OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
CALCULATION COVER SHEET

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1. PURPOSE

The objective of this calculation is to predict the temperatures of the ventilating air, waste package surface, and concrete pipe walls that will be developed during the Phase II ventilation tests involving various test conditions. The results will be used as inputs to validating numerical approach for modeling continuous ventilation, and be used to support the repository subsurface design.

The scope of the calculation is to identify the physical mechanisms and parameters related to thermal response in the Phase II ventilation tests, and describe numerical methods that are used to calculate the effects of continuous ventilation. The calculation is limited to thermal effect only.

This engineering work activity is conducted in accordance with the *Technical Work Plan for: Subsurface Performance Testing for License Application (LA) for Fiscal Year 2001* (CRWMS M&O 2000d). This technical work plan (TWP) includes an AP-2.21Q, *Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities*, activity evaluation (CRWMS M&O 2000d, Addendum A) that has determined this activity is subject to the YMP quality assurance (QA) program. The calculation is developed in accordance with the AP-3.12Q procedure, *Calculations*. Additional background information regarding this activity is contained in the *Development Plan for Ventilation Pretest Predictive Calculation* (DP) (CRWMS M&O 2000a).

2. METHOD

The calculation uses the numerical code ANSYS Version 5.6.2 (CRWMS M&O 2001c), a recently baselined software version, and Microsoft Excel 97 SR-2 spreadsheet to predict the temperatures of the air, the carbon steel pipe simulating waste package, and the concrete pipe simulating the emplacement drift for the Phase II ventilation tests. The scientific laws applied for predicting temperature distributions include Fourier’s Law of heat conduction, Newton’s Law of cooling, and the Stefan-Boltzmann Law of thermal radiation. Only two-dimensional cases were analyzed. Additional details of the approach used in the calculation are provided in Section 5. There is no variance in the method used from that planned (CRWMS M&O 2000a, Section 2).

Primary data were selected from the Technical Information Center (TIC), Document Control (DC), and other inputs in accordance with the AP-3.15Q procedure, *Managing Technical Product Inputs*. The control of the electronic management of data was accomplished in accordance with Sections 6 and 8 of the DP (CRWMS M&O 2000a, Sections 6 and 8), which indicates that no special controls are applicable, and the TWP (CRWMS M&O 2000d, Section 10).

3. ASSUMPTIONS

The following assumptions are made in the calculations:

3.1 The temperature of the air outside the insulation is assumed to remain constant at 25°C. The tests will be conducted indoor, and the indoor air temperature is planned to be controlled and measured. Any difference between the measured indoor air temperature and the assumed value will be considered in the adjustment of inputs to the posttest calculations. Therefore, further confirmation of this assumption for the purposes of this calculation is not required. Used in Section 5.

3.2 The initial temperature of the whole system is assumed to be 25°C. This temperature condition is planned to be controlled prior to the initiation of each series of tests (see Section 5.3.4.1). Any difference between the measured initial temperature and the assumed value will be considered in the adjustment of inputs to the posttest analysis. Therefore, further confirmation of this assumption for the purposes of this calculation is not required. Used in Section 5.

3.3 The assumed depth of invert is about 0.21 m. This dimension was measured during the test setup. Further confirmation of this assumption for the purposes of this calculation is not required. Used in Figure 5-1 and Attachment XIII.

3.4 The thickness of waste package steel pipe is assumed to be 0.0095 m. This dimension was measured from the steel pipe used for the test. Further confirmation of this assumption for the purposes of this calculation is not required. Used in Section 5.

3.5 The steel rod used for heater is assumed to have a diameter of 0.12 m and be located off-center close to the top of carbon steel pipe simulating waste package. The diameter was chosen to ensure numerical convergence in calculation since a rod with a very small diameter would cause divergence of the thermal analysis involving radiation. The use of off-center location is intended to simulate the effect of natural convection or air circulation within the waste package pipe, and should logically to result in a higher temperature near the top than near the bottom. Therefore, further confirmation of this assumption for the purposes of this calculation is not required. Used in Section 5.

3.6 The assumed density and thermal conductivity values used for the insulation material are listed in Table 5-3. Because these are based on the manufacturer's specifications (CertainTeed 1996) for the material used in the tests, they are appropriate and adequate for use in this calculation. Further confirmation of this assumption for the purposes of this calculation is not required. Used in Section 5.1.4.

3.7 The gap between two adjacent simulated waste package steel pipes is assumed to be 0.0254 m (1 in.). This dimension was measured during the test setup. Further confirmation of this assumption for the purposes of this calculation is not required. Used in Section 5.1.8.

3.8 The assumed density, thermal conductivity, and specific heat used for the invert material are listed in Table 5-4. These are based on the *Thermal and Physical Properties of Granular Materials* (CRWMS M&O 2000b, Item 2, Tables 4 and 6). They are appropriate for use in this calculation because they represent equivalent invert materials used in the ventilation tests. The values were also visually evaluated and judged as being reasonable and within the expected range for the materials tested. They are considered adequate for use in this predictive calculation, as variations of these properties and their impact will be addressed in the future posttest calculation or analysis. Used in Section 5.1.5.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 ANSYS COMPUTER SOFTWARE

A commercially available computer program, ANSYS Version 5.6.2 (CRWMS M&O 2001c, STN: 10145-5.6.2-00), was used to perform the pretest prediction calculations. ANSYS is a general purpose, finite-element analysis code, and is used in many disciplines of engineering such as structural, geotechnical, and mechanical, dealing with behavior of solids and fluids, including thermal response. ANSYS is installed on the Silicon Graphics (SGI) workstation with the Unix operating system (CRWMS M&O CPU#114441, located in Las Vegas, Nevada). ANSYS Version 5.6.2 has been verified and validated (CRWMS M&O 2001c) according to the AP-SI.1Q procedure, *Software Management*. The input and output files generated by ANSYS were submitted to the Technical Data Management System (TDMS) and the Records Processing Center (RPC) (DTN: MO0108MWDPPP18.012). The results are presented and described in Section 6 and Attachments I through XII. A detailed discussion of the general features and fields of application of the ANSYS code is presented in the *Software Users Manual ANSYS Version 5.6.2 Software* (CRWMS M&O 2001b).

The ANSYS Version 5.6.2 software was obtained from the Software Configuration Management (SCM) in accordance with the AP-SI.1Q procedure. The software was appropriate for the applications used in this calculation. The software was used within the range of validation as specified in the software qualification report (CRWMS M&O 2001a).

4.2 SPREADSHEET SOFTWARE

Microsoft Excel 97 SR-2 spreadsheet software was used in displaying some of the ANSYS results graphically and calculating the air temperatures. In the former application, the results from ANSYS analyses, such as temperatures, were used as inputs, and the outputs are presented in the forms of figures generated using Excel in Attachments I through XII. In the latter application, simple arithmetic operations, such as addition, subtraction, multiplication, and division, were used. User-defined formulas and/or algorithms are displayed where used. Both the inputs and outputs used in Excel are contained in DTN: MO0108MWDPPP18.012.

Microsoft Excel 97 SR-2 is an exempt software product in accordance with the AP-SI.1Q procedure.

5. CALCULATION

This section presents the inputs and approaches used in the calculation. The sources of inputs are documented in accordance with the AP-3.15Q procedure.

5.1 INPUTS

5.1.1 Stefan–Boltzmann Constant

For thermal radiation calculations, the Stefan–Boltzmann constant value of 5.669×10^{-8} $W/m^2 \cdot K^4$ is used (Holman 1997, p. 396).

5.1.2 Physical and Thermal Properties for Simulated Waste Package

The physical and thermal properties used in the calculation for the simulated waste package and heating rod are listed in Table 5-1. These values are for carbon steel material. The values of density, thermal conductivity, and specific heat are the averages over a temperature range of 20°C to 100°C measured for the corresponding parameters (Stroe 2001, p. 3). The emissivity value is obtained based on the *Heat Transfer* for sheet steel (Holman 1997, Table A-10, p. 651).

According to the *Conceptual Arrangement Simulated Emplacement Ventilation Test* (CRWMS M&O 2000c), the designed diameter of the waste package pipe is 0.4064 m (16 in.).

Table 5-1. Physical and Thermal Properties for Simulated Waste Package

Parameter	Value
Density (kg/m^3)	7840[a]
Thermal Conductivity (W/m·K)	38.93[a]
Specific Heat (J/kg·K)	420.01[a]
Emissivity	0.8[b]

Note: [a] Stroe 2001, p.3. Averaged over a temperature range of 20 to 100°C.
[b] Holman 1997, Table A-10, p. 651 for sheet steel.

5.1.3 Physical and Thermal Properties for Concrete Pipe

The physical and thermal properties for the concrete pipe used in the calculation are listed in Table 5-2. The values of density, thermal conductivity, and specific heat are the averages over a temperature range of 20°C to 100°C measured for the corresponding parameters (Stroe 2001, p. 3). The emissivity value is obtained based on the *Fundamentals of Heat and Mass Transfer* (Incropera and DeWitt 1985, Tables A.11).

The designed inner and outer diameters of the concrete pipe are 1.3716 m (54 in.) and 1.651 m (65 in.), respectively (CRWMS M&O 2000c).

Table 5-2. Physical and Thermal Properties for Concrete Pipe

Parameter	Value
Density (kg/m^3)	2280[a]
Thermal Conductivity (W/m·K)	2.64[a]
Specific Heat (J/kg·K)	1048.08[a]
Emissivity	0.93[b]

Note: [a] Stroe 2001, p.3. Averaged over a temperature range of 20 to 100°C.
[b] Incropera and DeWitt 1985, Table A.11.

5.1.4 Physical and Thermal Properties for Insulating Material

The physical and thermal properties for the insulating material (fiber glass) used in the calculation are listed in Table 5-3. The density and thermal conductivity are obtained from the *Standard Fiber Glass Duct Wrap* provided by the manufacturer (CertainTeed 1996). For use of these values, see Assumption 3.6. The other thermal property values are obtained based on the *Heat Transfer* (Holman 1997, Table A-3) and the *Fundamentals of Heat and Mass Transfer* (Incropera and DeWitt 1985, Tables A.11).

