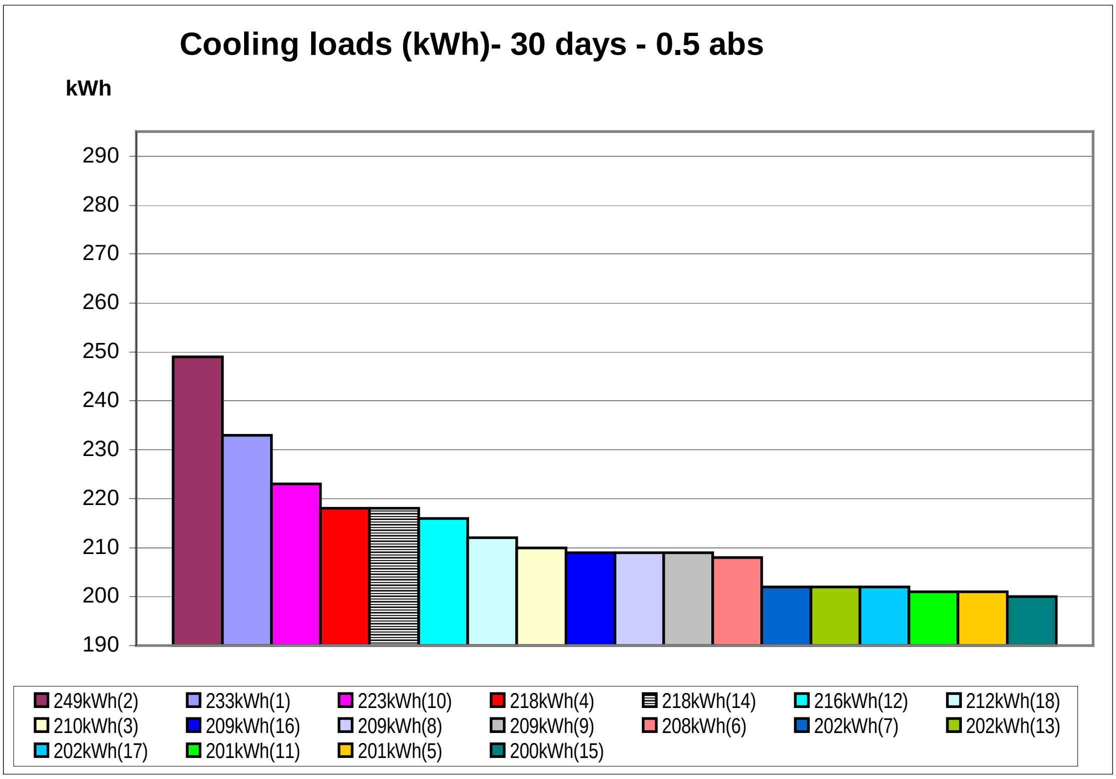
Graph 4.7. Cooling load for ABCB study. Master bedroom (kWh). (α 0.2).



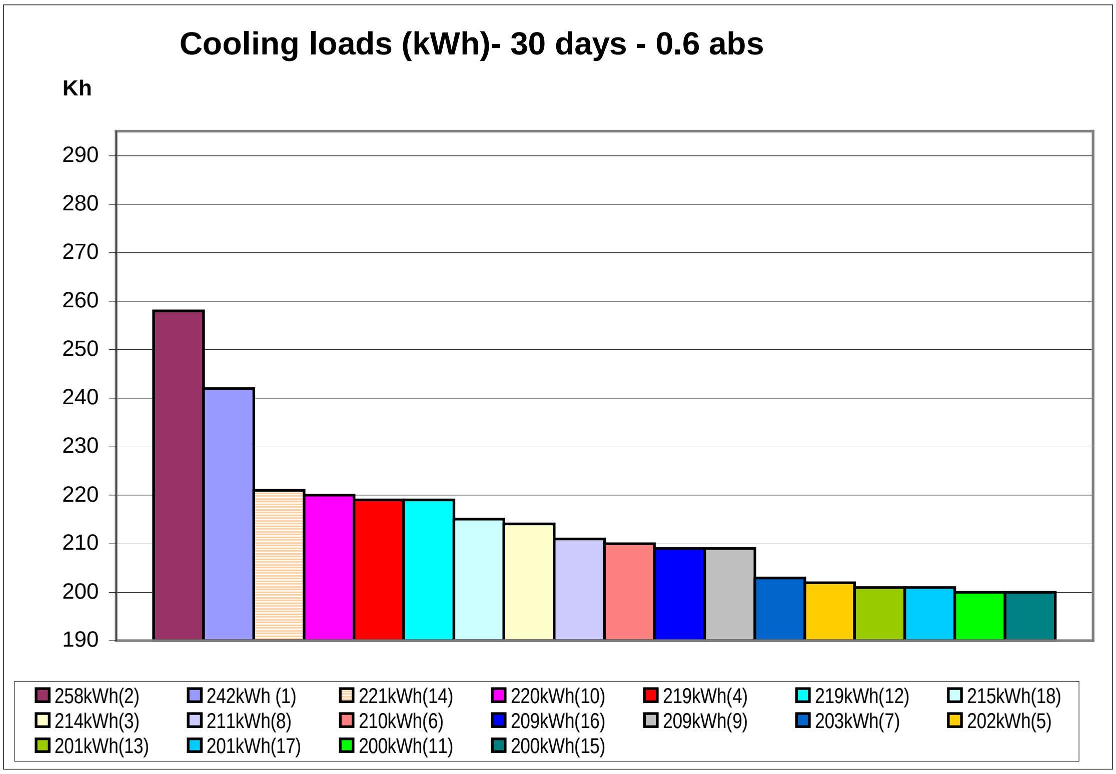
Graph 4.8. Cooling load for ABCB study. Master bedroom (kWh). (α 0.3).



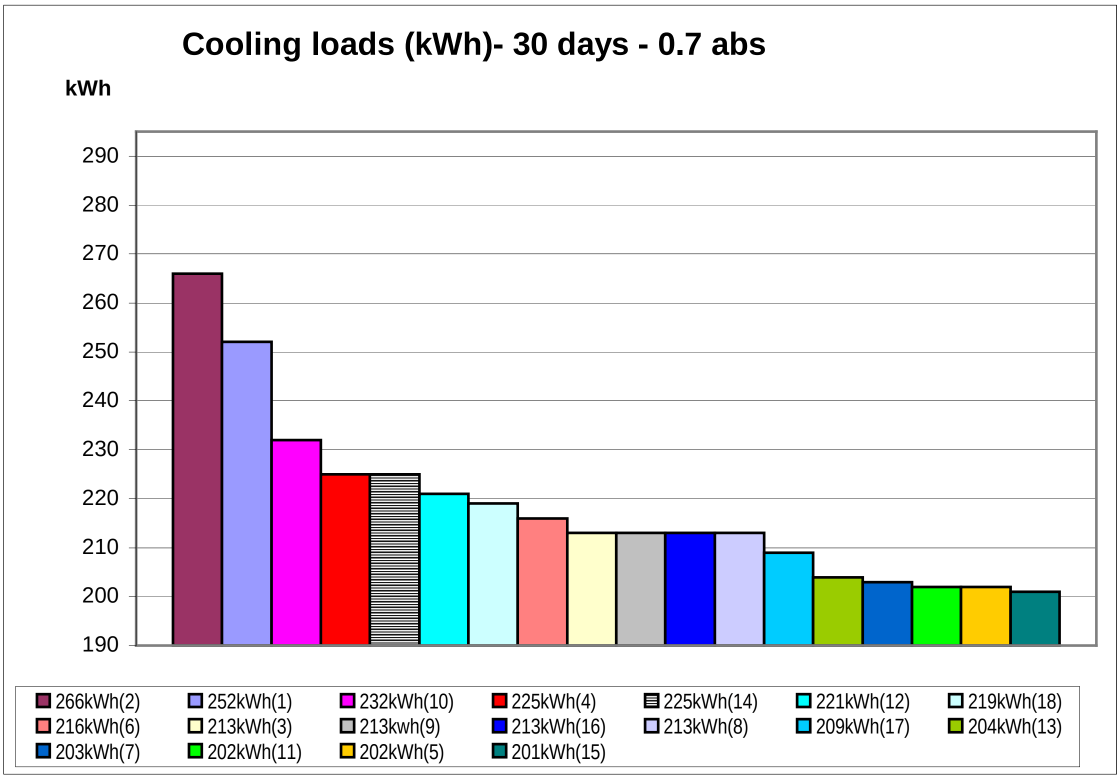
Graph 4.9. Cooling load for ABCB study. Master bedroom (kWh). (α 0.4).



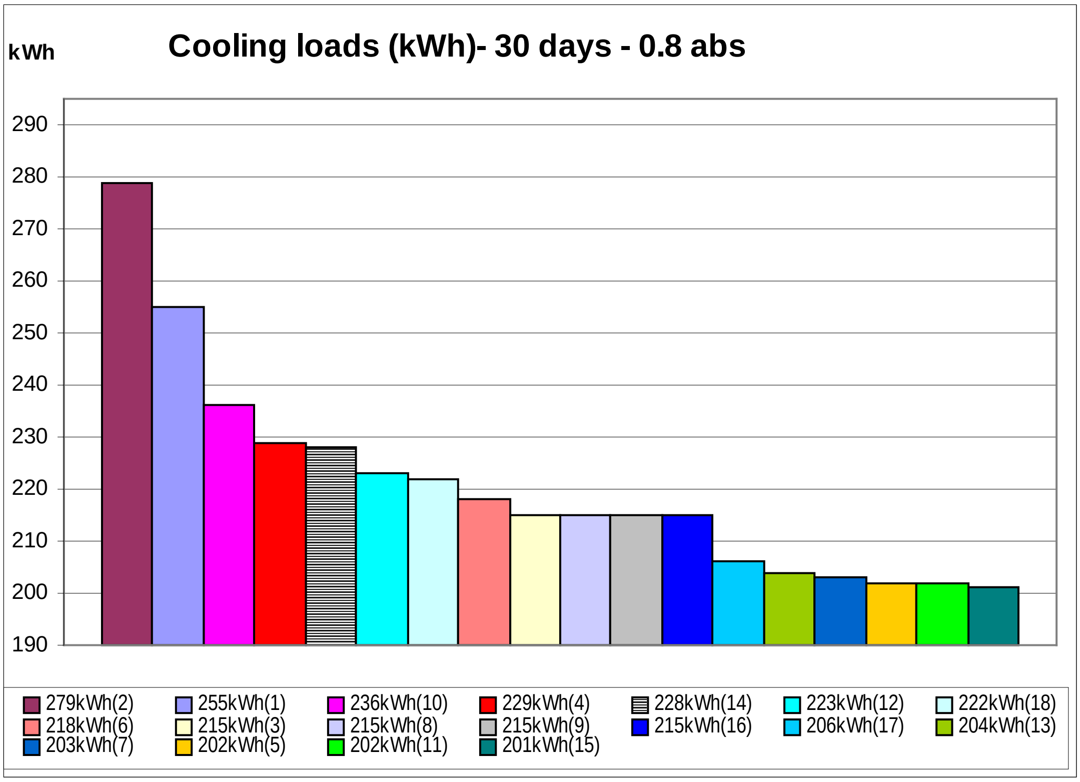
Graph 4.10. Cooling load for ABCB study. Master bedroom (kWh). (α 0.5).



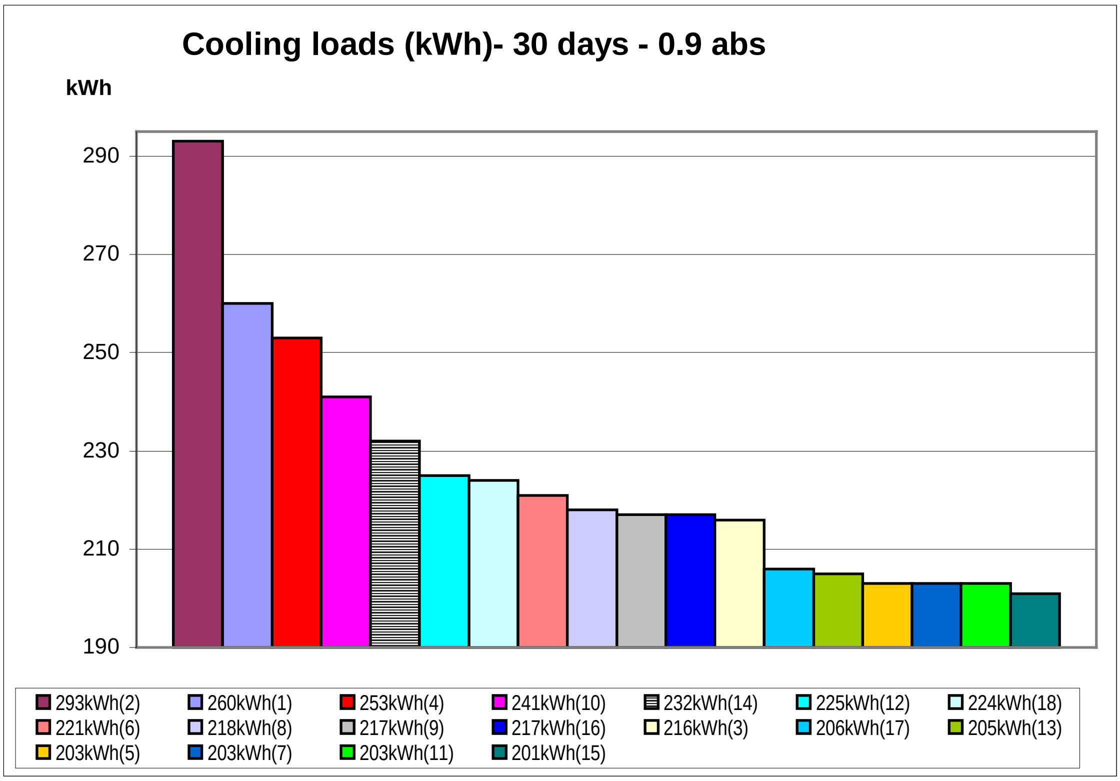
Graph 4.11. Cooling load for ABCB study. Master bedroom (kWh). (α 0.6).



Graph 4.12. Cooling load for ABCB study. Master bedroom (kWh). (α 0.7).

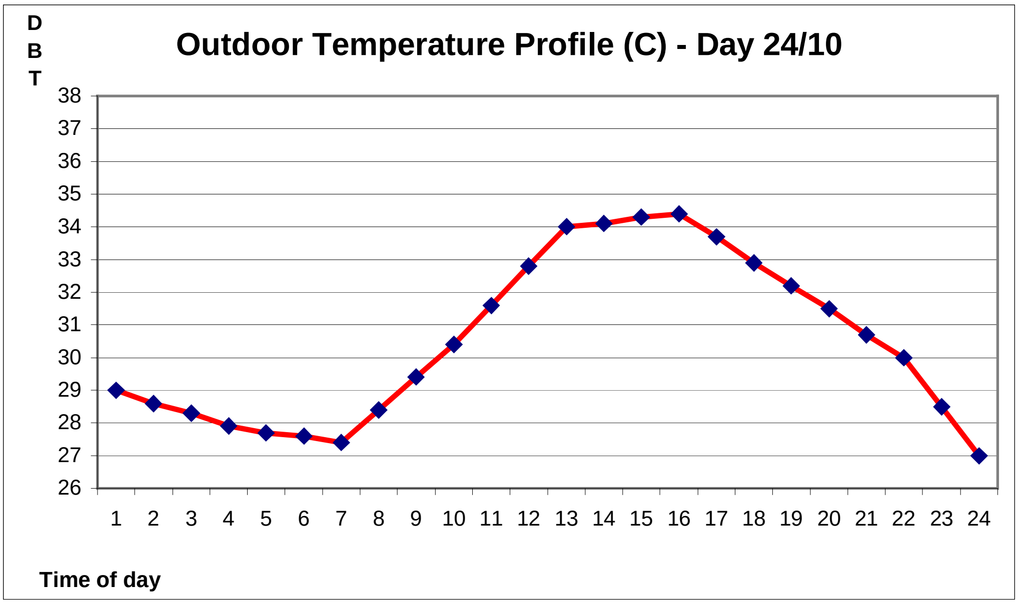


Graph 4.13. Cooling load for ABCB study. Master bedroom (kWh). (α 0.8).



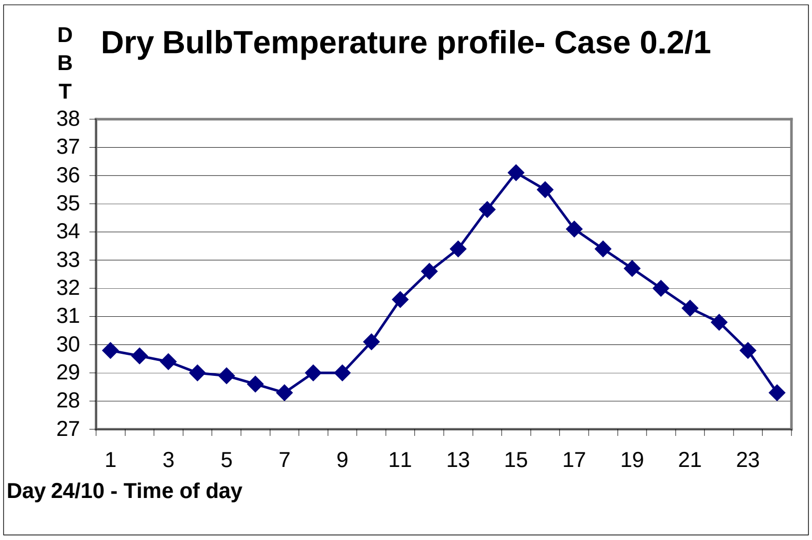
Graph 4.14. Cooling load for ABCB study. Master bedroom (kWh). (α 0.9).

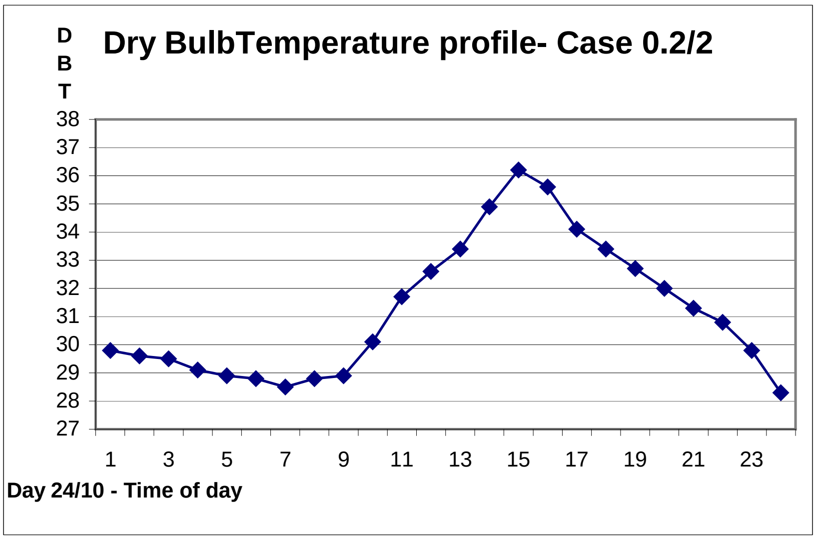
Table 4.1. compares the results for all the simulation runs (free running and air conditioned). Graph 4.15 demonstrates the chosen day (24/10) within the simulation period (October – 30 days), used for comparisons on the DBT profile for Master bedroom. Graphs 4.16-4.87 demonstrate the DBT profile for each case on the free running operation.

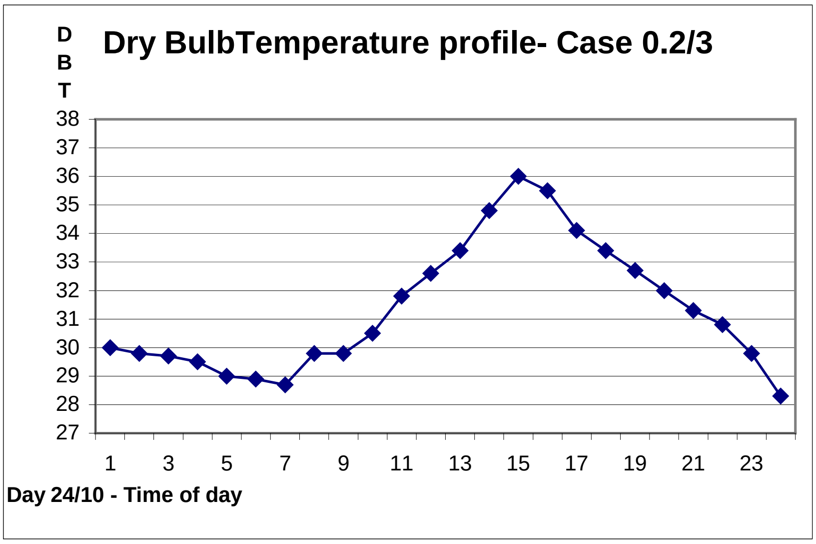


Graph 4.15. Outdoor temperature profile (day 24/10) .

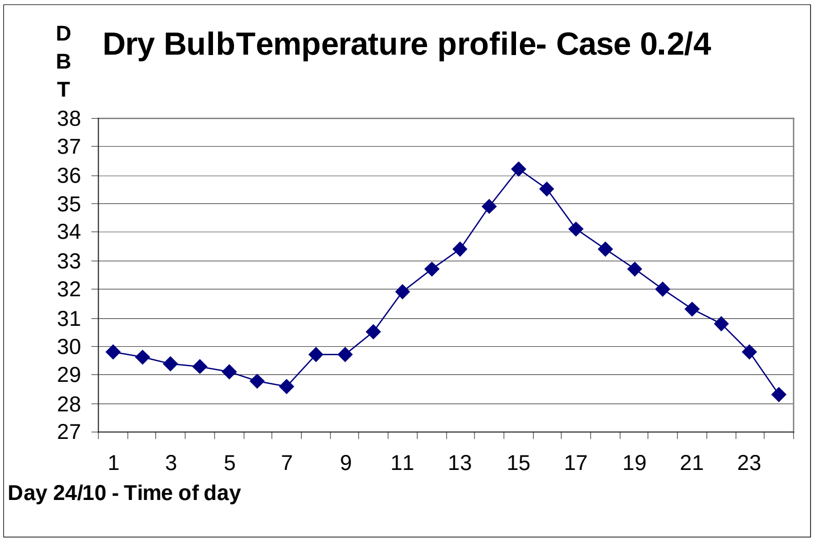
4.3. Dry Bulb Temperature profiles for Free running operation

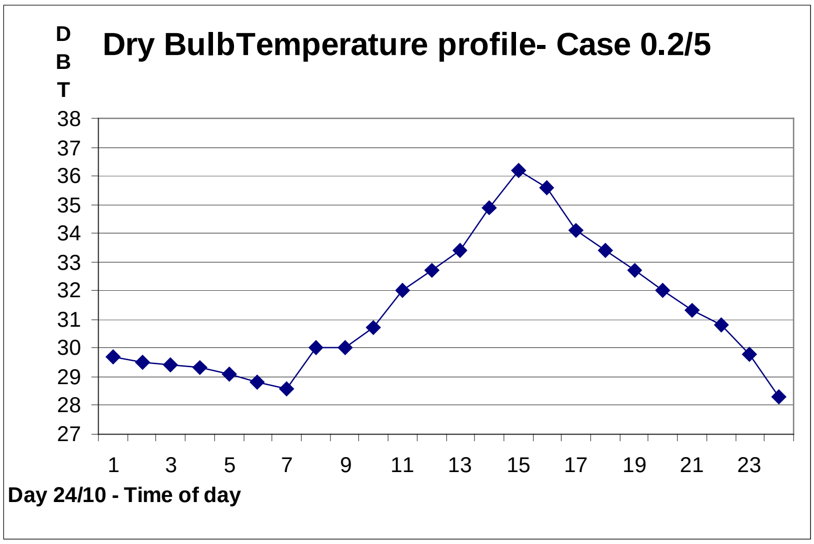


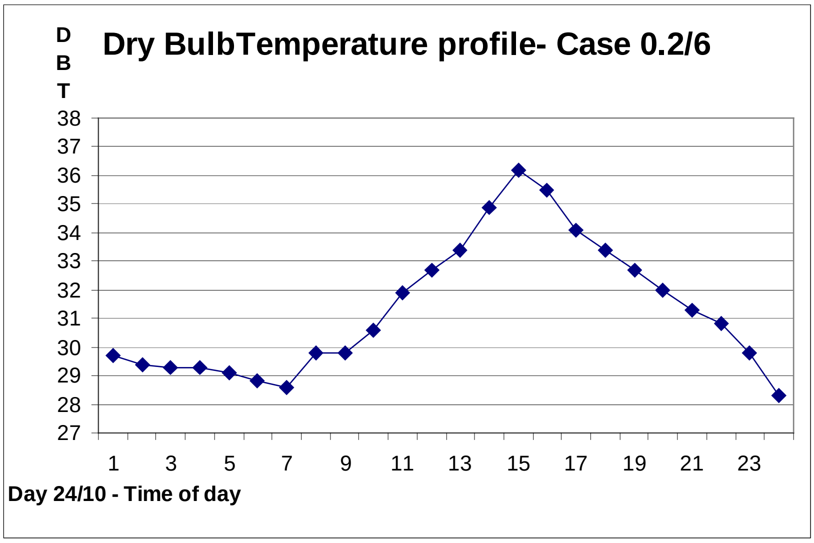




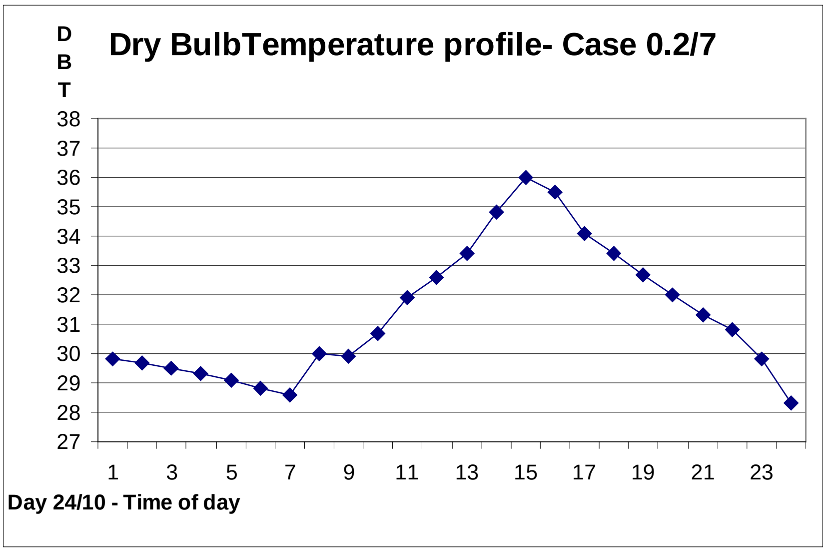
Graphs. 4.16-4.18. DBT profile Cases 0.2 (1-3)







Graphs. 4.19-4.21. DBT profile Cases 0.2 (4-6)


Dry BulbTemperature profile- Case 0.2/7
DBT
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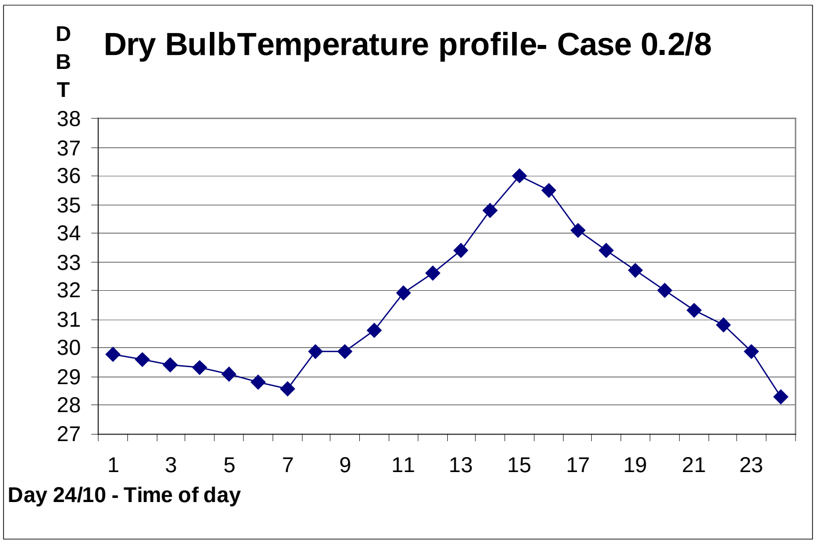
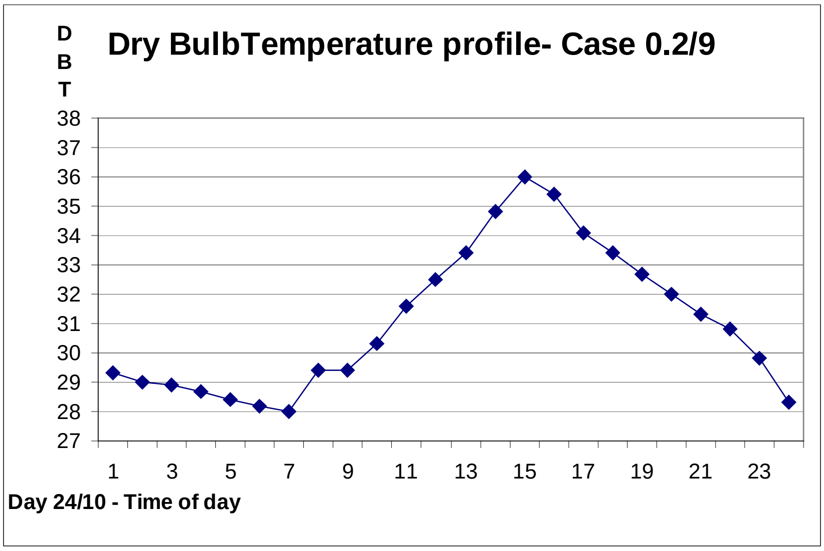
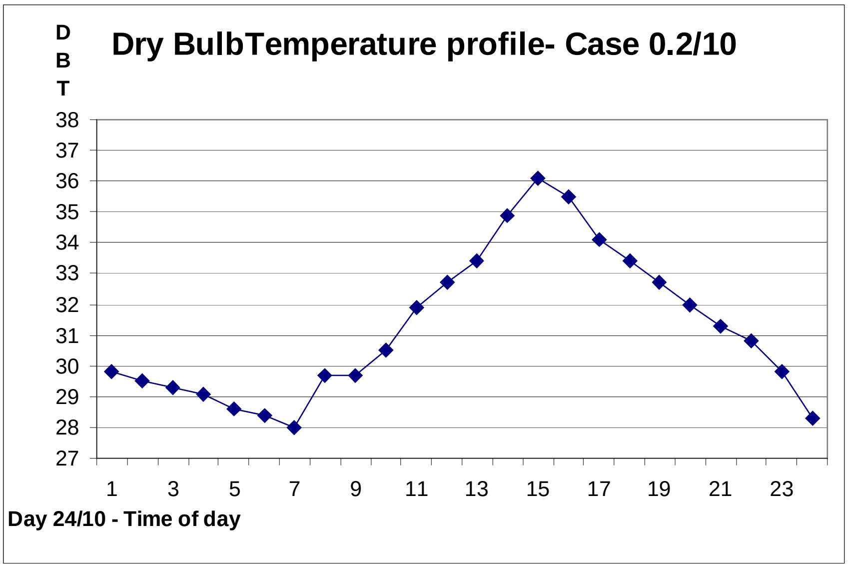
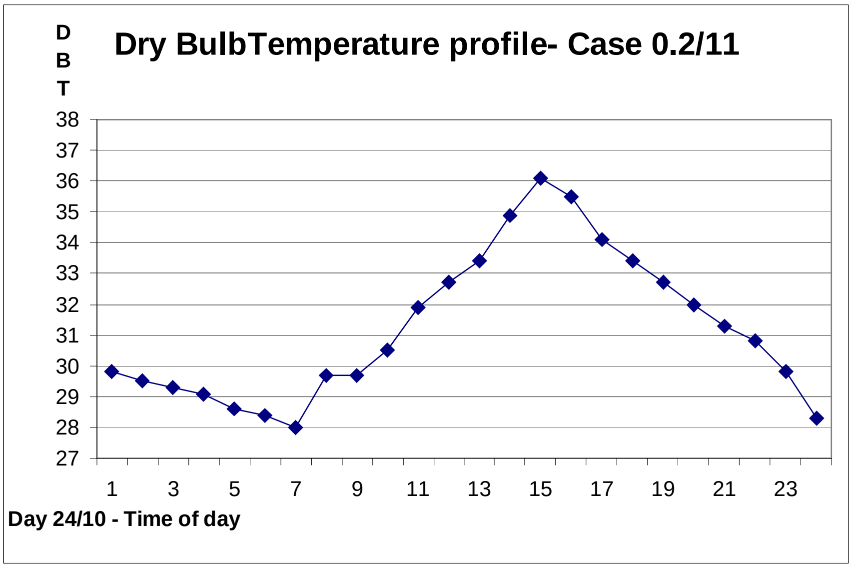
1 3 5 7 9 11 13 15 17 19 21 23
Day 24/10 - Time of day