The designed thickness of the insulation is 0.0508 m (2 in.) (CRWMS M&O 2000c).

Table 5-3. Physical and Thermal Properties for Insulating Material

Parameter	Value
Density (kg/m^3)	12[a]
Thermal Conductivity (W/m·K)	0.040[a]
Specific Heat (J/kg·K)	700[b]
Emissivity	0.96[c]

Note: [a] CertainTeed 1996.
[b] Holman 1997, Table A-3.
[c] Incropera and DeWitt 1985, Table A.11, selected from a range of 0.93 to 0.96 for asbestos sheet.

5.1.5 Physical and Thermal Properties for Invert Material

The physical and thermal properties for the invert material (4-10 crushed tuff) used in the calculation are listed in Table 5-4. The density, thermal conductivity, and specific heat values are assumed based on the *Thermal and Physical Properties of Granular Materials* (CRWMS M&O 2000b, Item 2, Tables 4 and 6) (see Assumption 3.8 for use in this calculation). The emissivity is obtained based on the *Fundamentals of Heat and Mass Transfer* (Incropera and DeWitt, Table A.11).

Table 5-4. Physical and Thermal Properties for Invert Material

Parameter	Value
Density (kg/m^3)	2530[a]
Thermal Conductivity (W/m·K)	0.16[b]
Specific Heat (J/kg·K)	930[b]
Emissivity	0.93[c]

Note: [a] CRWMS M&O 2000b, Item 2, Table 4, a mean value for fine crushed tuff.
[b] CRWMS M&O 2000b, Item 2, Table 6, mean values for 4-10 crushed tuff.
[c] Incropera and DeWitt 1985, Table A.11, selected from a range of 0.93 to 0.96 for red brick.

5.1.6 Physical and Thermal Properties for Waste Package Support

The physical and thermal properties for the waste package support (mild carbon steel) are listed in Table 5-5. The values of density, thermal conductivity, and specific heat are the averages over a temperature range of 20°C to 100°C measured for the corresponding parameters (Stroe 2001, p.

3). The emissivity value is obtained based on the *Heat Transfer* for sheet steel (Holman 1997, Table A-10, p. 651).

Table 5-5. Physical and Thermal Properties for Waste Package Support

Parameter	Value
Density (kg/m^3)	7800[a]
Thermal Conductivity (W/m·K)	50.20[a]
Specific Heat (J/kg·K)	483.05[a]
Emissivity	0.8[b]

Note: [a] Stroe 2001, p.3. Averaged over a temperature range of 20 to 100°C.
[b] Holman 1997, Table A-10, p. 651 for sheet steel.

5.1.7 Physical and Thermal Properties for Air

The physical and thermal properties for air at temperatures of 25°C, 35°C, and 45°C are listed in Table 5-6. These values are interpolated from the data based on *Heat Transfer* (Holman 1997, Table A-5).

Table 5-6. Physical and Thermal Properties for Ventilation Air at 298K (25°C), 308K (35°C), and 318 K (45°C)

Parameter	At 298 K (25°C)	At 308 K (35°C)	At 318 K (45°C)
Density (kg/m^3)	1.1868	1.1487	1.1128
Thermal Conductivity (W/m·K)	0.0261	0.0269	0.0276
Specific Heat (J/kg·K)	1,005.7	1,006.2	1,006.9
Dynamic Viscosity (kg/m·s)	1.8363×10^{-5}	1.8828×10^{-5}	1.9286×10^{-5}
Prandtl Number (dimensionless)	0.709	0.706	0.704

Source: Holman 1997, Table A-5. Interpolated for the temperatures considered.

5.1.8 Effective Length of Test Section

There are a total of twenty-five waste package steel pipes, each of which has a length of 1.3335 m (52.5 in.) (CRWMS M&O 2000c). The gap between two adjacent waste packages is 0.0254 m (see Assumption 3.7). So, the effective length of test section where the waste packages are located is about 33.95 m (111.38 feet) (25 × 52.5 in. + 24 × 1 in. = 1,336.5 in. = 111.38 ft.).

5.1.9 Controlled Test Parameters and Values

There are four controlled test parameters. They are the power level, intake air volume or flow rate, intake air temperature, and intake air relative humidity. Among them, the power level, intake air volume and temperature are used as inputs to this calculation. The proposed values for these parameters for the Phase II ventilation tests are listed in Table 5-7, based on the *Guidance for the Ventilation Test Rev 02* (Kramer 2001, Section 5.0, p. 3).

Table 5-7. Controlled Test Parameters and Values

Power Level (kW/m)	Intake Air Volume (m^3/s)	Intake Air Temperature (ºC)
0.18 and 0.36	0.5 and 1.0	25, 35, and 45

Source: Kramer 2001, Section 5.0, p. 3.

5.2 THEORETICAL BACKGROUND

Heat transfer mechanisms in the ventilation tests involve conduction, convection, and radiation. Conductive heat flow occurs within the waste package pipe, invert, concrete pipe, and insulating material whenever there is a thermal gradient. Convective heat transfer occurs between the waste package surface and the ventilating air as well as between the concrete wall and the air. Electromagnetic radiation heat transfer occurs between the waste package pipe outside surface and the concrete pipe, between the waste package pipe outside surface and the invert surface, and the heating rod surface and the waste package inside surface.

5.2.1 Conduction

According to Fourier's law of heat conduction, the general 3D heat conduction equation can be expressed in Cartesian coordinates as (Holman 1997, Equation 1-3, p. 5):

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q'''=\rho c_p\frac{\partial T}{\partial t} \quad \text{(Eq. 5-1)}$$

Where T = temperature, K
t = time, s
k = thermal conductivity, W/m·K
ρ = density, kg/m^3
q''' = heat generation rate per unit volume, W/m^3
c_p = specific heat, J/kg·K

Fourier's law of heat conduction is embedded in ANSYS thermal product. When a temperature gradient exists in a medium, such as concrete pipe or waste package, a heat or energy transfer from the high-temperature region to the low-temperature region by conduction occurs and is calculated by ANSYS with Fourier's law. Details on how heat conduction calculation is performed by ANSYS are discussed in the *Software Users Manual ANSYS Version 5.6.2 Software* (CRWMS M&O 2001b, p. II-18).

5.2.2 Convection

For an air-ventilated test section, the overall effect of convection can be evaluated using Newton's law of cooling (Holman 1997, Equation 1-8, p. 12):

$$q = hA(T_w - T_a) \quad \text{(Eq. 5-2)}$$

Where q = heat flow rate, W

h	=	convection heat transfer coefficient, W/m^2·K
A	=	convection surface area, m^2
T_w	=	concrete pipe or waste package surface temperature, K
T_a	=	ventilation air temperature, K

Newton's law of cooling is embedded in ANSYS thermal product. In addition, this equation is also used in Excel spreadsheets (see discussion in Section 5.3.3 below) to calculate the ventilating air temperature. Convection heat transfer occurs at the interface of a solid and a fluid due to a temperature gradient between these two media. In ANSYS thermal product, convection heat transfer is treated as a boundary condition, while in Excel spreadsheet, it is used in energy balance calculation. Hence, a convection heat transfer coefficient (h) and a fluid temperature (T_a) are required as inputs. Details on how Newton's law of cooling is used in ANSYS are provided in the *Software Users Manual ANSYS Version 5.6.2 Software* (CRWMS M&O 2001b, p. II-18). Discussion on the evaluation of convection heat transfer coefficient for continuous ventilation is presented in Section 5.3.3.2.

5.2.3 Radiation

The heat from the waste packages to the concrete wall is transferred mainly through thermal radiation. In the ANSYS predictive assessment, the waste packages are completely enclosed by the concrete pipe and invert, so the total radiant exchange can be calculated using the following equation based on the Stefan-Boltzmann law (Holman 1997, Equation 1-11, p. 14):

$$q = F_\varepsilon F_G \sigma A\left(T_w^4 - T_c^4\right) \qquad \text{(Eq. 5-3)}$$

Where	q	=	heat flow rate, W
	F_ε	=	emissivity function, dimensionless
	F_G	=	geometric view factor function, dimensionless
	σ	=	Stefan-Boltzmann constant with a value of 5.669×10^{-8} W/m^2·K^4
	A	=	radiation surface area, m^2
	T_w	=	absolute temperature of the waste package surface, K
	T_c	=	absolute temperature of the concrete pipe surface, K

The Stefan–Boltzmann law is embedded in ANSYS thermal product. In contract to the mechanisms of conduction and convection, where heat transfer through a material medium is involved, electromagnetic radiant heat exchange occurs without involvement of a material medium. Since the heat transfer due to radiation varies with the fourth power of the surface's absolute temperature, the thermal calculation is highly nonlinear. In ANSYS thermal calculation, radiation heat transfer is handled with the help of a radiation matrix generator. The radiation matrix generator involves generating a matrix of view factors between radiating surfaces and using the matrix as a superelement in the thermal analysis. It is used when the analysis involving two or more surfaces receiving and emitting radiant heat. Use of the radiation superelement in the thermal analysis with ANSYS is optional, and other methods are also available. Details on the thermal analysis involving radiation heat transfer are discussed in the *Software Users Manual ANSYS Version 5.6.2 Software* (CRWMS M&O 2001b, p. II-18).

5.2.4 Coupled Heat and Fluid Flow

In thermal analyses, three heat transfer mechanisms, conduction, convection, and radiation, are coupled within ANSYS code "automatically" depending on the number of mechanisms selected. In this predictive calculation for Phase II ventilation tests, the thermal analysis will require all three mechanisms to be coupled.

Evaluation of heat exchange in a ventilation test is a very complex three-dimensional, time-dependent, and coupled heat and fluid flow problem. The ANSYS thermal product used in this calculation can only handle heat transfer without fluid flow, at least not directly. Convection is treated as a boundary condition, which is different from many computational fluid dynamics (CFD) codes. To achieve the coupling of heat and fluid flow, a numerical approach is developed by using ANSYS for heat transfer, involving conduction, convection, and radiation, and Excel spreadsheet for fluid energy balance, involving convection only. Detail on the approach is presented in Section 5.3.3.1.

5.3 CALCULATION APPROACH

5.3.1 Calculation Configurations

The calculation configuration used in ANSYS thermal calculations is illustrated in Figure 5-1. The configuration contains a waste package, heating rod, waste package support, invert, concrete pipe, and insulation. The waste package is simulated by steel pipe, which encloses a heating rod locating off-center close to the top of waste package (Section 3.5). Materials for the waste package, heating rod, and waste package support are carbon steel. The invert is composed of crushed tuff. Material for the insulation is fiber glass (see Section 5.1.4). As will be discussed in Section 5.3.3.1, a two-dimensional analysis is used for the ventilation calculations.

5.3.2 Initial and Boundary Conditions

Initial temperature of the system including the waste package, concrete pipe, invert, waste package support, heating rod, and insulation is set at 25°C (Section 3.2).

Three types of boundary conditions, temperature, convection and radiation, are used in the calculation. A constant temperature of 25°C is prescribed on the outside surface of the insulation (Section 3.1). The convection and radiation boundaries exist on the surfaces of the heating rod, waste package, concrete pipe, invert, and waste package support.

5.3.3 Approach

As stated in Section 5.2.4, determination of heat exchange in a ventilation test section is a complex three-dimensional, time-dependent, and coupled heat and fluid flow problem. Due to the limitation and ANSYS thermal product, a numerical approach using the ANSYS computer code together with Excel spreadsheet is employed. A description of the approach is discussed below.

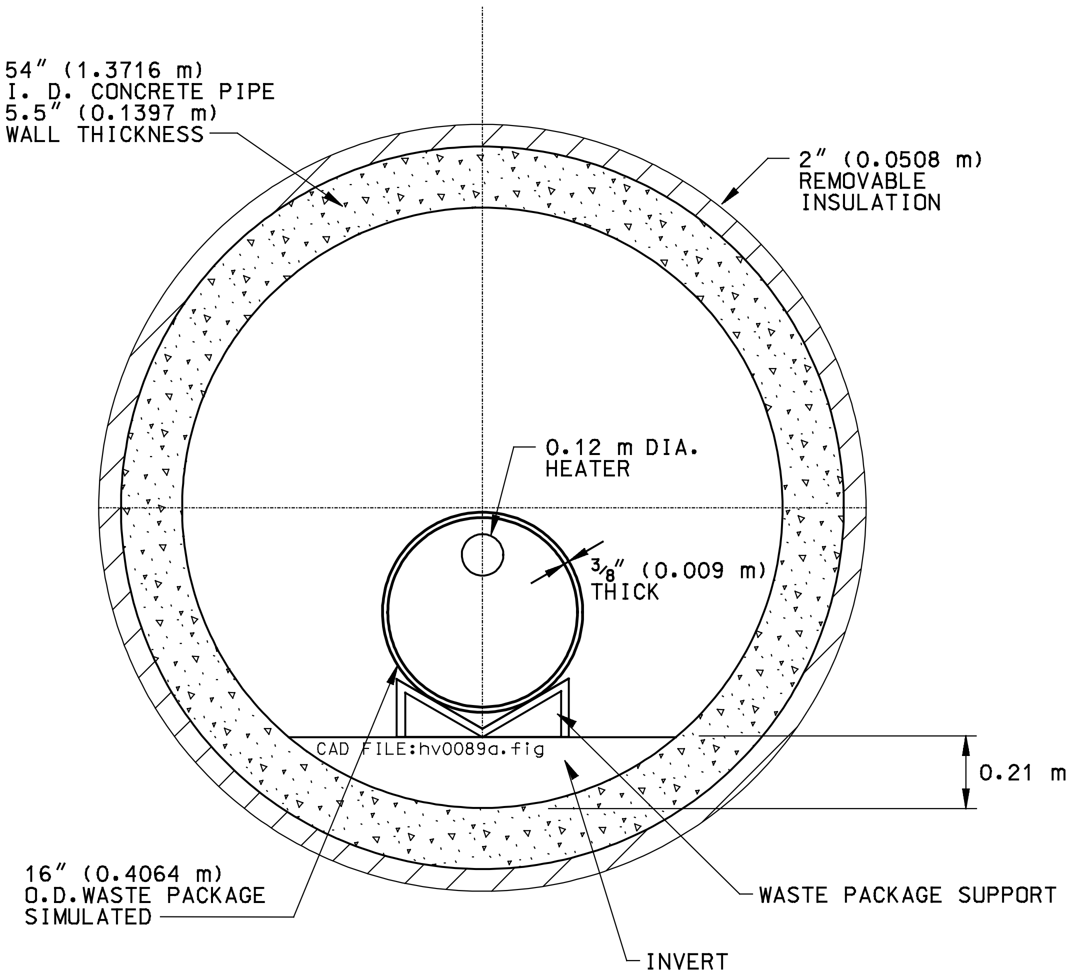

Figure 5-1. Configuration Used in ANSYS Calculations for Ventilation Test

5.3.3.1 Computation of Continuous Ventilation

First, an entire test section, subjected to continuous ventilation, with a length of *L* (see Section 5.1.8 for effective length of air flow) is divided into a finite number of segments, *m*. During this computation, the segments are treated as a series of connected elements, and the exit air temperature at a segment is used as an intake air temperature for the subsequent segment. The ventilating air, concrete pipe surface, and waste package surface temperatures at a specific time are set to be uniform over the length of a segment. Theoretically, the length of segments should be selected as short as possible so that the changing air, concrete pipe surface, and waste package surface temperatures along a segment can be reasonably represented by their averaged constants. But practically, a relatively long segment can be used as long as the results are not very sensitive to the segment length selected. If the length of a segment is changed, the number of divisions will be changed accordingly. The number of computational runs is equal to the number of divisions for each ventilation case analyzed.

For the purpose of reduction of computational effort, a 33.95-meter-long test section (Section 5.1.8) was divided into four (4) segments, with a length of about 8.49 meters for each segment.

Second, the ventilation time, t_{vent}, is partitioned into a number of time-steps, *n*, for each computational run. The size of each time-step, Δt_i, $i=1,2,\cdots,n$, is determined based on experience regarding the degree of computational accuracy. In this calculation, the size of time-steps selected varies from 1 hour to 72 hours for a computing time of up to 168 hours. Within each time step, the minimum and maximum sizes of sub-steps are defined to further control accuracy of calculations. The size of the first sub-step is equal to the minimum one. The sizes of other sub-steps are determined “automatically” by ANSYS based on computational convergence criteria, and may vary from one second to one hour.

Third, after the selection of segment length and time-step size, the ANSYS program is executed over the total ventilation duration for a total number of *m* times for each test case analyzed. Resulting concrete pipe and waste package surface temperatures for the currently calculated segment are utilized to calculate the average exhaust air temperatures of the segment by means of Newton’s cooling law (Equation 5-2). These exhaust air temperatures are then used as the intake air temperatures for the subsequent segment. This process is repeated until the computational run for the last segment is completed.

The approach described above is applicable to all cases analyzed in this calculation. The following outlines the process of using Newton’s cooling law (Equation 5-2) and energy balance (Equation 5-6 below) to calculate the rates of heat removal and the exhaust air temperatures in a segment.

The rates of heat removed from concrete pipe and waste package surfaces in a segment by ventilation are determined using Newton's cooling as follows:

$$q_w^i = hA_w\left(T_{wa}^i - T_{ain}^i\right) \qquad \text{(Eq. 5-4)}$$

and

$$q_p^i = hA_p\left(T_{pa}^i - T_{ain}^i\right) \quad \text{(Eq. 5-5)}$$

where
q^i_w = rate of heat removed from concrete pipe surface at time step *i*, W
q^i_p = rate of heat removed from waste package surface at time step *i*, W
h = convection heat transfer coefficient, $W/m^2{\cdot}K$
A_w = concrete pipe surface area, m^2
A_p = waste package surface area, m^2
T^i_{wa} = average concrete pipe surface temperature at time step *i*, K
T^i_{pa} = average waste package surface temperature at time step *i*, K
T^i_{ain} = intake air temperature at time step *i*, K

The exhaust air temperature is calculated based on Holman (1997, Equation 6-1, p. 286) as

$$T_{aout}^i = T_{ain}^i + \frac{q_w^i + q_p^i}{\dot{m}c} = T_{ain}^i + \frac{q_w^i + q_p^i}{Qpc} \quad \text{(Eq. 5-6)}$$

where
T^i_{aout} = exhaust air temperature, K
T^i_{ain} = intake air temperature, K
q^i_w = rate of heat removed from concrete pipe surface, W
q^i_p = rate of heat removed from waste package surface, W
m' = rate of air mass, kg/s ($m'=Q\rho$)
Q = ventilation air flow rate, m^3/s
ρ = density of air, kg/m^3
c = specific heat of air, J/kg·K

It is noted that use of Equations 5-4 and 5-5 will most likely overstate the rates of heat removed from concrete pipe and waste package surfaces, and consequently overstate the increase of ventilating air temperature estimated based on Equation 5-6. To improve the estimation of heat removal rates, some adjustments are needed. Three types of adjustments, so-called corrections, are discussed here. The first is related to the axial variation of air temperature, and called the spatial correction. With the spatial correction, the intake air temperature, T^i_{ain}, in Equations (5-4) and (5-5) is substituted by the average of the intake and exhaust air temperatures of a given segment at a given time step, to calculate the rates of heat removed by ventilation,

$$q_{rm}^i = \overline{q}_w^i + \overline{q}_p^i = hA_w\left(T_{wa}^i - T_{aa}^i\right) + hA_p\left(T_{pa}^i - T_{aa}^i\right) \quad \text{(Eq. 5-7)}$$

where
T^i_{aa} = average of intake and exhaust air temperature in a segment at time step *i*, defined as

$$T_{aa}^i = \frac{T_{ain}^i + T_{aout}^i}{2} \quad \text{(Eq. 5-8)}$$

where
T^i_{ain} = intake air temperature at time step *i*, K
T^i_{aout} = exhaust air temperature at time step *i*, K

This adjustment is considered because the temperatures of concrete pipe and waste package surfaces obtained from ANSYS calculations are the average over a segment analyzed, and therefore, the average ventilating air temperature should be used to reasonably estimate the ventilation heat removal rate.