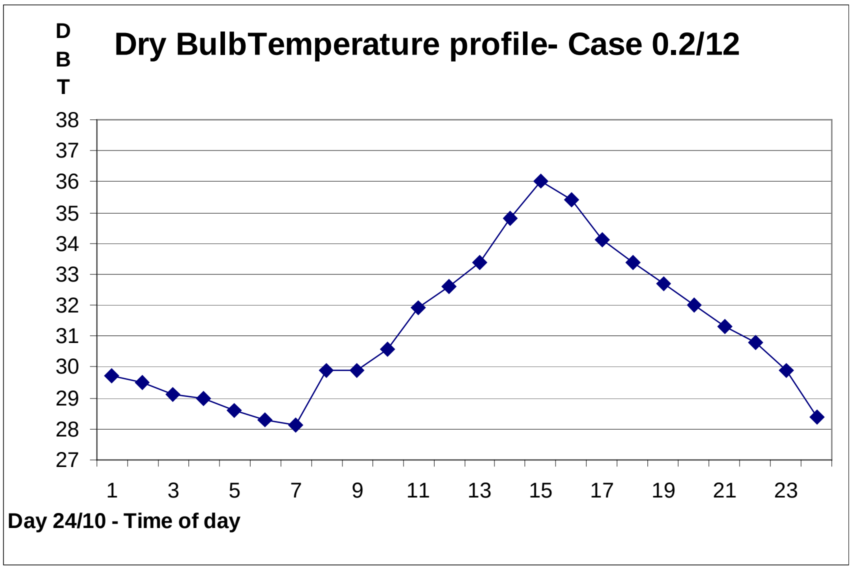




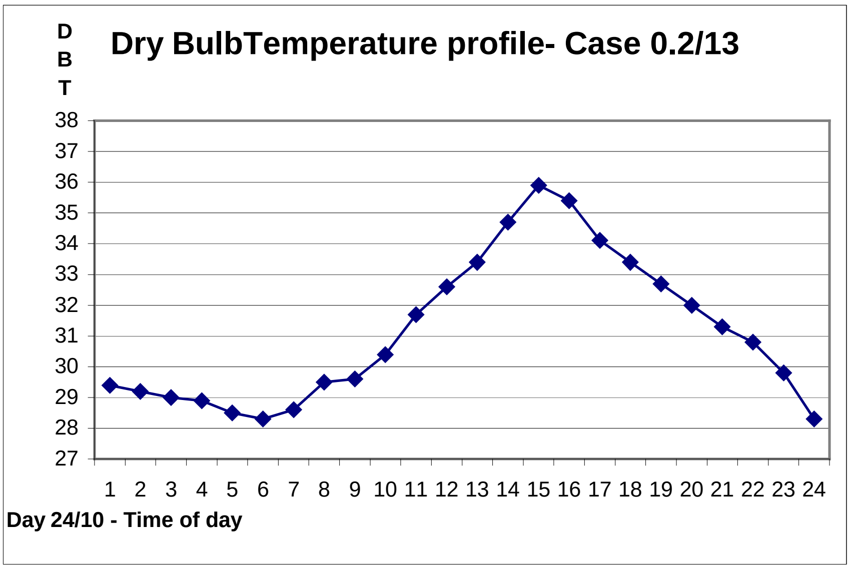
Graphs. 4.22-4.24. DBT profile Cases 0.2 (7-9)

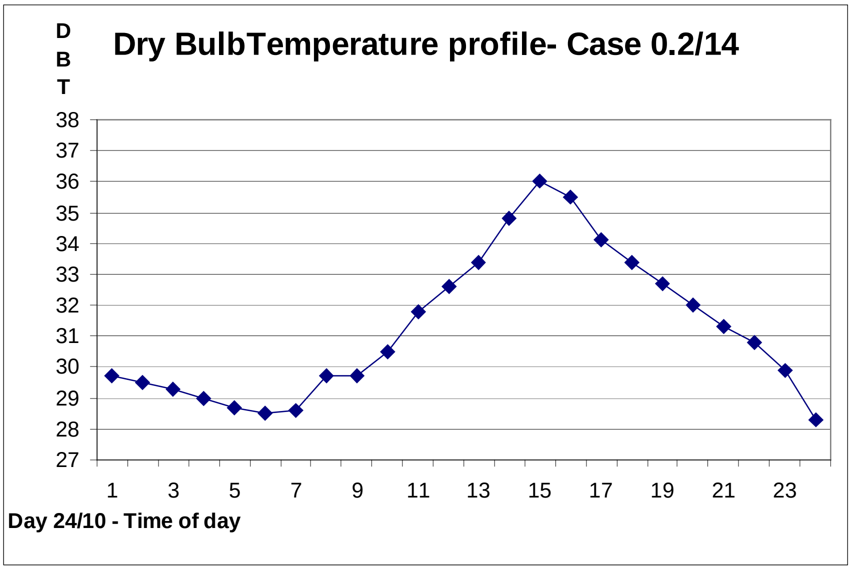


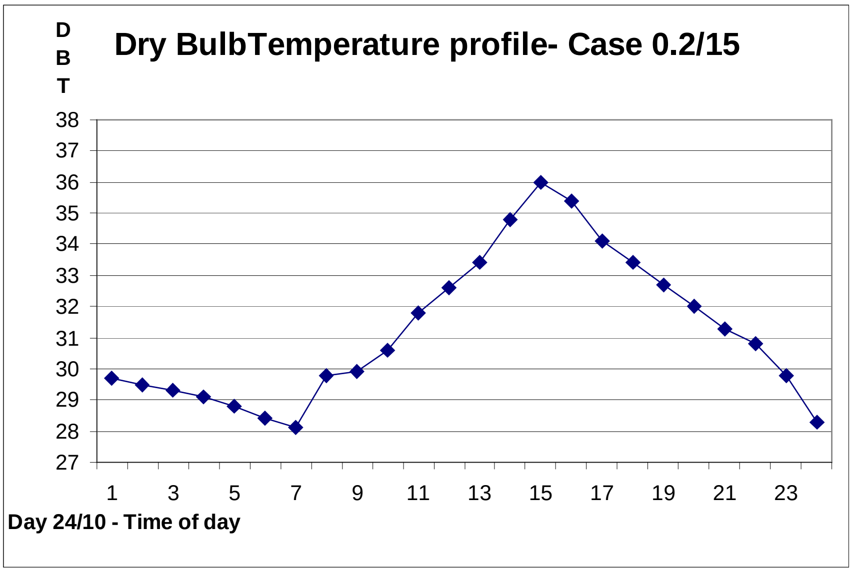




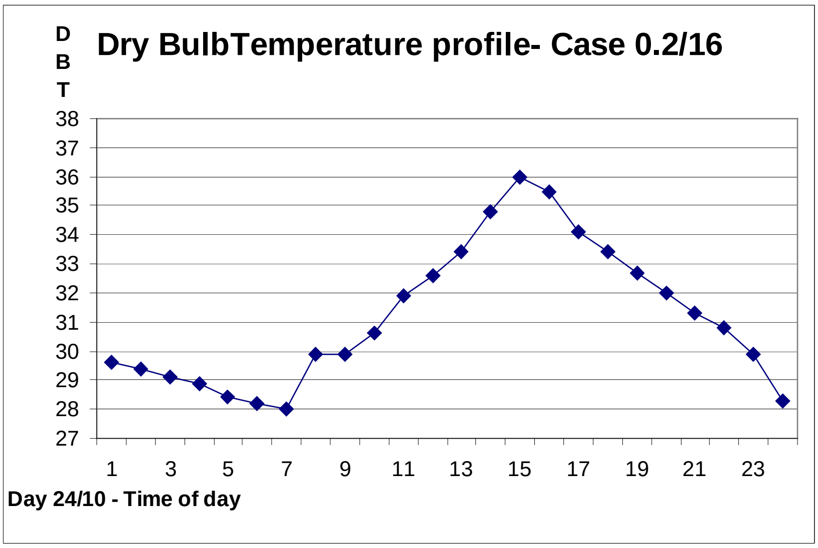
Graphs. 4.25-4.27. DBT profile Cases 0.2 (10-12)

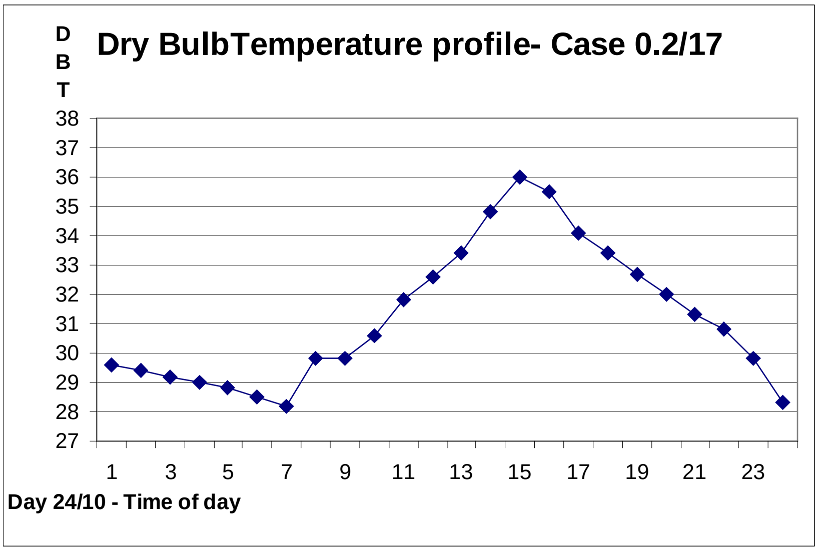


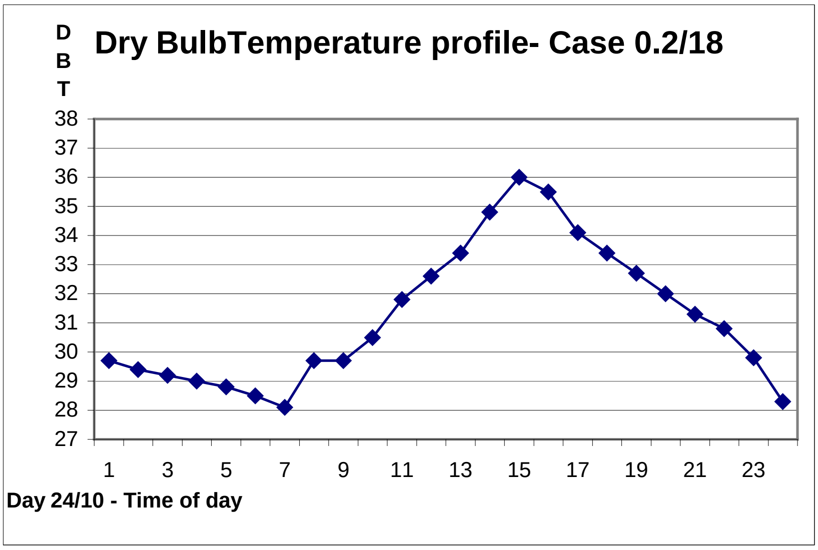




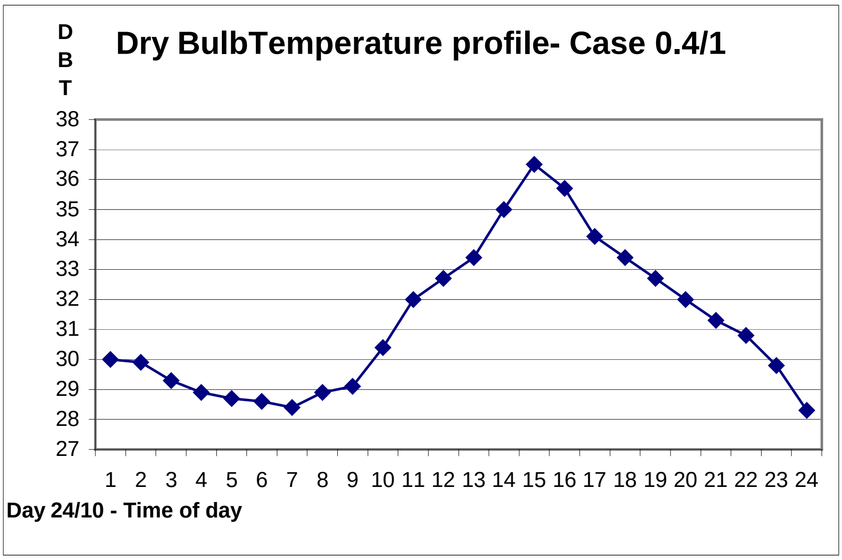
Graphs. 4.28-4.30. DBT profile Cases 0.2 (13-15)







Graphs. 4.31-4.33. DBT profile Cases 0.2 (16-18)