The second adjustment is called the temporal correction, which is related to the variation of air temperature in time. This correction is achieved by substituting the intake air temperature, T^{i}_{ain}, in Equations (5-4) and (5-5) by the average of the intake air temperatures of a given segment at the previous time step *i-1* and the current time step *i*,

$$T_{aa}^{i} = \frac{T_{ain}^{i-1} + T_{ain}^{i}}{2} \quad \text{(Eq. 5-9)}$$

where	T^{i-1}_{ain}	=	intake air temperature at time step *i-1*, K
	T^{i}_{ain}	=	intake air temperature at time step *i*, K

The temporal correction is considered because in ANSYS calculations the convection air temperature is linearly interpolated between two sequential time steps. Without this adjustment, the heat removal rate will likely be understated.

The third correction is the combination of spatial and temporal corrections. With this correction, the intake air temperature, T^{i}_{ain}, in Equations (5-4) and (5-5) is substituted by the average of the intake air temperatures of a given segment at the previous time step *i-1* and the current time step *i* and the exhaust air temperature at the current time step *i*,

$$T_{aa}^{i} = \frac{T_{ain}^{i-1} + T_{ain}^{i} + T_{aout}^{i}}{3} \quad \text{(Eq. 5-10)}$$

where	T^{i-1}_{ain}	=	intake air temperature at time step *i-1*, K
	T^{i}_{ain}	=	intake air temperature at time step *i*, K
	T^{i}_{aout}	=	exhaust air temperature at time step *i*, K

Since the exhaust air temperature calculated from Equation (5-6) is also the input to Equations (5-4) and (5-5) because of the spatial correction, iterations are required in order to obtain more accurate estimation on the heat removal rates and exhaust air temperature. The iterations are performed within the Excel spreadsheet. In the first iteration, the heat removal rate using Equations (5-4) and (5-5) and exhaust air temperature using Equation (5-6) are calculated without considering any spatial correction. In the second and subsequent iterations, the exhaust air temperature obtained from the previous iteration is used to re-estimate the heat removal rate based on the combined spatial and temporal correction. Then, the exhaust air temperature is revised using the re-estimated heat removal rate. This process is repeated until the heat removal rates or the exhaust air temperatures calculated from the current and the previous iterations agree within a tolerance criterion.

5.3.3.2 Calculation of Convection Heat Transfer Coefficients

To calculate the convection heat transfer coefficients, the following equations were employed:

Air flow velocity, v, based on *Fluid Mechanics* (White 1986, Equation 1.21, p. 16):

$$v = \frac{Q}{A_{flow}} \qquad \text{(Eq. 5-11)}$$

where Q = ventilation air flow rate, m^3/s
A_{flow} = area of flow cross section, m^2

Reynolds No., Re (Holman 1997, Equation 5-2, p. 220):

$$Re = \frac{\rho v D_h}{\mu} \qquad \text{(Eq. 5-12)}$$

where ρ = density, kg/m^3
v = air flow velocity, m/s
D_h = hydraulic diameter of the cross section, m, defined as (Perry et al. 1984, Table 5-8, p. 5-25)

$$D_h = 4r_h = \frac{4A_{flow}}{P} \qquad \text{(Eq. 5-13)}$$

P = wetted perimeter, m
μ = dynamic viscosity of air, kg/m·s

Nusselt No., Nu (Perry et al. 1984, Equation 10-60, p. 10-17):

$$Nu = 0.020 Re^{0.8} Pr^{1/3} \left(\frac{D_w}{D_p} \right)^{0.53} \qquad \text{(Eq. 5-14)}$$

where Re = Reynolds number, dimensionless
Pr = Prandtl number, dimensionless
D_w = drift diameter, m
D_p = waste package diameter, m

The expression (5-14) is for calculation of heat transfer in turbulent flow in a smooth annulus, and considered applicable.

Convection heat transfer coefficient, h (Holman 1997, Equation 5-107, p. 261):

$$h = \frac{kNu}{D_h} \qquad \text{(Eq. 5-15)}$$

where k = thermal conductivity, W/m·K
Nu = Nusselt Number, dimensionless
D_h = hydraulic diameter of the cross section, m

Table 5-8 summaries the results of calculation of the convection heat transfer coefficients for the air flow rates of 0.5 and 1 m^3/s. Details of the calculations are presented in Attachment XIII. The values of air properties, such as density, thermal conductivity, specific heat, dynamic viscosity, and Prandtl number, used to calculate the convection heat transfer coefficients are given in Table 5-6, Section 5.1.7. These values are temperature dependent, and obtained based on the intake air temperatures. The effect of variation in air relative humidity on the convection heat transfer coefficients is ignored.

Table 5-8. Convection Heat Transfer Coefficients for Ventilation Calculation

Parameter	Values					
Air Flow Rate, *Q*, (m^3/s)	0.5			1.0		
Intake Air Temperature (°C)	25	35	45	25	35	45
Hydraulic Diameter, D_h, (m)	0.86					
Area of Flow Cross Section, A_{flow}, (m^2)	1.20					
Air Flow Velocity, *v*, (m/s)	0.42			0.83		
Reynolds No., *Re*	23141.01	21844.94	20659.67	46282.02	43689.87	41319.33
Nusselt No., *Nu*	105.37	100.48	96.01	183.47	174.95	167.16
Convection Heat Transfer Coefficient, *h*, ($W/m^2{\cdot}K$)	3.19	3.13	3.07	5.55	5.45	5.35

5.3.3.3 Calculation of Volumetric Heat Generation Rates

Based on the power levels, 0.18 and 0.36 kW/m (Section 5.1.9, Table 5-7), and the diameter (0.12 m) of heating rod (Assumption 3.5), the volumetric heat generation rates (*q*) can be calculated as follows:

Volume of heating rod per linear meter:

$$V_r = \frac{\pi}{4} D_r^2 L = \frac{\pi}{4} \times 0.12^2 \times 1.0 = 0.0113 \text{m}^3$$

Volumetric heat generation rate per linear meter for power level of 0.18 kW/m:

$$q = \frac{0.18 \times 1000}{0.0113} = 15915.49 \text{W/m}^3\text{/m}$$

Volumetric heat generation rate per linear meter for power level of 0.36 kW/m:

$$q = \frac{0.36 \times 1000}{0.0113} = 31830.99 \text{W/m}^3\text{/m}$$

5.3.4 Test Matrix and Sequence and Computation Considerations

5.3.4.1 Test Matrix and Sequence

Test matrix considered for the Phase II ventilation tests is presented in Table 5-9. A total of fourteen (14) tests are proposed, with two air flow rates, 0.5 and 1 m^3/s, two heat power levels, 0.18 and 0.36 kW/m, and three intake air temperature levels, 25, 35, and 45°C (see Section 5.1.9, Table 5-7). The intake air relative humidity of 30, 17, and 10 percent is associated with the intake air temperature of 25, 35, and 45°C, respectively (Jurani 2001). Two tests (Tests #4 and #8) with an intake air temperature of 45°C and a relative humidity of 15 percent were proposed to evaluate the effect of relative humidity on temperature response. Note that the intake air relative humidity is not an input to this calculation though it is one of the controlled test parameters. It is discussed here for the purposes of completeness.

The tests can be divided into four groups. Within each group, a series of three or four tests will be conducted in sequence. Each series of tests will be started with a test at an intake air temperature of 25°C and a corresponding relative humidity of 30 percent. Once temperatures of the system reach a steady state under the imposed test condition, the next test within the series will be initiated with an increased intake air temperature and a corresponding intake air relative humidity. So the steady state condition of a test in a series will be the initial condition for the subsequent test in the same series. This process is repeated until the last test in the series is completed.

5.3.4.2 Computation Considerations

In simulating the test cases, the very first test case in a series is calculated as usual: a transient thermal analysis was performed beginning with an initial condition of 25°C. For any subsequent case in the series, the calculation was started with a steady state condition at a ventilating air temperature used for the previous case in the series, and then followed by a transient analysis with an air temperature specified for the case. For example, to run the Case #2 with a ventilating air temperature of 35°C, a steady state solution under an air temperature of 25°C is obtained prior to the transient analysis under an air temperature of 35°C is initiated. The steady state condition reached at an air temperature of 25°C combined with a heat load of 0.18 kW/m and an air flow rate of 1.0 m^3/s is served as an initial condition for the Case #2. This approach is used for all four series.

Though the cases #4 and #8 were included in the test matrix (see Table 5-9), they were not analyzed since the effect of variations in air relative humidity could not be considered in ANSYS ventilation calculations.

Table 5-9. Test Matrix for Phase II Ventilation Test

Test ID	Power Level (kW/m)	Intake Air Volume (m^3/s)	Intake Air Temperature (°C)	Intake Air Relative Humidity (%)
1	0.18	1.0	25	30
2			35	17
3			45	10
4			45	15
5	0.36	1.0	25	30
6			35	17
7			45	10
8			45	15
9	0.18	0.5	25	30
10			35	17
11			45	10
12	0.36	0.5	25	30
13			35	17
14			45	10

6. RESULTS

This section summarizes the results of the calculation. These results can be found in DTN: MO0108MWDPPP18.012.

The predicted temperatures of the ventilating air, concrete inside wall, and waste package surface for all test cases as shown in Table 5-9 (except test cases #4 and #8; see Section 5.3.4.2) are presented in Attachments I through XII. The predicted peak temperatures for these cases are summarized in Table 6-1.