Dry BulbTemperature profile- Case 0.4/1
DBT
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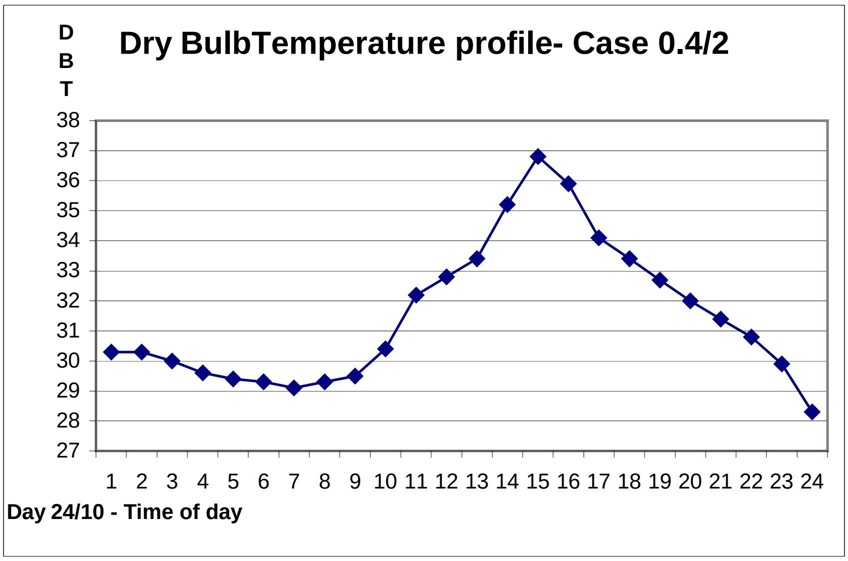
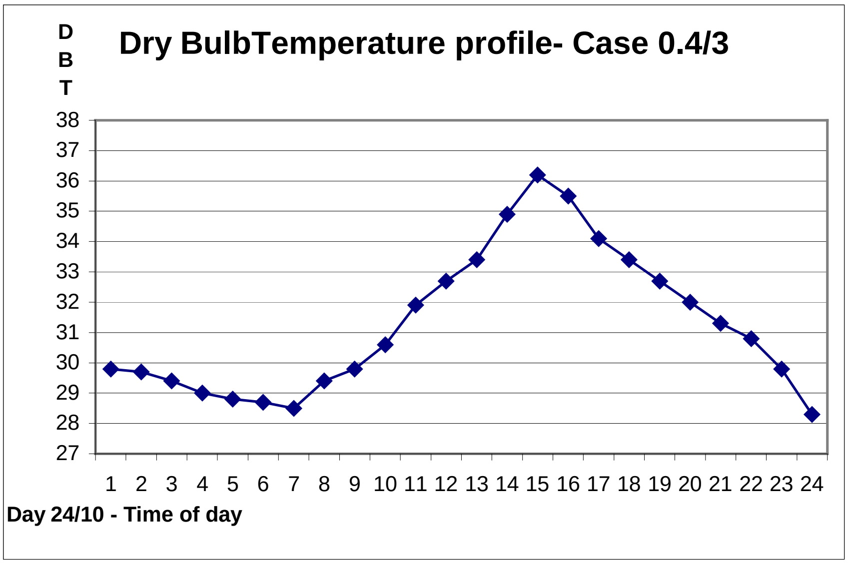
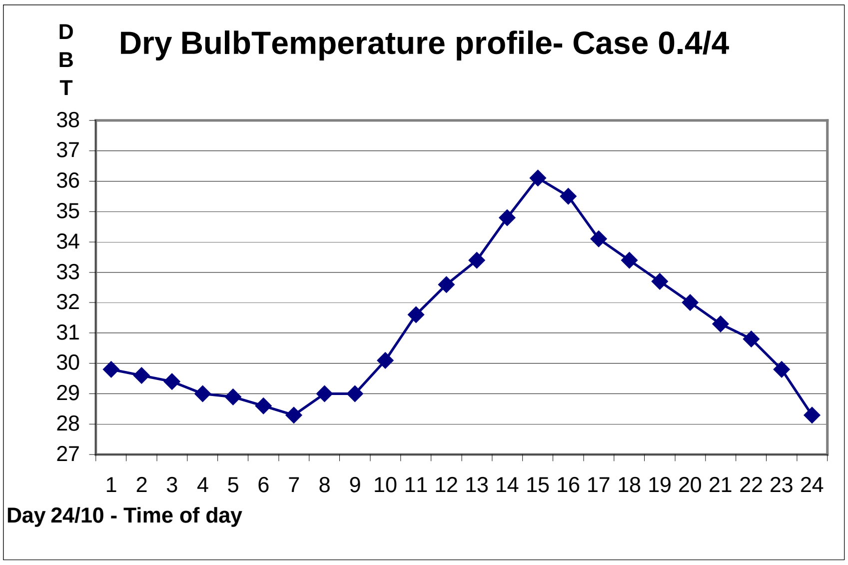
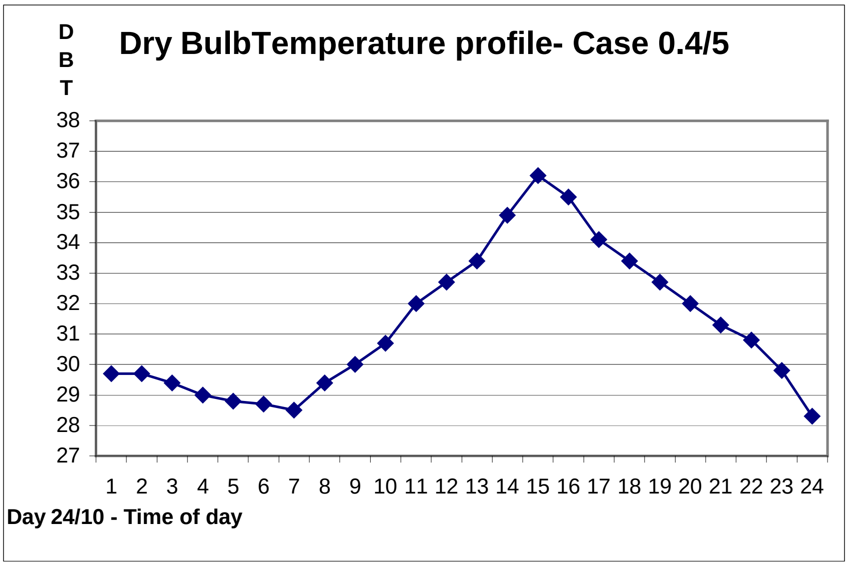
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Day 24/10 - Time of day

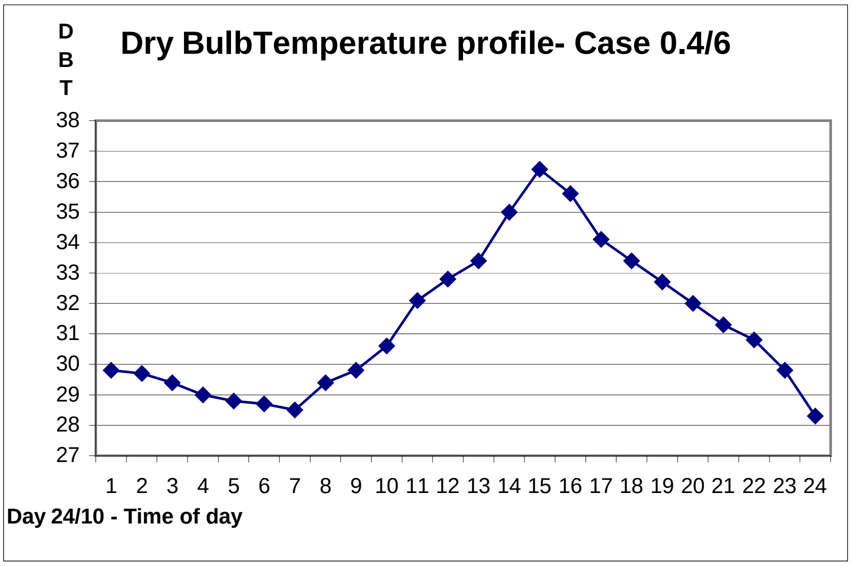




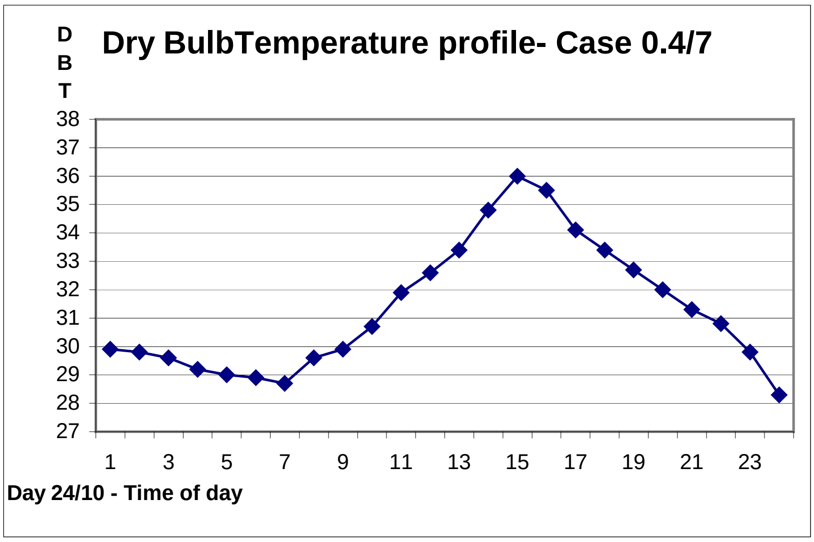
Graphs. 4.34-4.36. DBT profile Cases 0.4 (1-3)







Graphs. 4.37-4.39. DBT profile Cases 0.4 (4-6)


Dry BulbTemperature profile- Case 0.4/7
DBT
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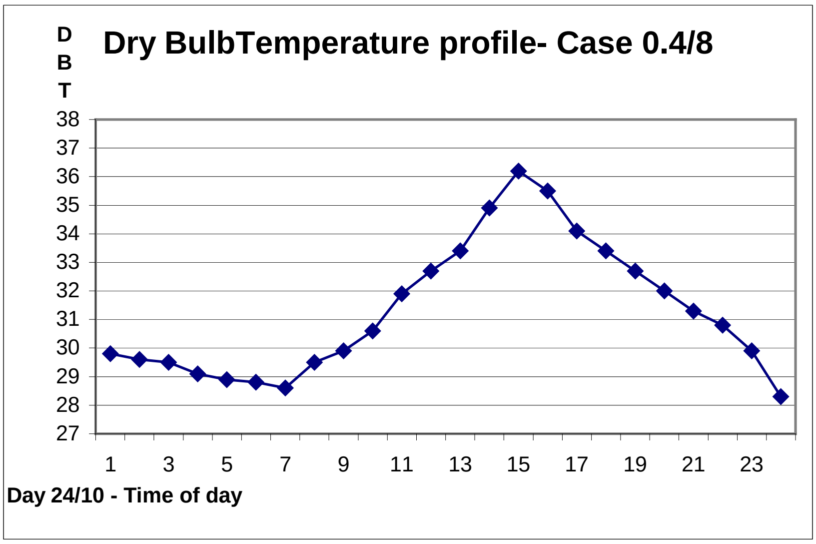
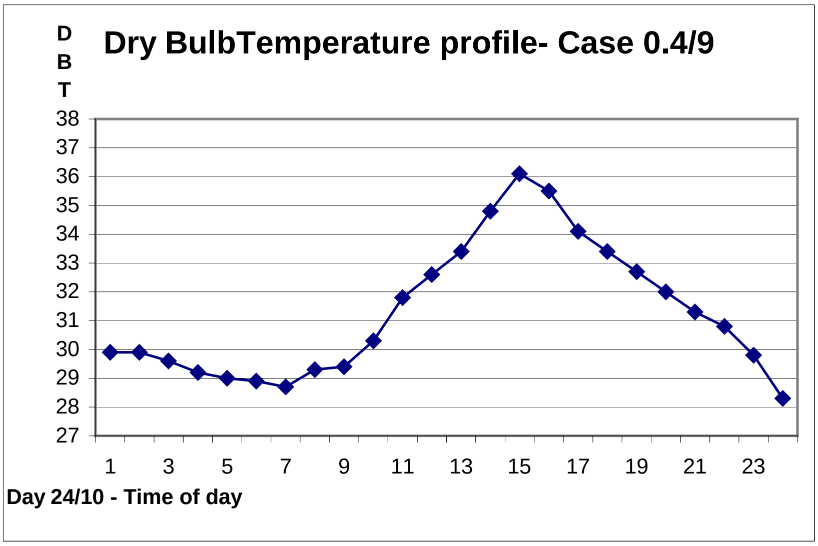
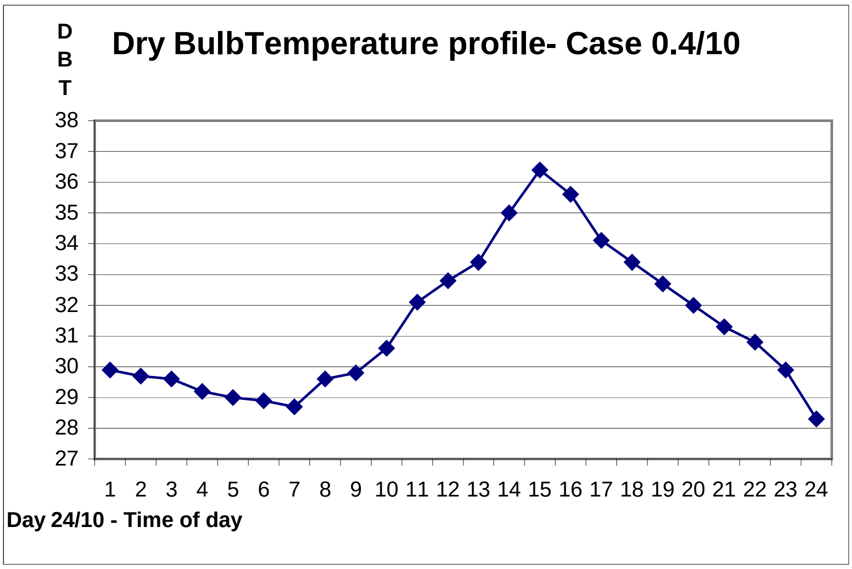
1 3 5 7 9 11 13 15 17 19 21 23
Day 24/10 - Time of day





Graphs. 4.40-4.42. DBT profile Cases 0.4 (7-9)


Dry BulbTemperature profile- Case 0.4/10
DBT
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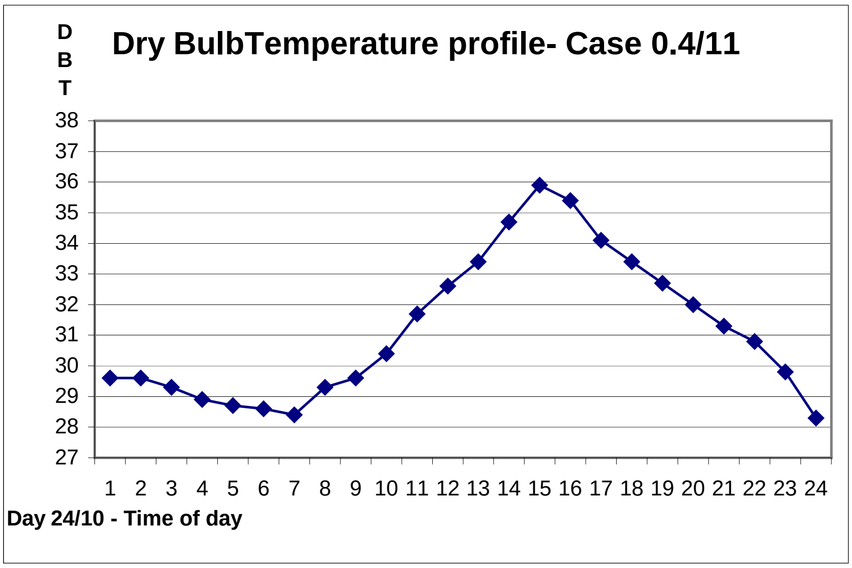
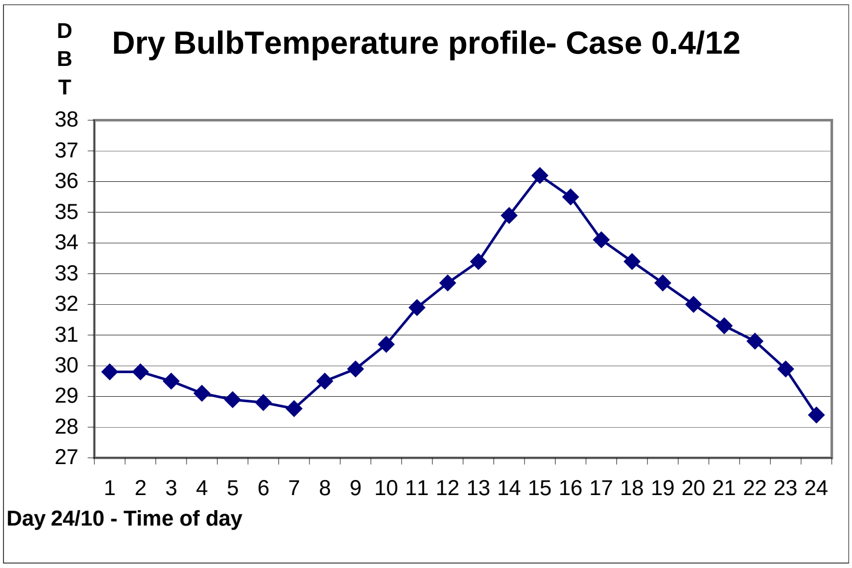
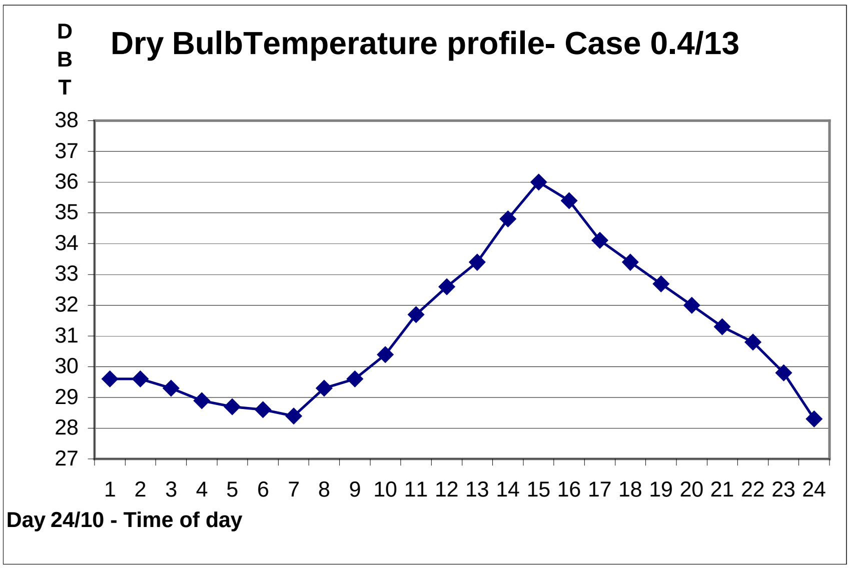
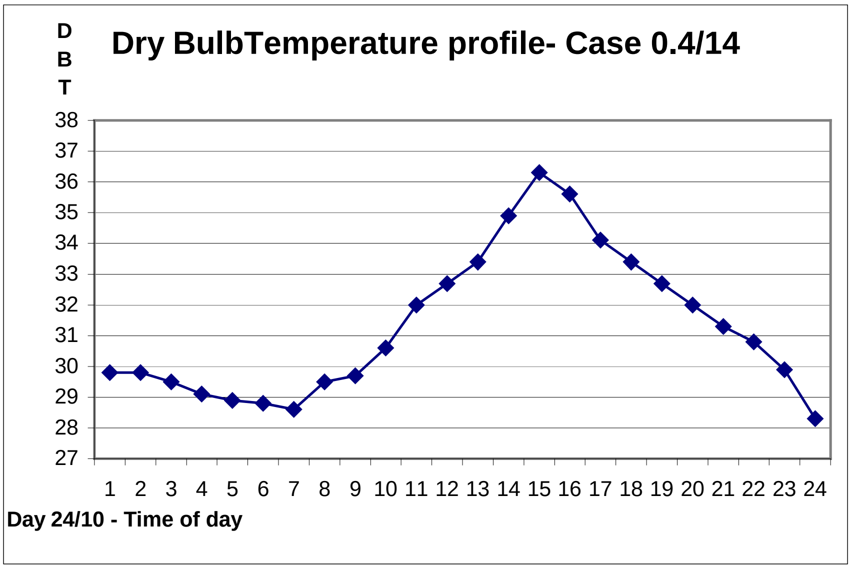
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Day 24/10 - Time of day