Table 6-1. Summary of Predicted Peak Temperatures

Case Identification and Description	Ventilating Air (°C)	WP Surface (°C)		Concrete Pipe Wall (°C)	
		Top	Bottom	Top	Sidewall
1 - Heat output = 0.18 kW/m, air flow rate = 1 m^3/s, intake air temperature = 25°C, and intake air relative humidity = 30 percent.	28.69	44.09	39.07	30.09	29.93
2 - Heat output = 0.18 kW/m, air flow rate = 1 m^3/s, intake air temperature = 35°C, and intake air relative humidity = 17 percent.	35.93	51.44	46.72	37.32	37.18
3 - Heat output = 0.18 kW/m, air flow rate = 1 m^3/s, intake air temperature = 45°C, and intake air relative humidity = 10 percent.	45.73	60.23	55.89	46.02	45.93
5 - Heat output = 0.36 kW/m, air flow rate = 1 m^3/s, intake air temperature = 25°C, and intake air relative humidity = 30 percent.	32.31	61.80	52.38	35.37	35.03
6 - Heat output = 0.36 kW/m, air flow rate = 1 m^3/s, intake air temperature = 35°C, and intake air relative humidity = 17 percent.	37.04	67.50	58.42	41.29	40.97
7 - Heat output = 0.36 kW/m, air flow rate = 1 m^3/s, intake air temperature = 45°C, and intake air relative humidity = 10 percent.	46.85	75.91	67.29	50.11	49.81
9 - Heat output = 0.18 kW/m, air flow rate = 0.5 m^3/s, intake air temperature = 25°C, and intake air relative humidity = 30 percent.	31.29	50.43	45.28	33.92	33.72
10 - Heat output = 0.18 kW/m, air flow rate = 0.5 m^3/s, intake air temperature = 35°C, and intake air relative humidity = 17 percent.	36.62	56.16	51.32	39.63	39.47
11 - Heat output = 0.18 kW/m, air flow rate = 0.5 m^3/s, intake air temperature = 45°C, and intake air relative humidity = 10 percent.	46.25	64.10	59.67	47.60	47.49
12 - Heat output = 0.36 kW/m, air flow rate = 0.5 m^3/s, intake air temperature = 25°C, and intake air relative humidity = 30 percent.	37.39	73.14	63.74	43.15	42.75
13 - Heat output = 0.36 kW/m, air flow rate = 0.5 m^3/s, intake air temperature = 35°C, and intake air relative humidity = 17 percent.	38.57	76.58	67.45	46.85	46.48
14 - Heat output = 0.36 kW/m, air flow rate = 0.5 m^3/s, intake air temperature = 45°C, and intake air relative humidity = 10 percent.	48.23	84.08	75.46	54.99	54.66

7. REFERENCES

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7.3 SOFTWARE USED

CRWMS M&O 2001c. *Software Code: ANSYS*. V5.6.2. IRIX 6.5. 10145-5.6.2-00.

7.4 SOURCE DATA

None.

7.5 OUTPUT DATA

MO0108MWDPPP018.012. Pretest Predictions for Phase II Ventilation Tests. Submittal date: 08/29/2001.

ATTACHMENT I TEMPERATURES FOR CASE #1

This attachment provides the results of calculations of temperatures for the Case #1: a linear heat load of 0.18 kW/m, an intake air volume of 1.0 m^3/s, an intake air temperature of 25°C with a relative humidity of 30 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table I-1. Average Air Temperatures (°C) at Different Time and Locations for Case #1

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00	25.00
1.0	25.00	25.03	25.03	25.03	25.03
24.0	25.00	25.46	25.89	26.29	26.67
48.0	25.00	25.90	26.74	27.54	28.28
72.0	25.00	25.94	26.84	27.70	28.52
96.0	25.00	25.94	26.87	27.76	28.64
120.0	25.00	25.95	26.87	27.78	28.67
144.0	25.00	25.95	26.88	27.79	28.68
168.0	25.00	25.95	26.88	27.79	28.69

Source: DTN: MO0108MWDPPP18.012

Table I-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #1

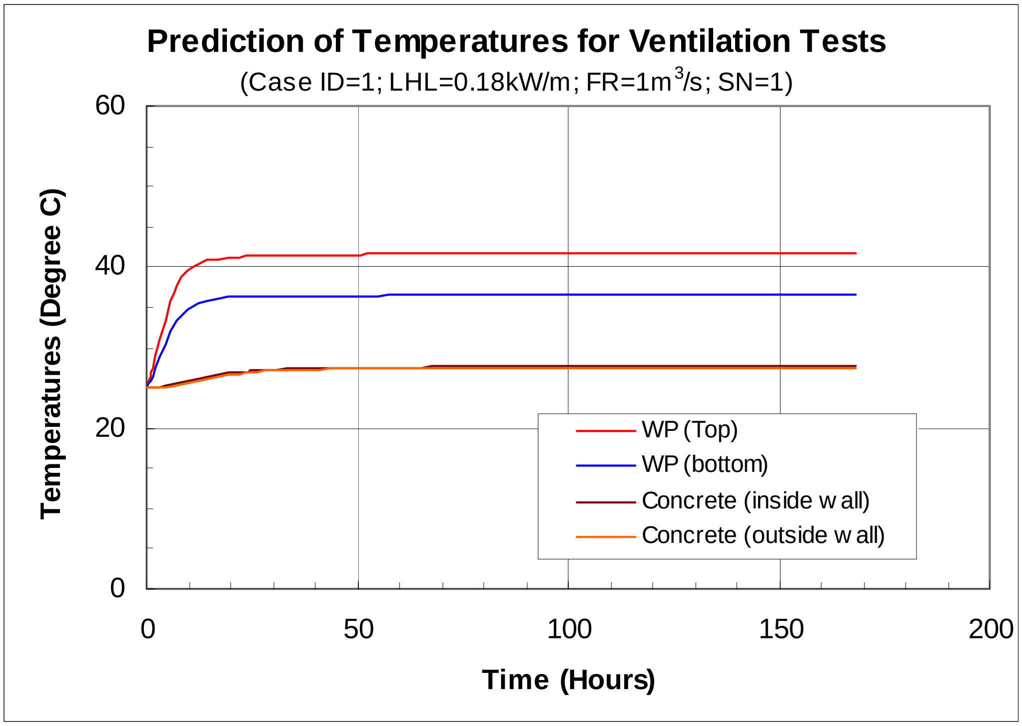
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
--1.0	26.07	26.08	26.08	26.08
24.0	38.33	38.65	38.94	39.21
48.0	38.55	39.25	39.91	40.53
72.0	38.59	39.41	40.19	40.94
96.0	38.60	39.44	40.27	41.06
120.0	38.61	39.46	40.29	41.11
144.0	38.61	39.47	40.31	41.13
168.0	38.61	39.47	40.31	41.14

Source: DTN: MO0108MWDPPP18.012

Table I-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #1

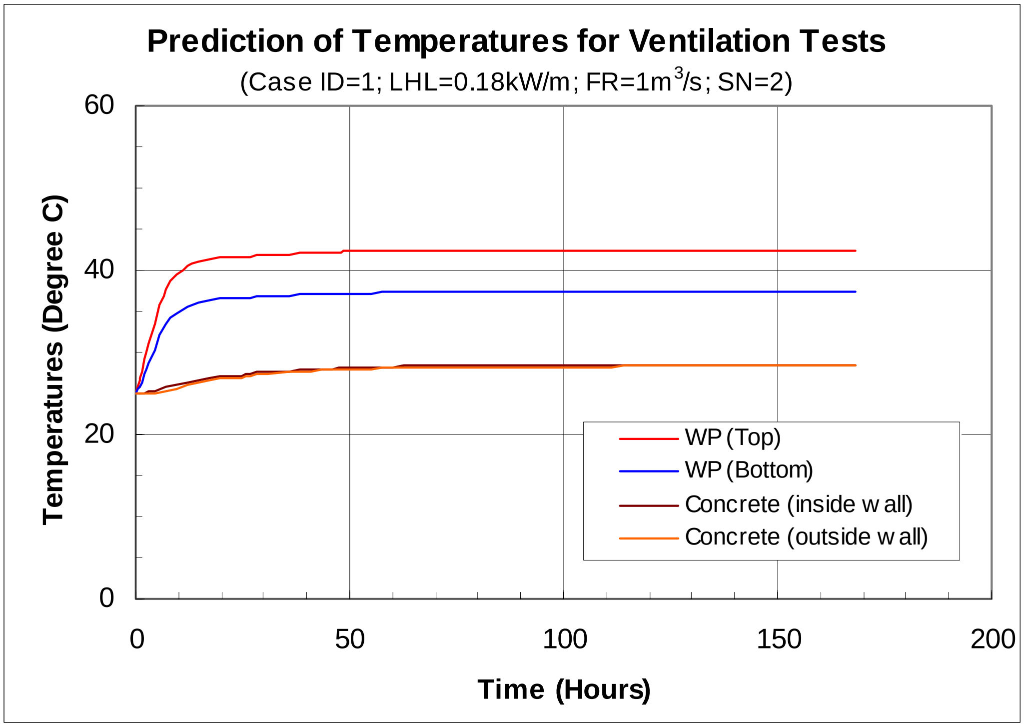
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
1.0	25.02	25.03	25.03	25.03
24.0	26.93	27.16	27.36	27.55
48.0	27.41	27.99	28.54	29.05
72.0	27.51	28.27	29.00	29.69
96.0	27.53	28.34	29.13	29.89
120.0	27.54	28.37	29.18	29.96
144.0	27.54	28.38	29.20	29.99
168.0	27.55	28.38	29.20	30.01