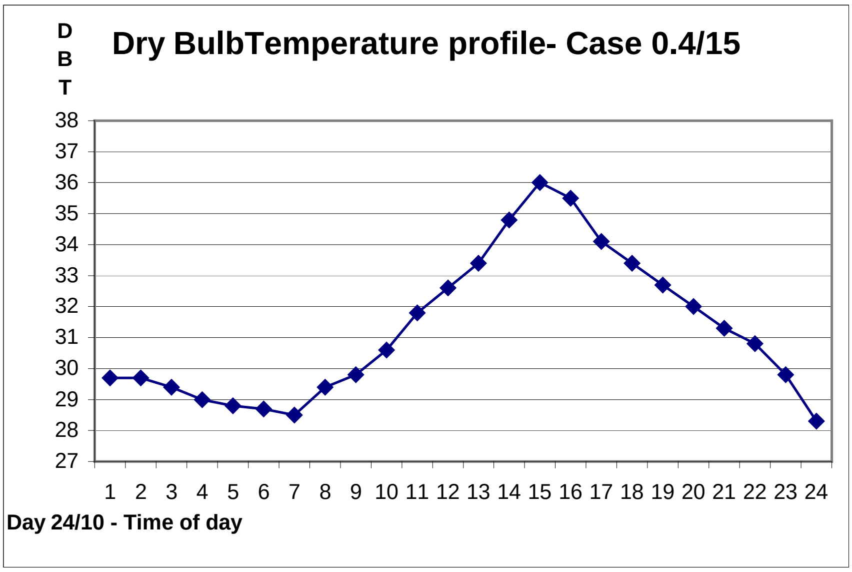




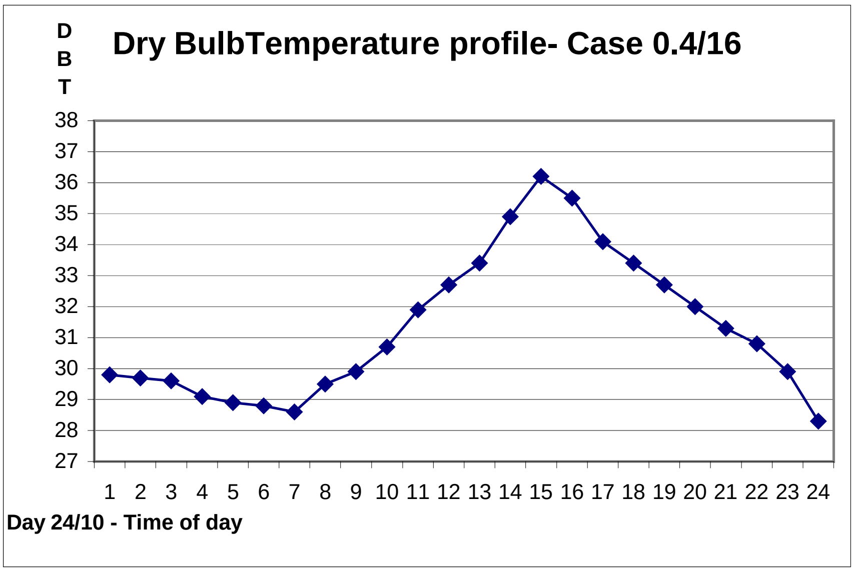
Graphs. 4.43-4.45. DBT profile Cases 0.4 (10-12)

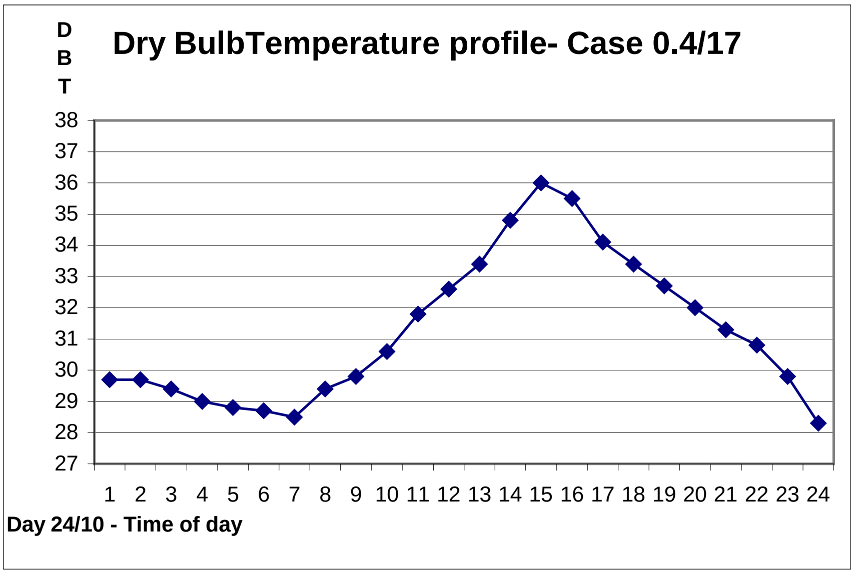


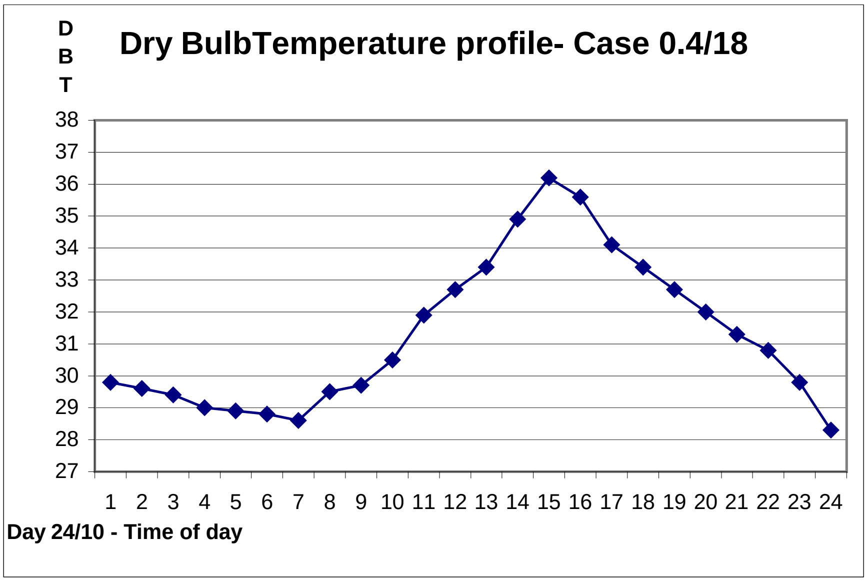




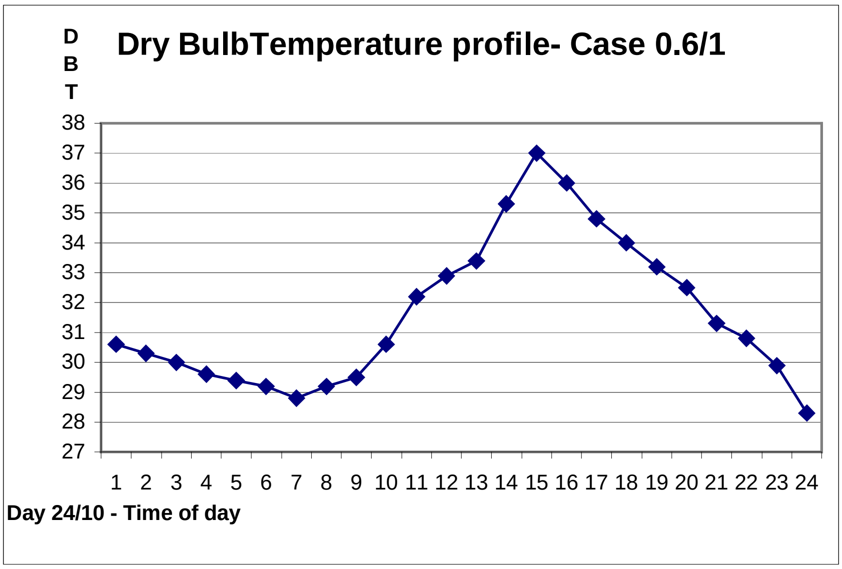
Graphs. 4.46-4.48. DBT profile Cases 0.4 (13-15)

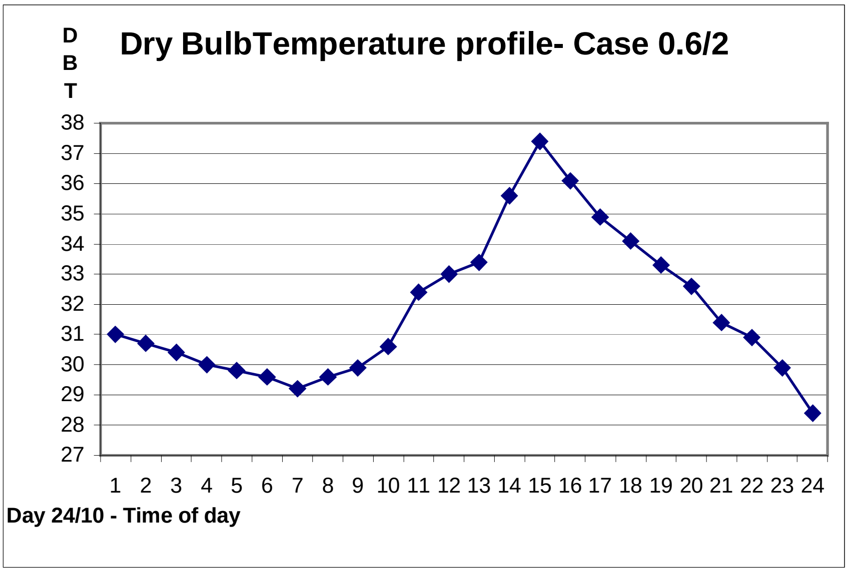


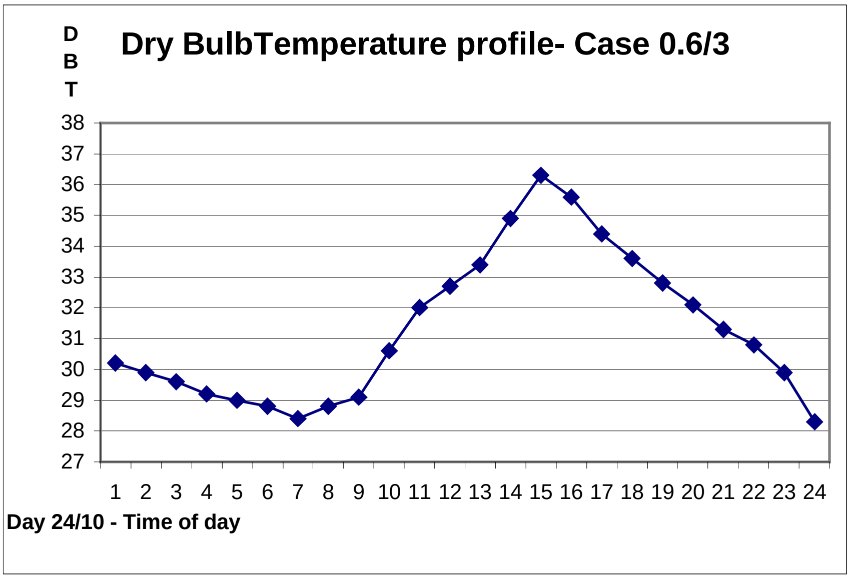




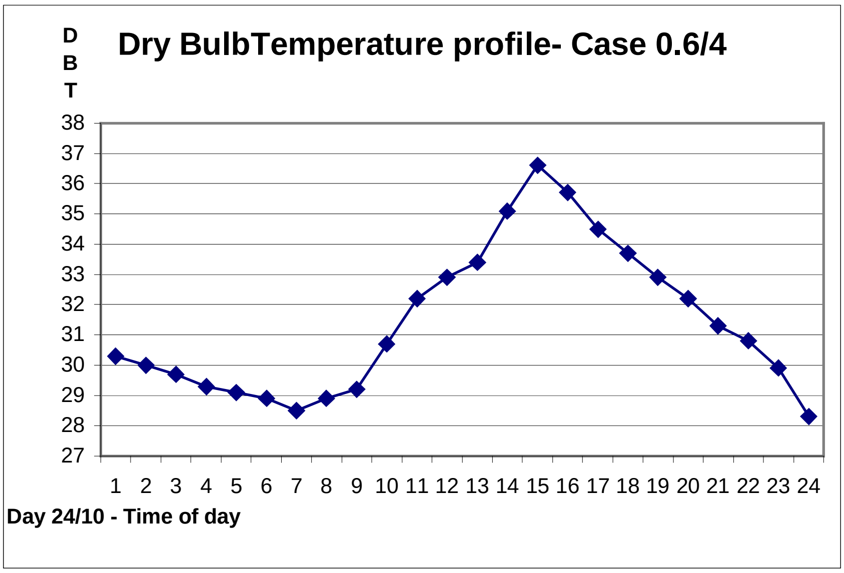
Graphs. 4.49-4.51. DBT profile Cases 0.4 (16-18)

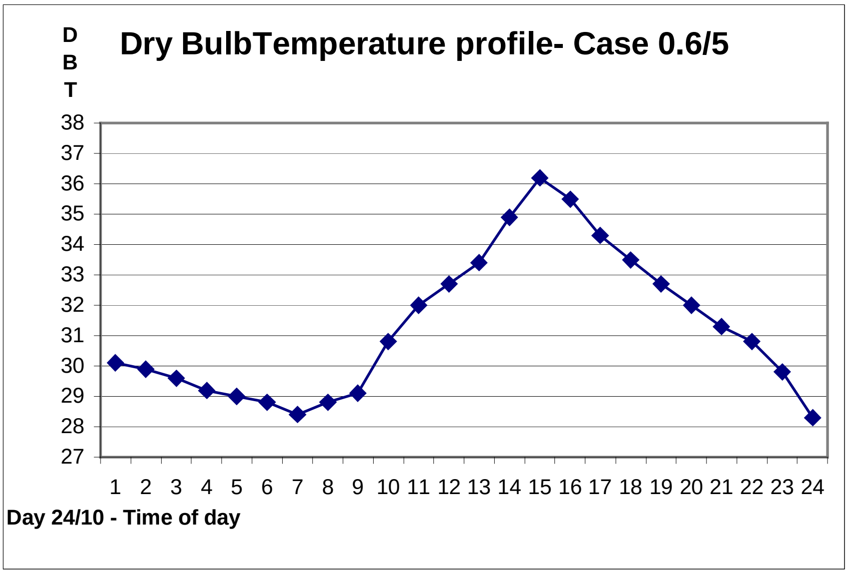


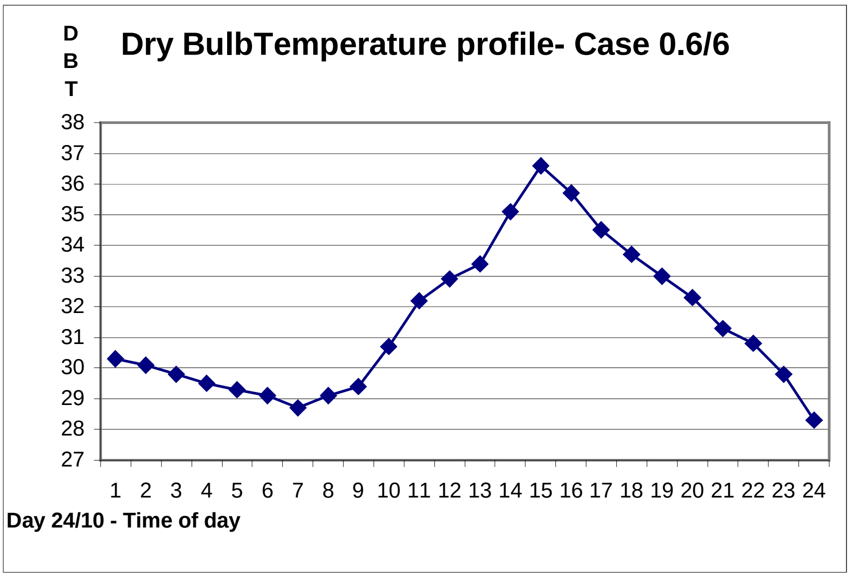




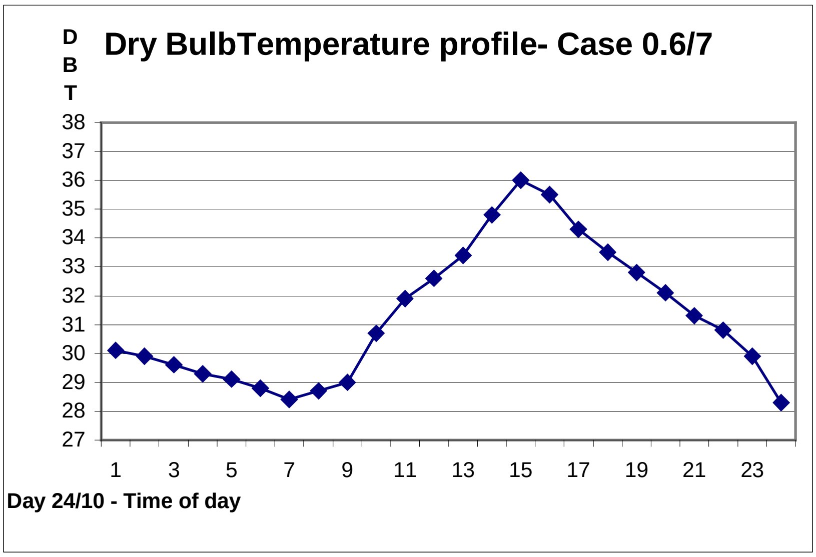
Graphs. 4.52-4.54. DBT profile Cases 0.6 (1-3)

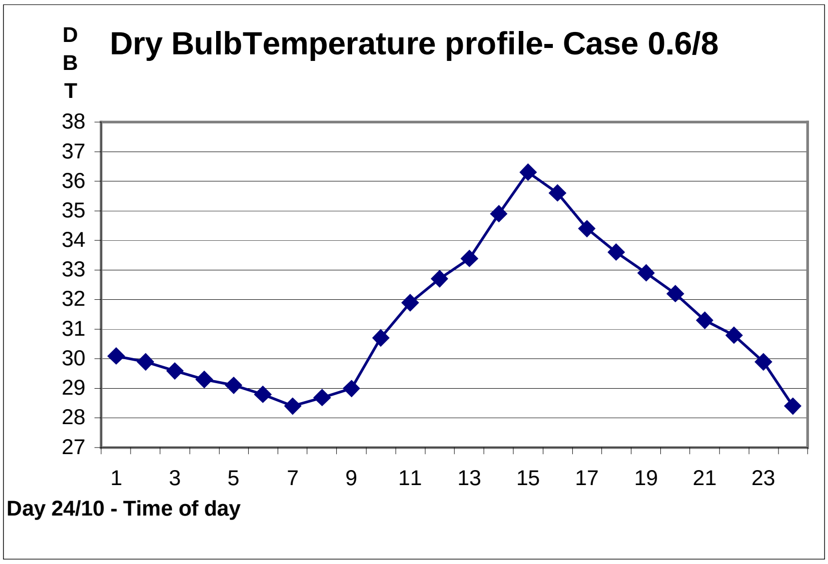


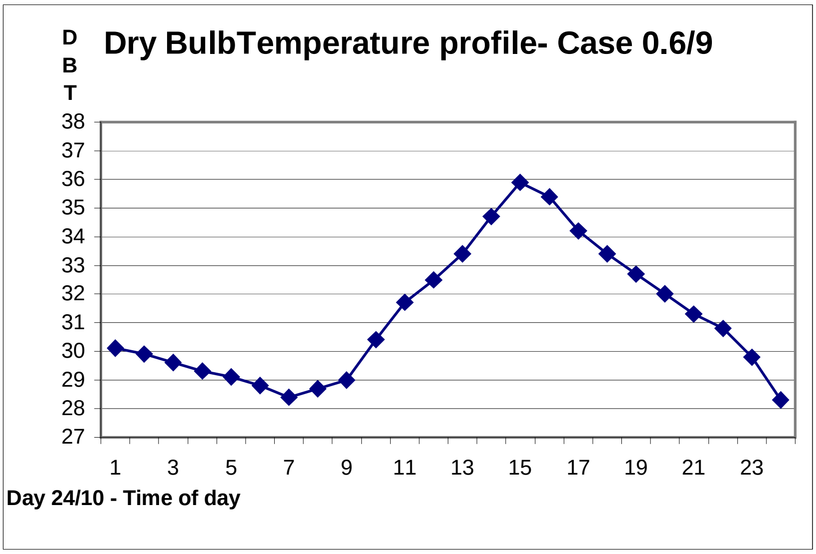




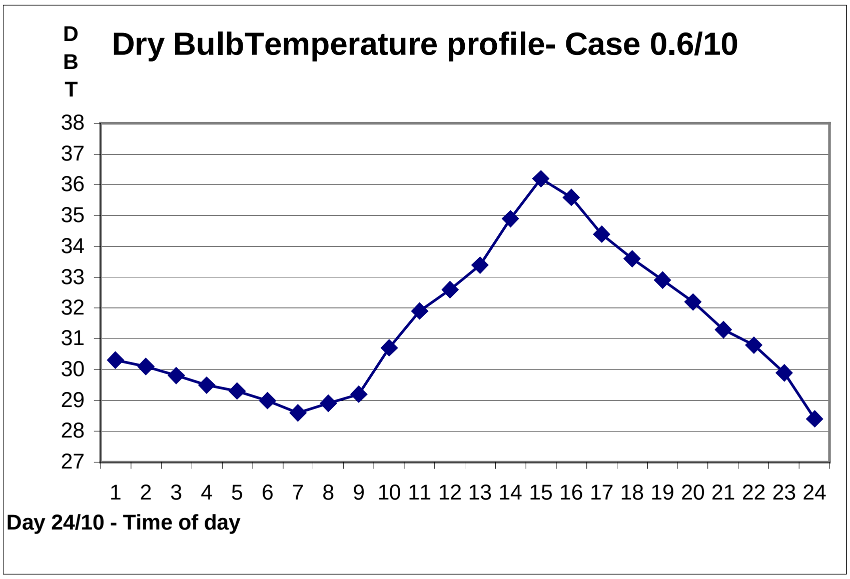
Graphs. 4.55-4.57. DBT profile Cases 0.6 (4-6)

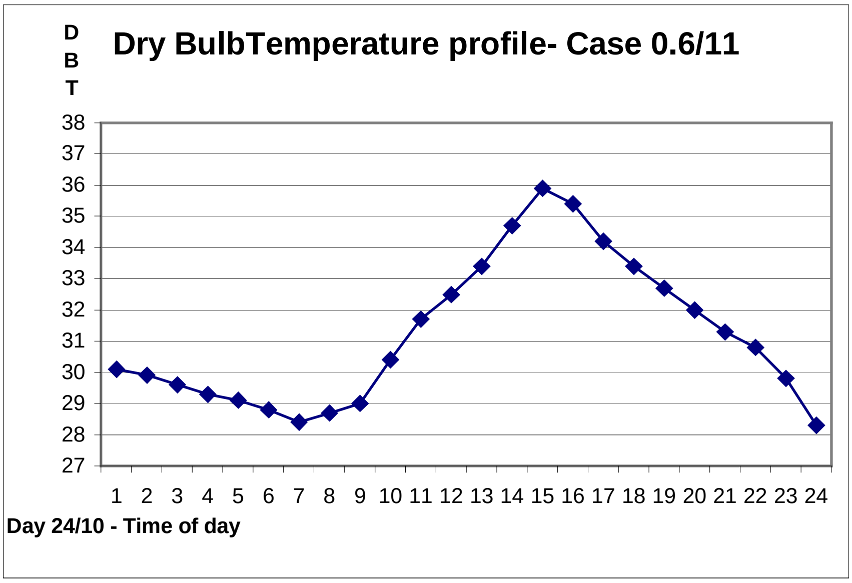


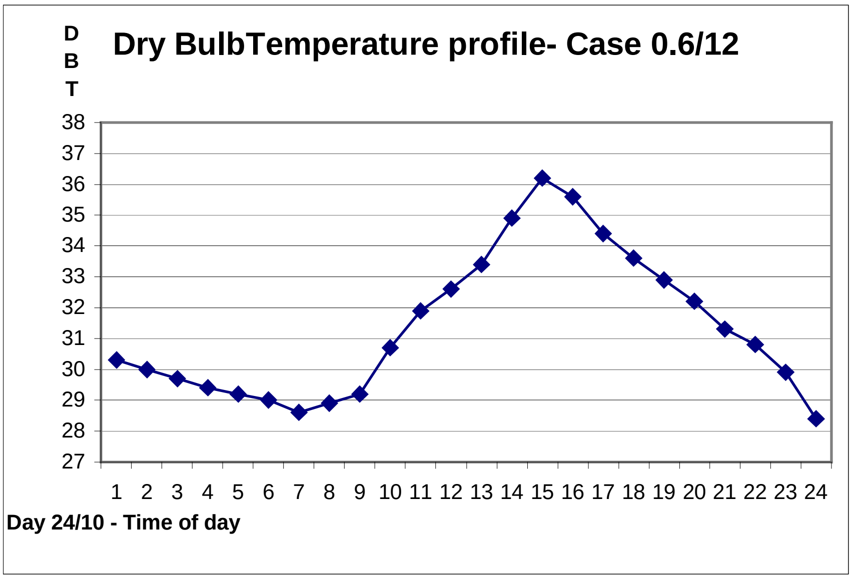




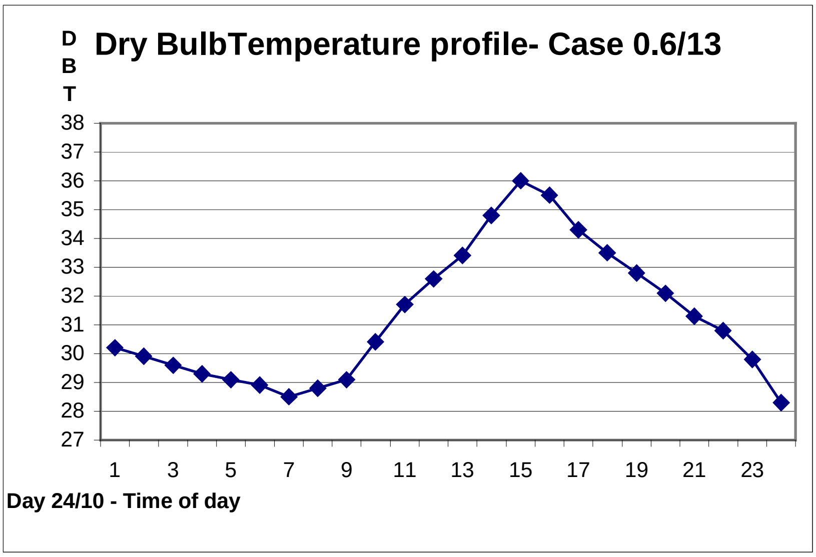
Graphs. 4.58-4.60. DBT profile Cases 0.6 (7-9)







Graphs. 4.61-4.63. DBT profile Cases 0.6 (10-12)


Dry BulbTemperature profile- Case 0.6/13
DBT
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15
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19
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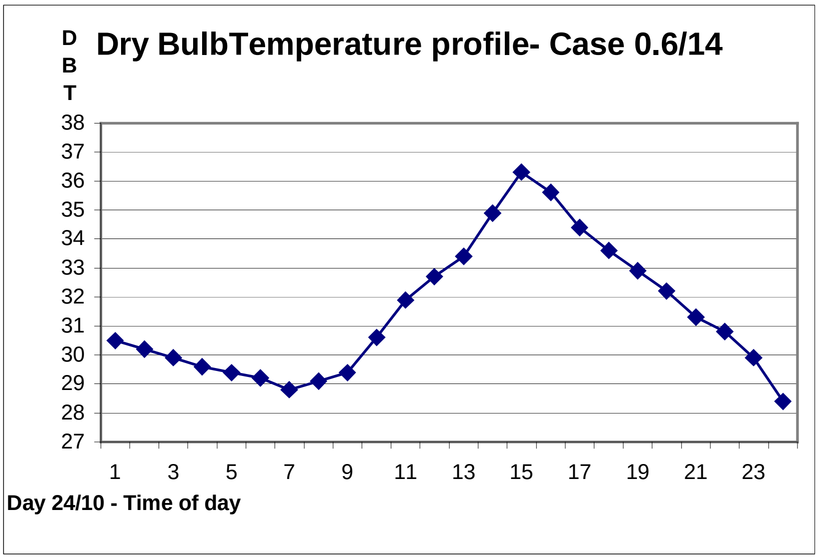
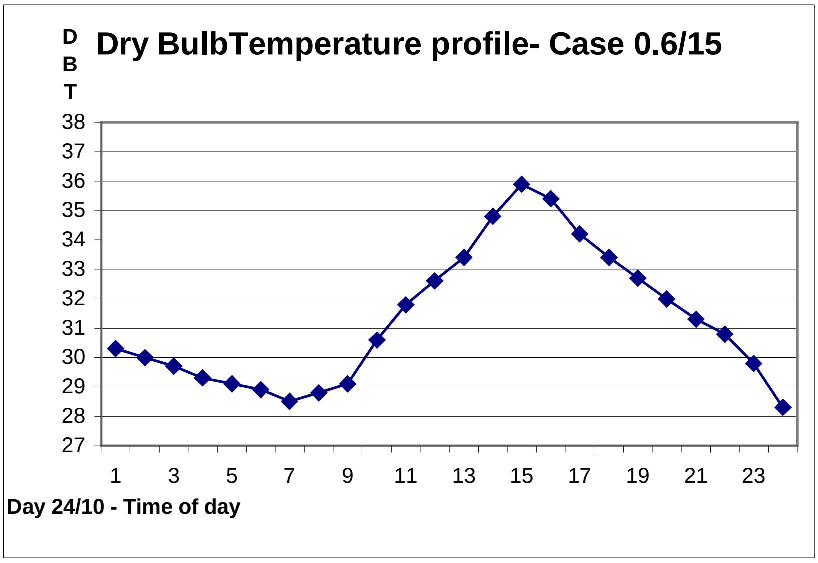
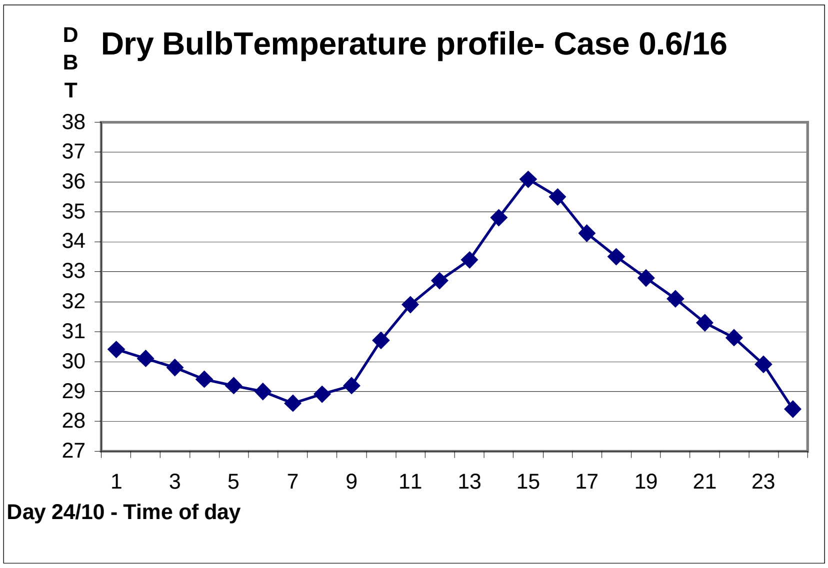
23
Day 24/10 - Time of day