Source: DTN: MO0108MWDPPP18.012



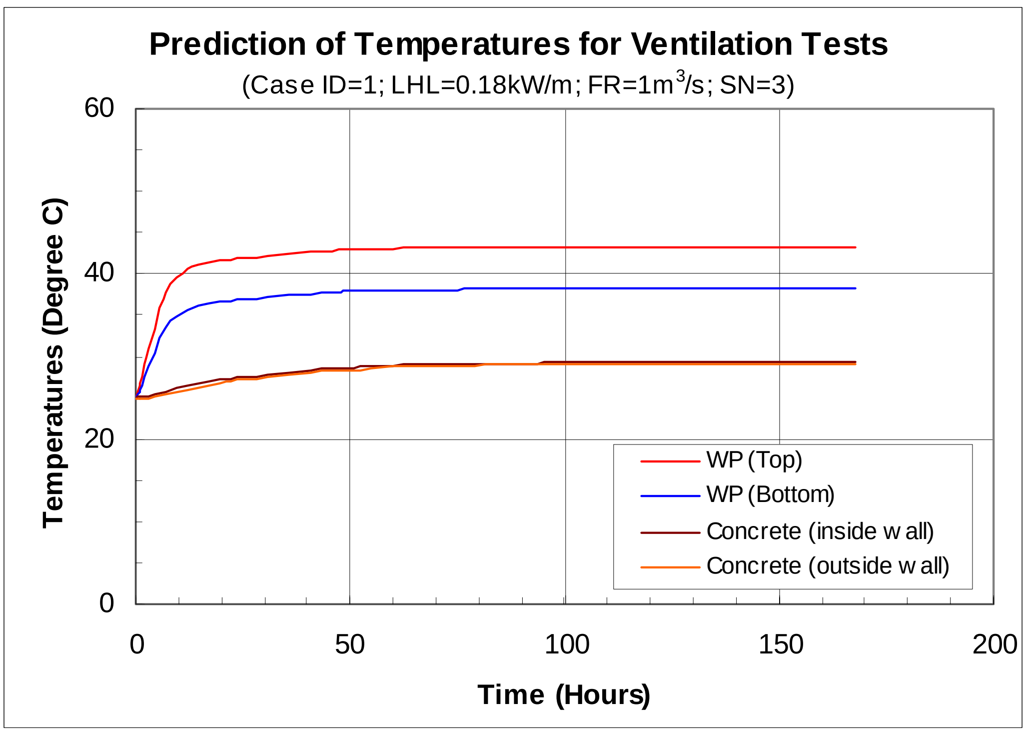
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure I-1. Predicted Average Temperatures in Segment No. 1 for Case #1



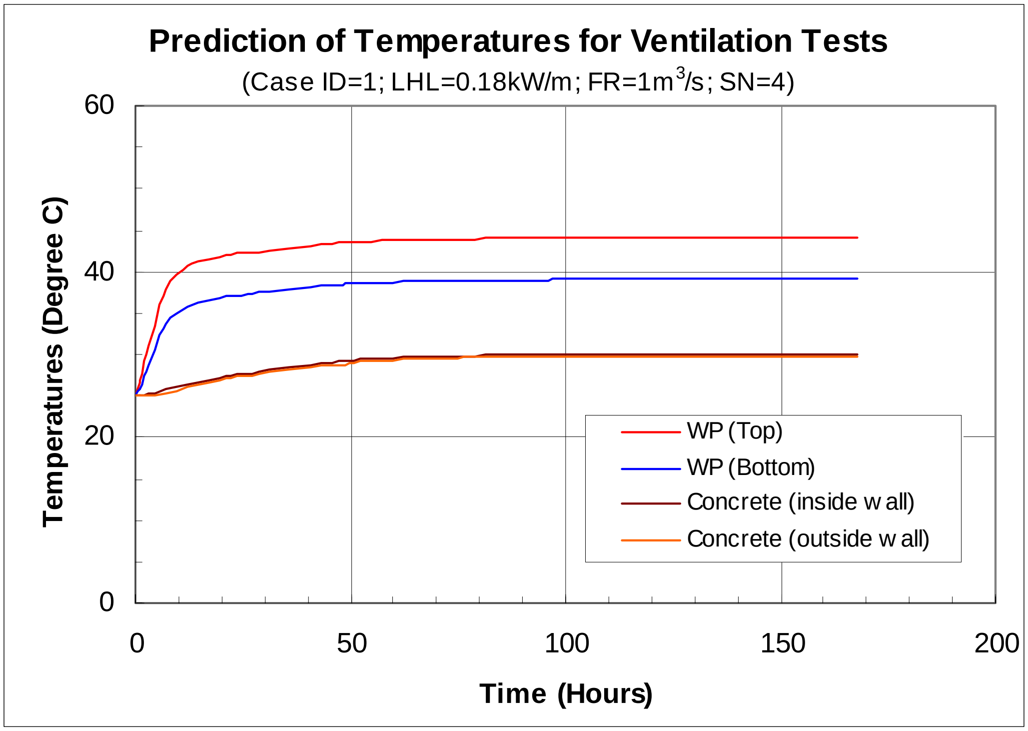
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure I-2. Predicted Average Temperatures in Segment No. 2 for Case #1



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure I-3. Predicted Average Temperatures in Segment No. 3 for Case #1



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure I-4. Predicted Average Temperatures in Segment No. 4 for Case #1

ATTACHMENT II TEMPERATURES FOR CASE #2

This attachment provides the results of calculations of temperatures for the Case #2: a linear heat load of 0.18 kW/m, an intake air volume of 1.0 m^3/s, an intake air temperature of 35°C with a relative humidity of 17 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table II-1. Average Air Temperatures (°C) at Different Time and Locations for Case #2

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	35.00	35.00	35.00	35.00	35.00
1.0	35.00	34.45	34.45	34.45	34.45
24.0	35.00	35.09	35.07	35.07	35.07
48.0	35.00	35.64	35.66	35.66	35.66
72.0	35.00	35.75	35.83	35.83	35.83
96.0	35.00	35.77	35.88	35.89	35.89
120.0	35.00	35.78	35.89	35.91	35.91
144.0	35.00	35.79	35.90	35.92	35.92
168.0	35.00	35.79	35.91	35.92	35.93

Source: DTN: MO0108MWDPPP18.012

Table II-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #2

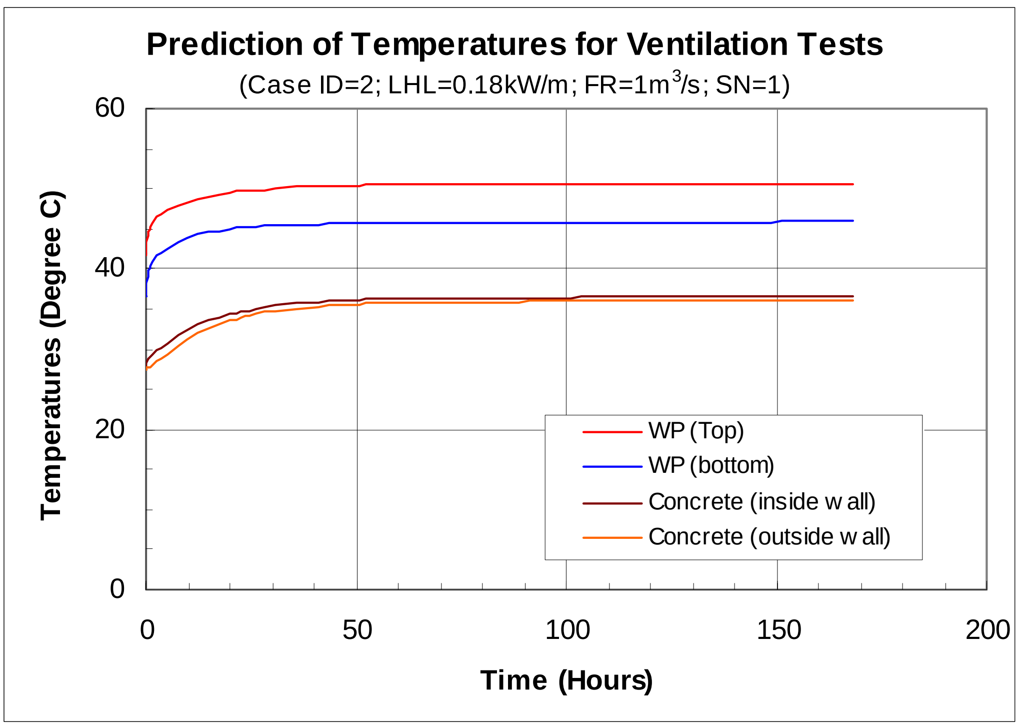
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	38.76	38.76	38.76	38.76
1.0	42.30	42.11	42.11	42.11
24.0	47.02	47.00	46.99	46.99
48.0	47.59	48.03	48.04	48.04
72.0	47.72	48.35	48.40	48.40
96.0	47.77	48.45	48.53	48.54
120.0	47.79	48.49	48.58	48.60
144.0	47.80	48.51	48.61	48.63
168.0	47.81	48.52	48.63	48.64