Graphs. 4.64-4.66. DBT profile Cases 0.6 (13-15)


Dry BulbTemperature profile- Case 0.6/16
DBT
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11
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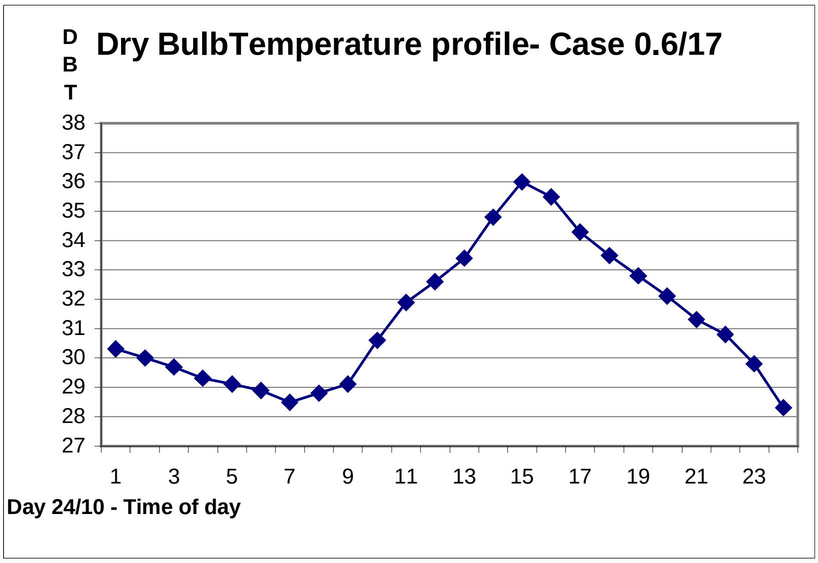
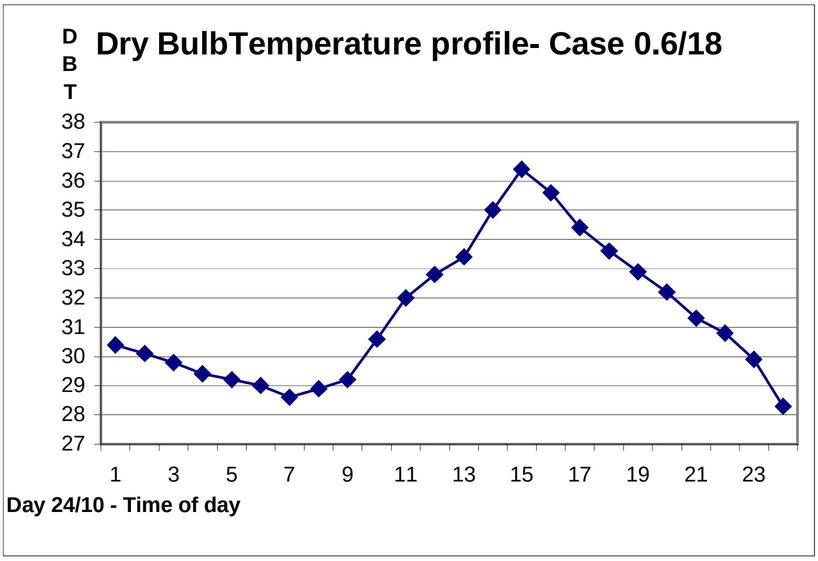
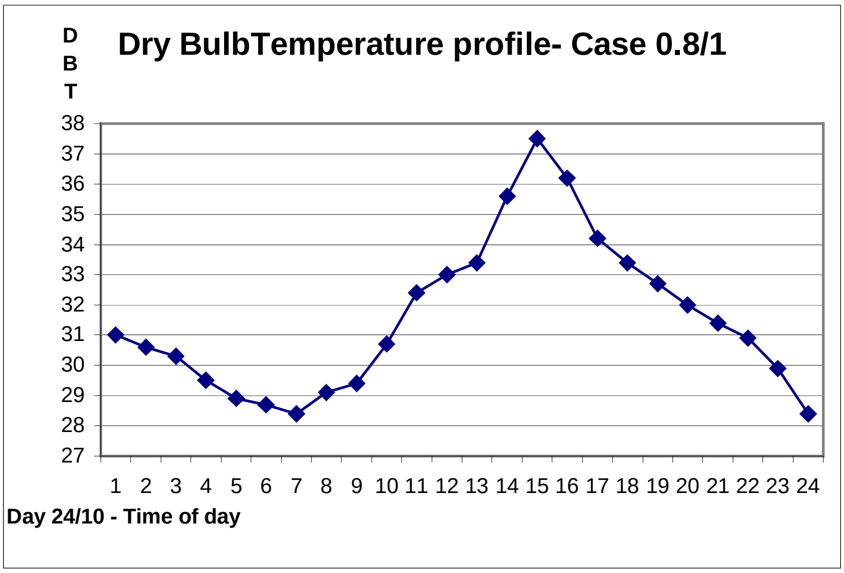
17
19
21
23
Day 24/10 - Time of day





Graphs. 4.67-4.69. DBT profile Cases 0.6 (16-18)


Dry BulbTemperature profile- Case 0.8/1
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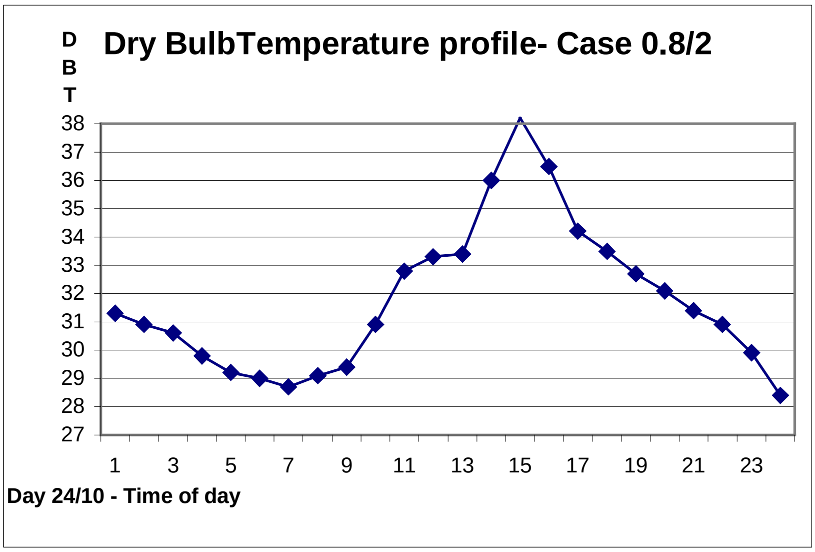
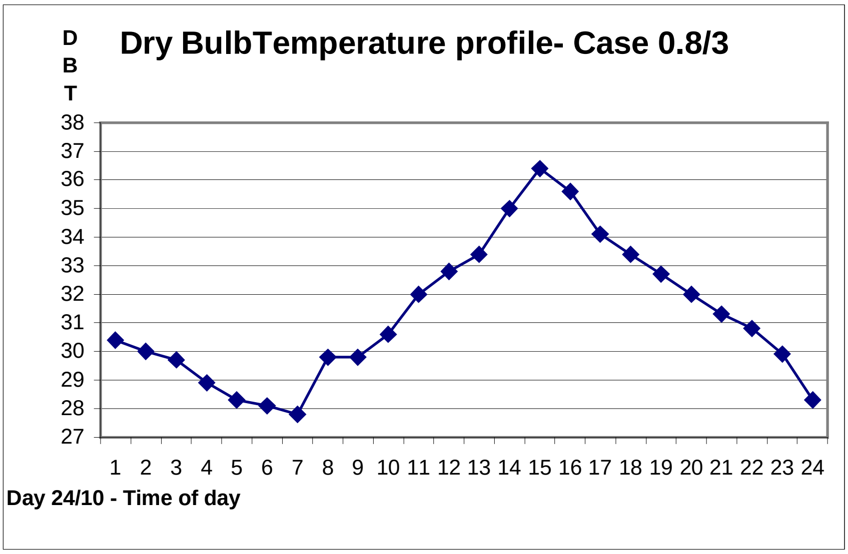
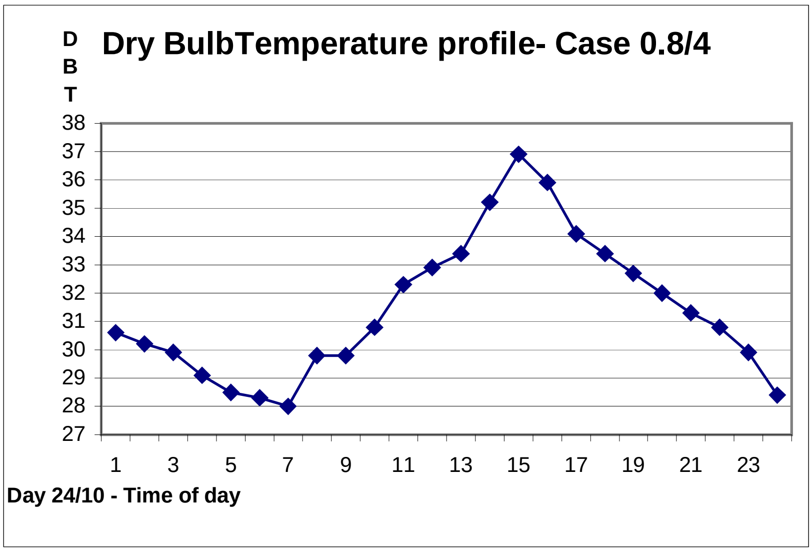
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Day 24/10 - Time of day





Graphs. 4.70-4.72. DBT profile Cases 0.8 (1-3)


Dry BulbTemperature profile- Case 0.8/4
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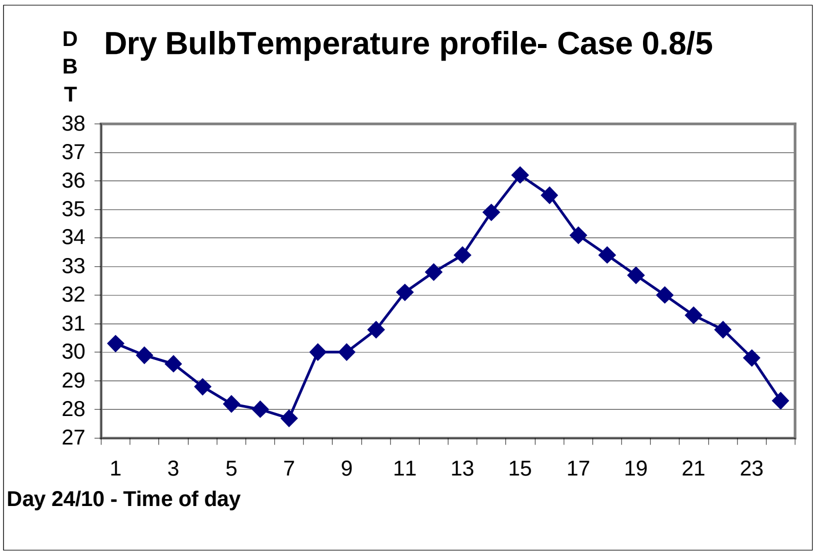
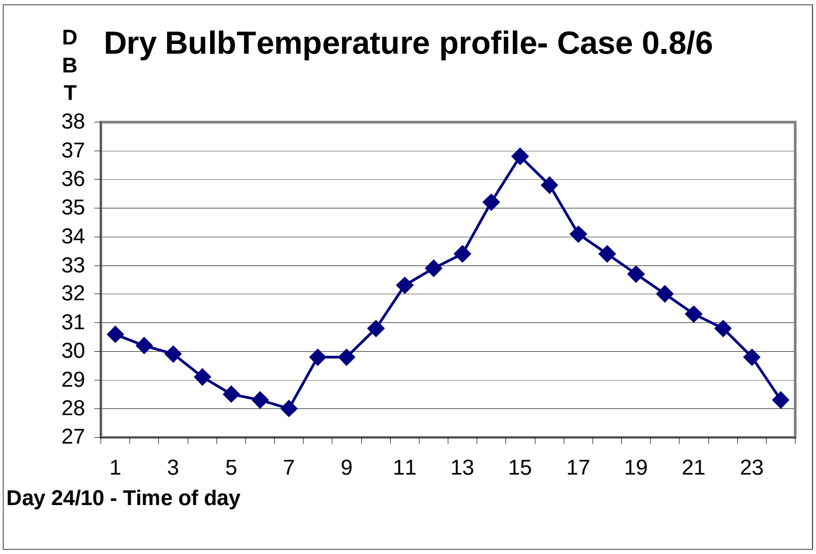
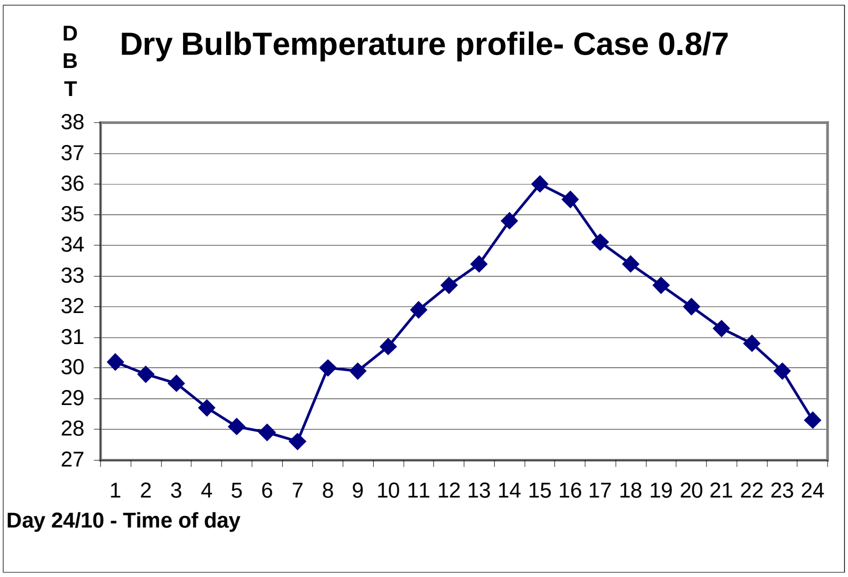
1 3 5 7 9 11 13 15 17 19 21 23
Day 24/10 - Time of day





Graphs. 4.73-4.75. DBT profile Cases 0.8 (4-6)


Dry BulbTemperature profile- Case 0.8/7
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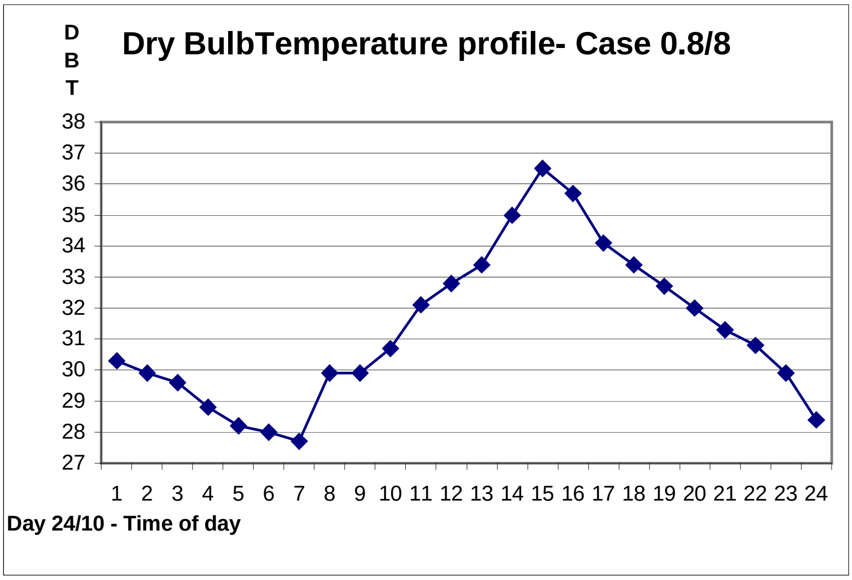
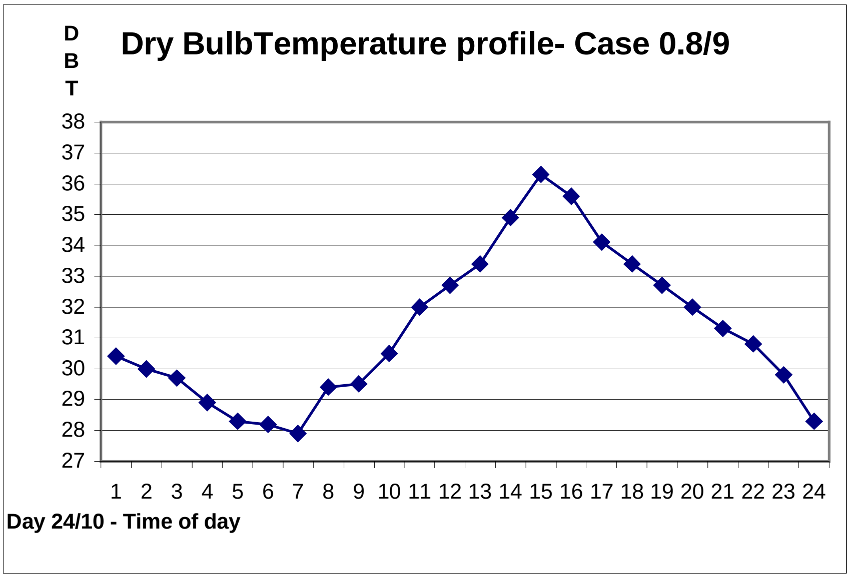
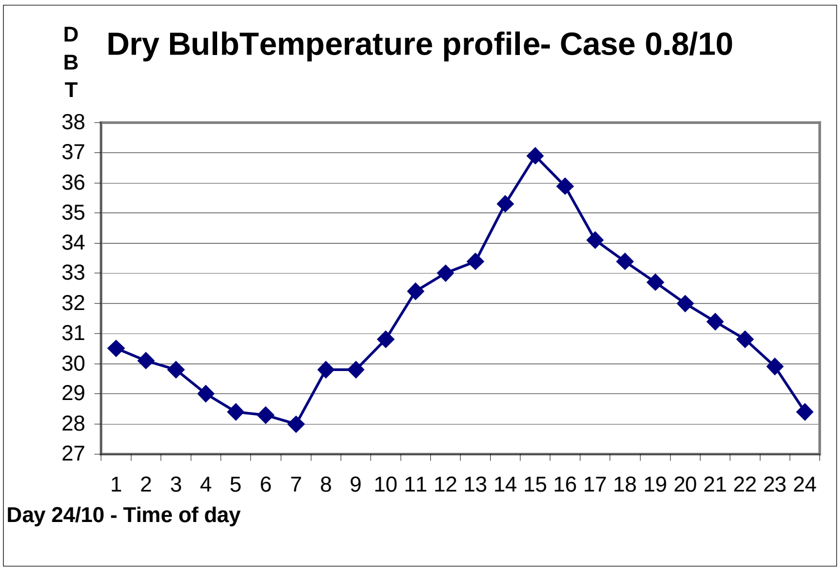
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Day 24/10 - Time of day





Graphs. 4.76-4.78. DBT profile Cases 0.8 (7-9)


Dry BulbTemperature profile- Case 0.8/10
DBT
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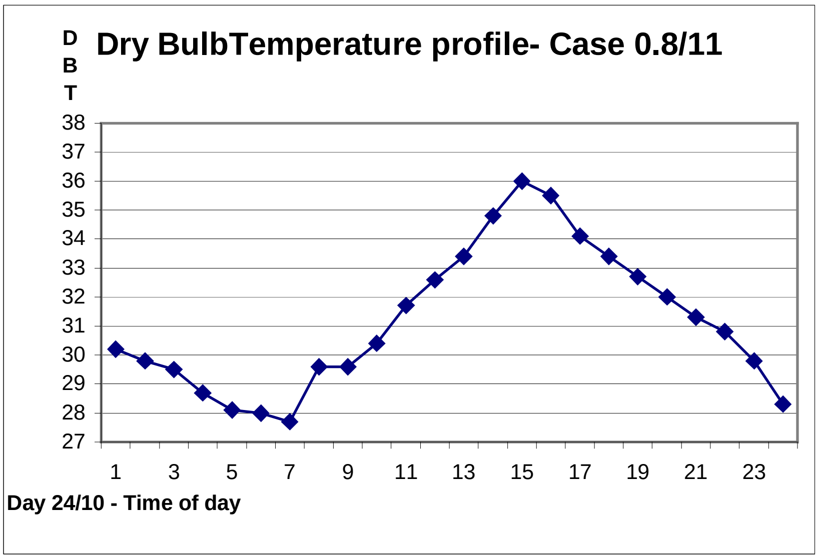
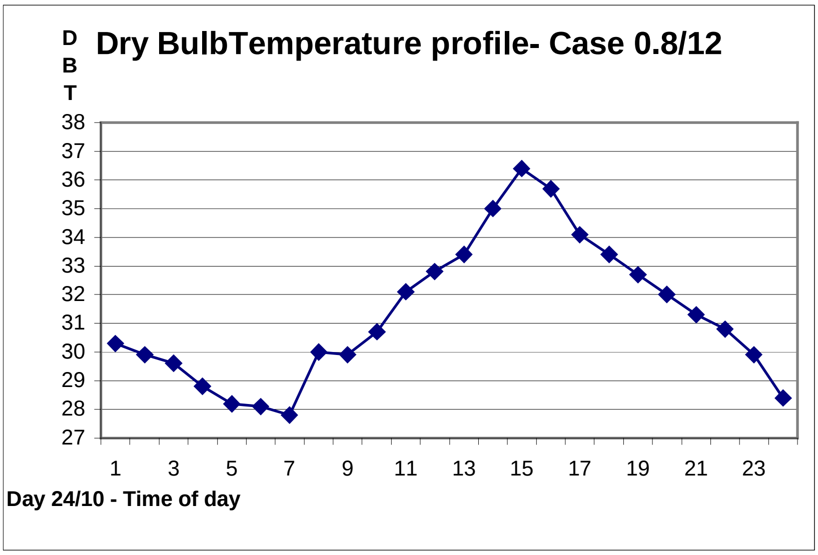
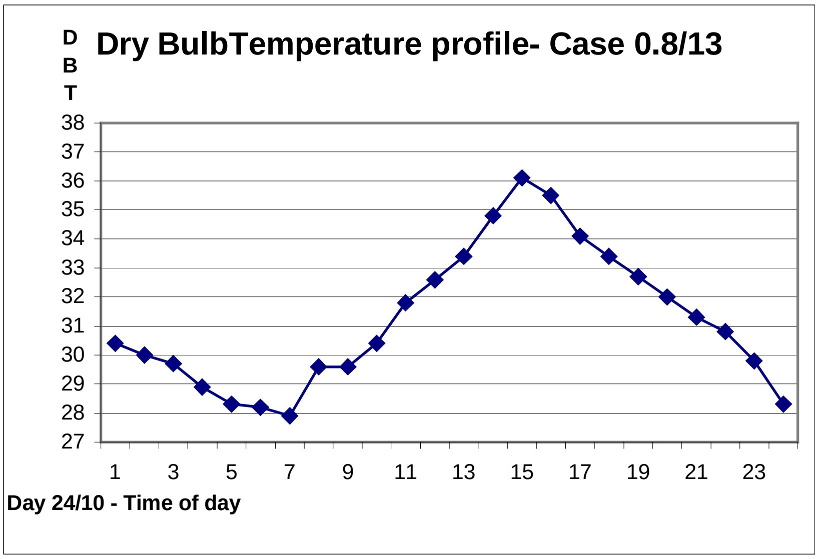
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Day 24/10 - Time of day





Graphs. 4.79-4.81. DBT profile Cases 0.8 (10-12)


Dry BulbTemperature profile- Case 0.8/13
DBT
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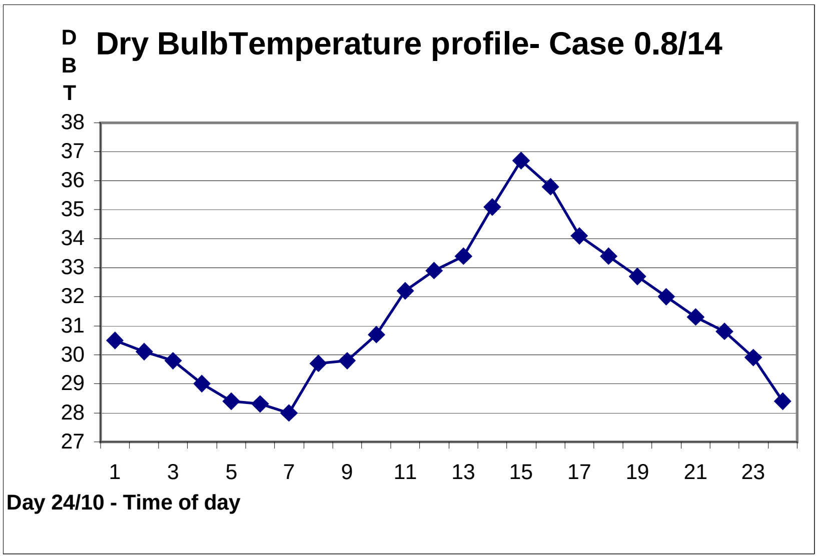
1 3 5 7 9 11 13 15 17 19 21 23
Day 24/10 - Time of day


Dry BulbTemperature profile- Case 0.8/14
DBT
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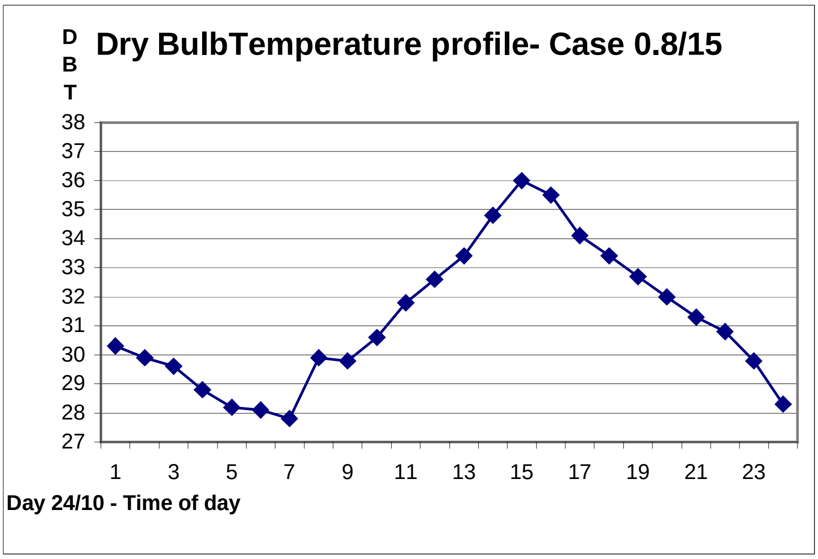
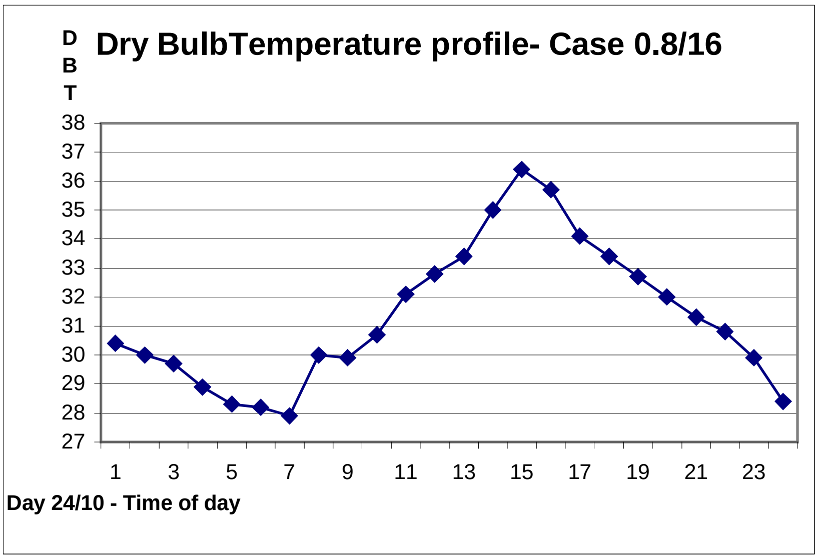
1 3 5 7 9 11 13 15 17 19 21 23
Day 24/10 - Time of day



Graphs. 4.82-4.84. DBT profile Cases 0.8 (13-15)


Dry BulbTemperature profile- Case 0.8/16
DBT
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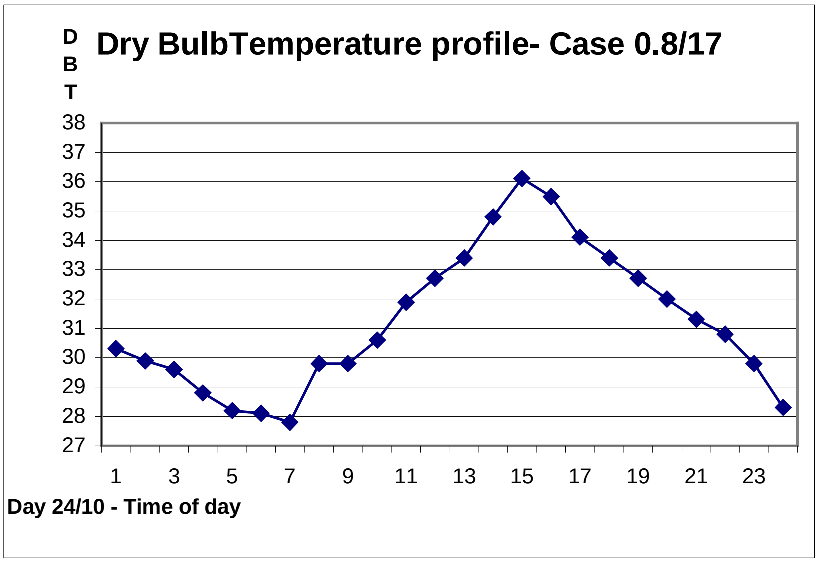
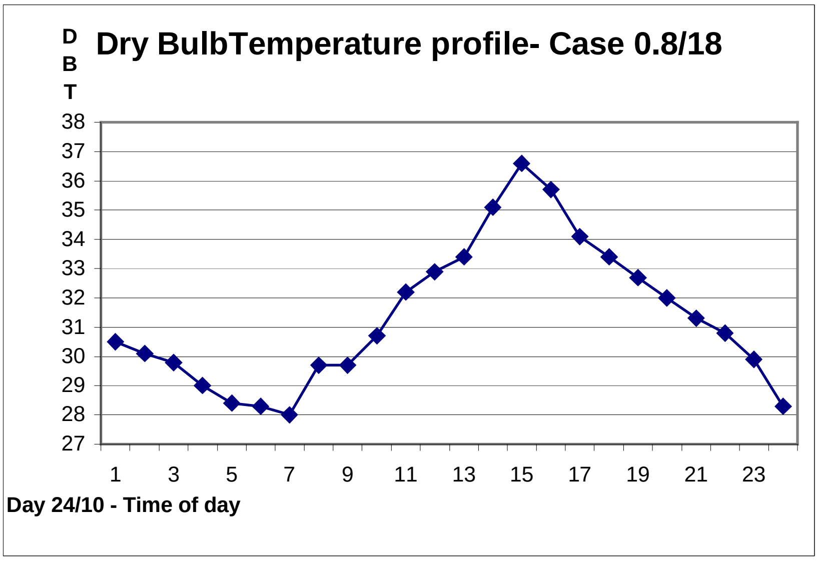
Day 24/10 - Time of day





Graphs. 4.85-4.87. DBT profile Cases 0.8 (16-18)

5.0 References

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6.0 Appendix