Source: DTN: MO0108MWDPPP18.012

Table II-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #2

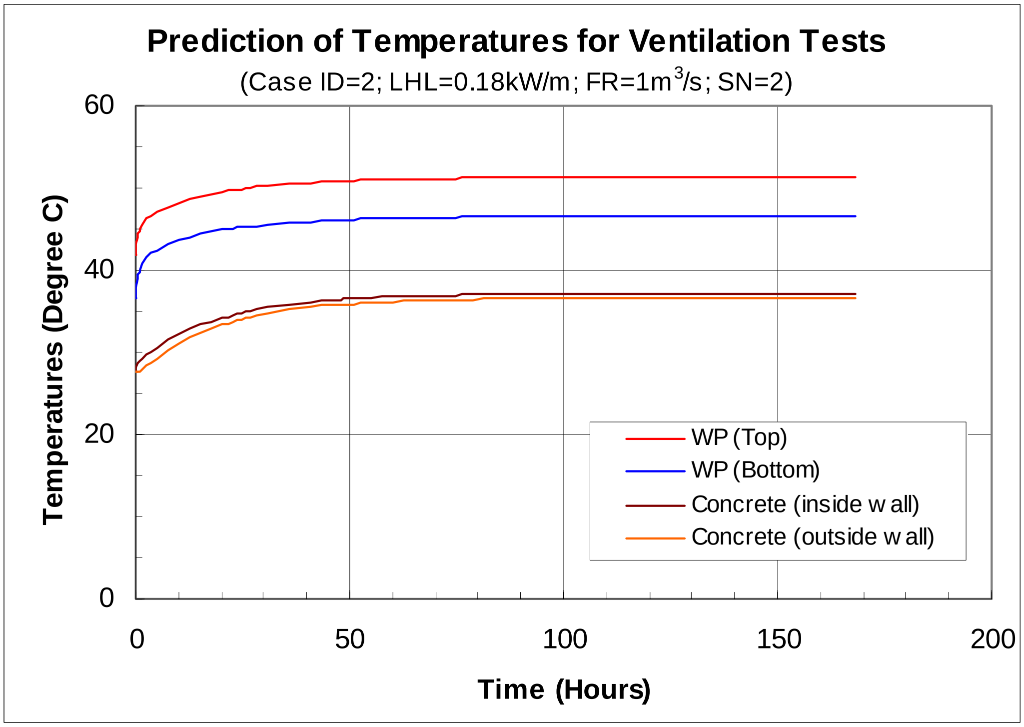
Time (Hours)	**Location Measured from Air-intake End (m)**			
	8.49	16.97	25.46	33.95
0	27.61	27.61	27.61	27.61
1.0	28.94	28.87	28.87	28.87
24.0	34.78	34.69	34.68	34.68
48.0	36.02	36.33	36.33	36.33
72.0	36.30	36.86	36.90	36.90
96.0	36.38	37.03	37.10	37.11
120.0	36.41	37.09	37.18	37.19
144.0	36.43	37.12	37.22	37.23
168.0	36.44	37.14	37.24	37.25

Source: DTN: MO0108MWDPPP18.012



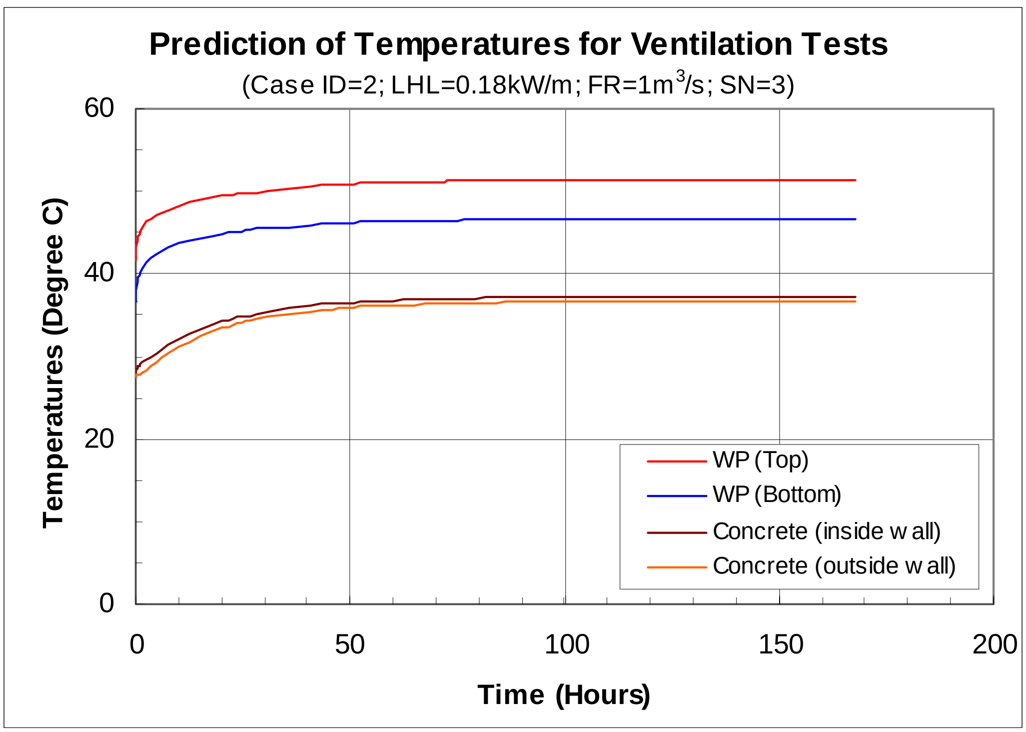
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure II-1. Predicted Average Temperatures in Segment No. 1 for Case #2



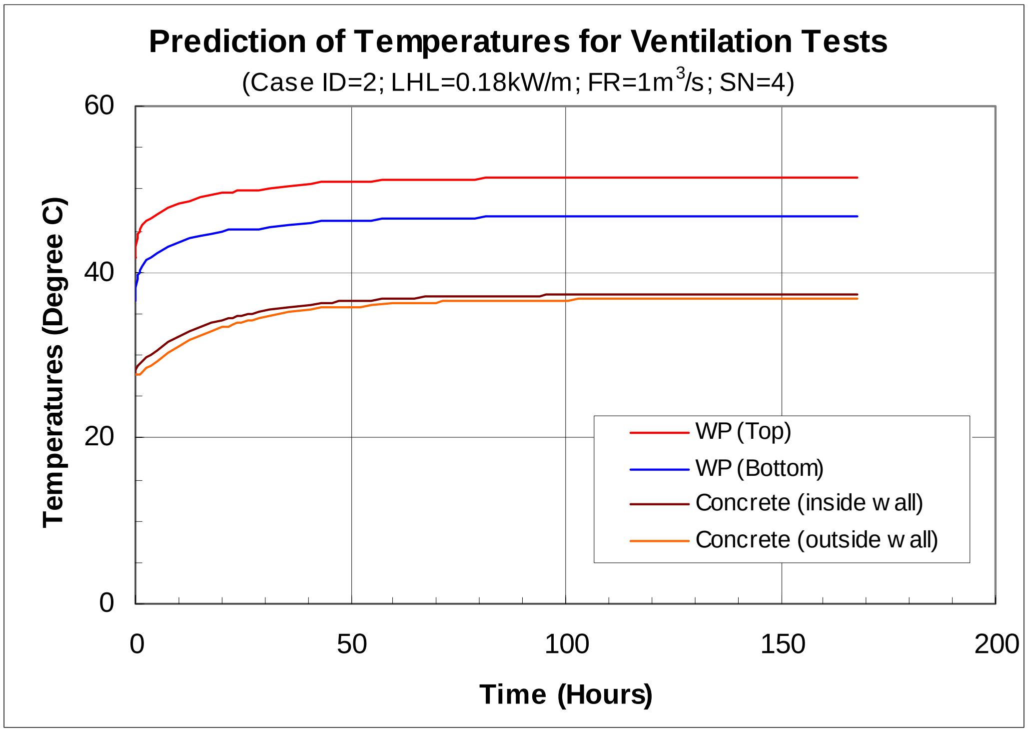
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure II-2. Predicted Average Temperatures in Segment No. 2 for Case #2



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure II-3. Predicted Average Temperatures in Segment No. 3 for Case #2



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure II-4. Predicted Average Temperatures in Segment No. 4 for Case #2

ATTACHMENT III TEMPERATURES FOR CASE #3

This attachment provides the results of calculations of temperatures for the Case #3: a linear heat load of 0.18 kW/m, an intake air volume of 1.0 m^3/s, an intake air temperature of 45°C with a relative humidity of 10 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table III-1. Average Air Temperatures (°C) at Different Time and Locations for Case #3

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	45.00	45.00	45.00	45.00	45.00
1.0	45.00	44.27	44.26	44.26	44.26
24.0	45.00	44.90	44.87	44.87	44.87
48.0	45.00	45.47	45.46	45.46	45.46
72.0	45.00	45.58	45.63	45.63	45.63
96.0	45.00	45.61	45.69	45.69	45.69
120.0	45.00	45.62	45.70	45.71	45.72
144.0	45.00	45.62	45.71	45.72	45.73
168.0	45.00	45.62	45.72	45.73	45.73

Source: DTN: MO0108MWDPPP18.012

Table III-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #3

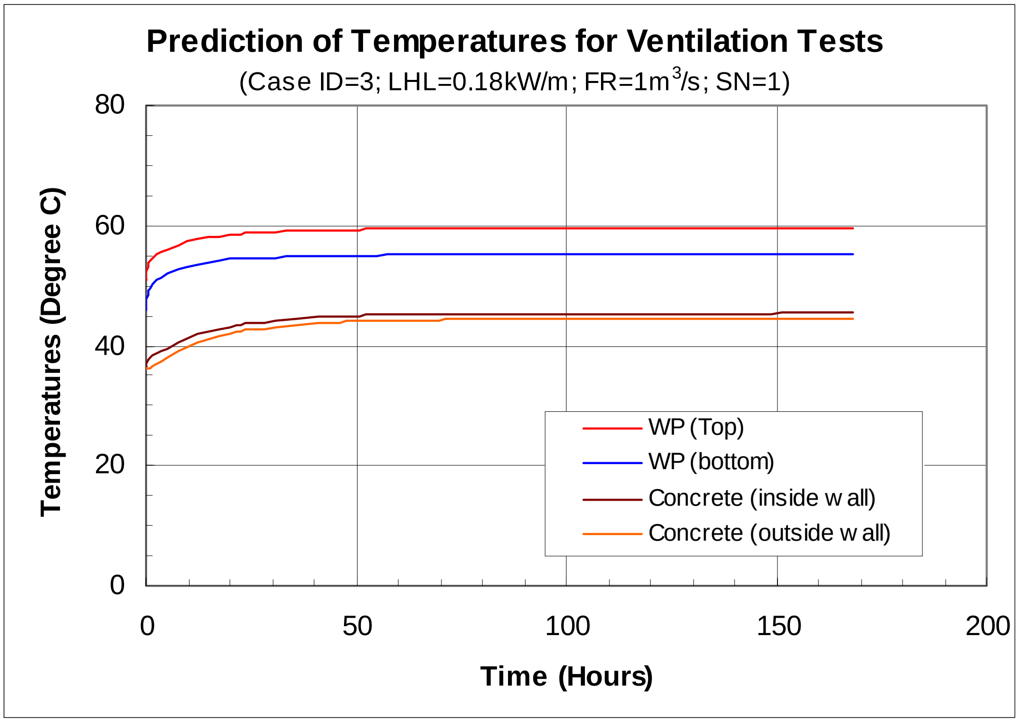
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	47.98	47.98	47.98	47.98
1.0	51.38	51.13	51.13	51.13
24.0	56.12	55.94	55.92	55.92
48.0	56.72	57.00	56.99	56.99
72.0	56.87	57.34	57.37	57.37
96.0	56.92	57.45	57.51	57.51
120.0	56.94	57.49	57.56	57.57
144.0	56.96	57.51	57.59	57.60
168.0	56.96	57.52	57.61	57.61

Source: DTN: MO0108MWDPPP18.012

Table III-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #3

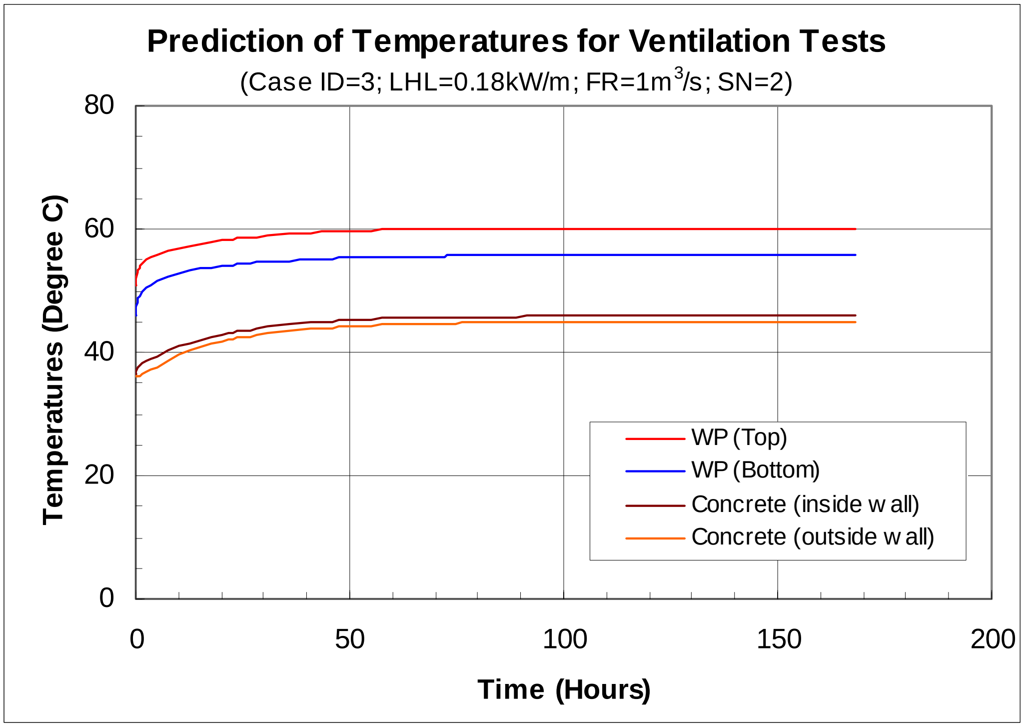
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	36.51	36.51	36.51	36.51
1.0	37.82	37.73	37.72	37.72
24.0	43.65	43.42	43.40	43.40
48.0	44.90	45.06	45.05	45.05
72.0	45.19	45.60	45.62	45.62
96.0	45.27	45.77	45.83	45.83
120.0	45.31	45.84	45.91	45.91
144.0	45.33	45.87	45.94	45.95
168.0	45.34	45.88	45.97	45.98

Source: DTN: MO0108MWDPPP18.012



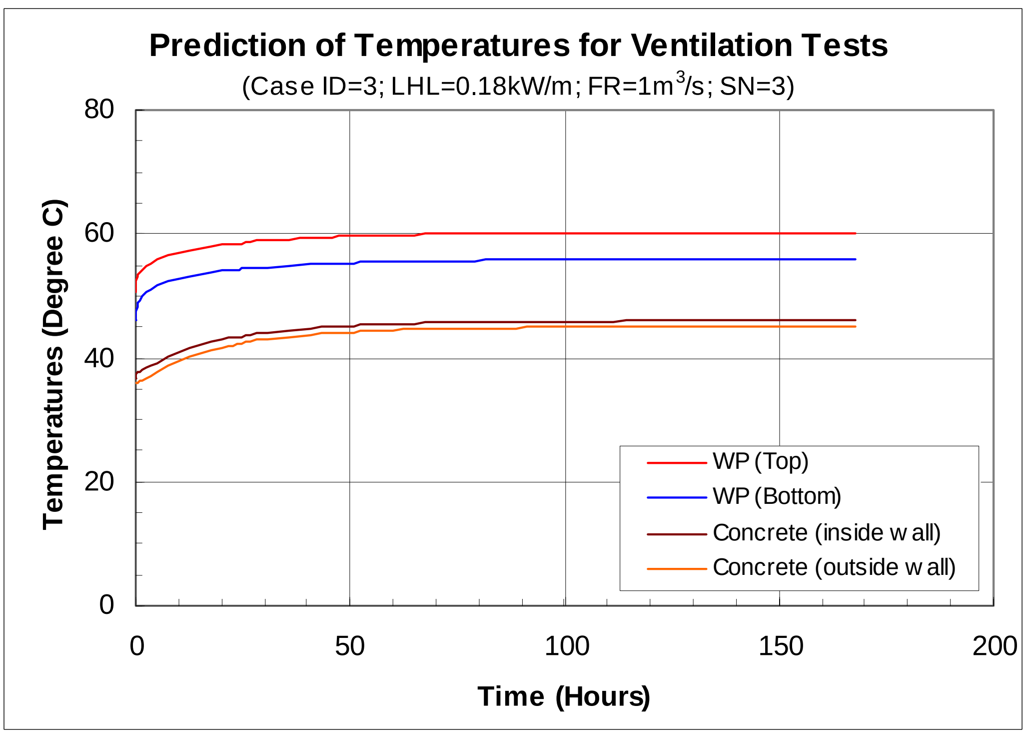
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure III-1. Predicted Average Temperatures in Segment No. 1 for Case #3



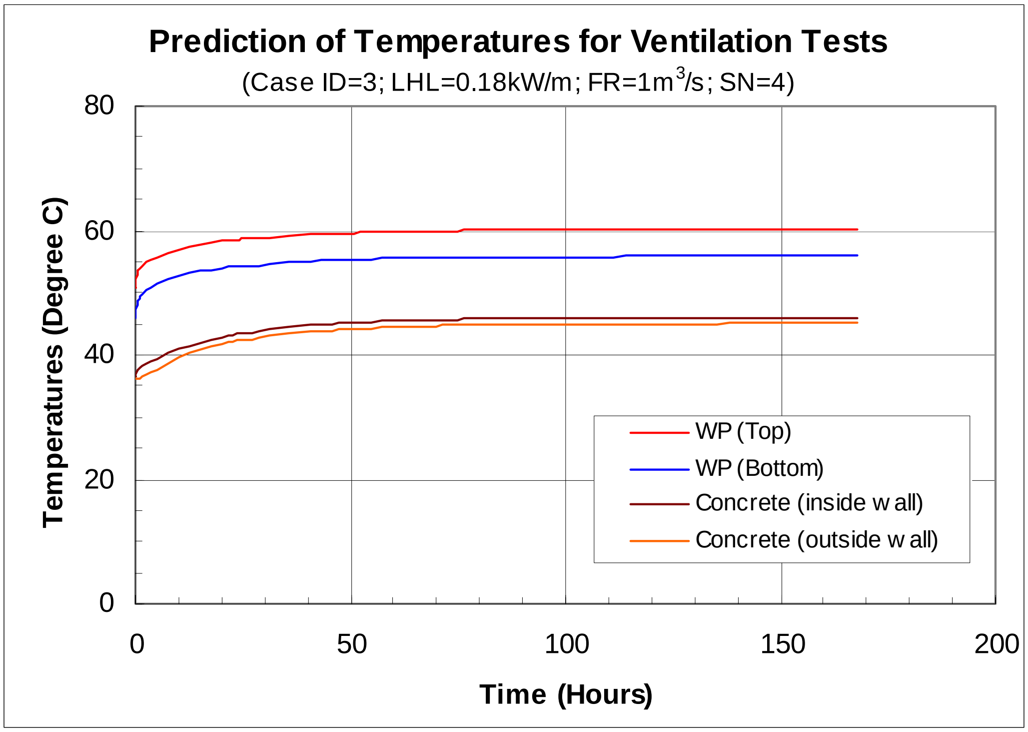
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure III-2. Predicted Average Temperatures in Segment No. 2 for Case #3



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure III-3. Predicted Average Temperatures in Segment No. 3 for Case #3



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure III-4. Predicted Average Temperatures in Segment No. 4 for Case #3

ATTACHMENT IV TEMPERATURES FOR CASE #5

This attachment provides the results of calculations of temperatures for the Case #5: a linear heat load of 0.36 kW/m, an intake air volume of 1.0 m^3/s, an intake air temperature of 25°C with a relative humidity of 30 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table IV-1. Average Air Temperatures (°C) at Different Time and Locations for Case #5

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00	25.00
1.0	25.00	25.06	25.06	25.06	25.06
24.0	25.00	25.91	26.77	27.58	28.33
48.0	25.00	26.78	28.46	30.04	31.52
72.0	25.00	26.86	28.64	30.35	31.98
96.0	25.00	26.87	28.70	30.48	32.20
120.0	25.00	26.88	28.72	30.51	32.27
144.0	25.00	26.88	28.72	30.53	32.29
168.0	25.00	26.88	28.73	30.53	32.31

Source: DTN: MO0108MWDPPP18.012

Table IV-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #5

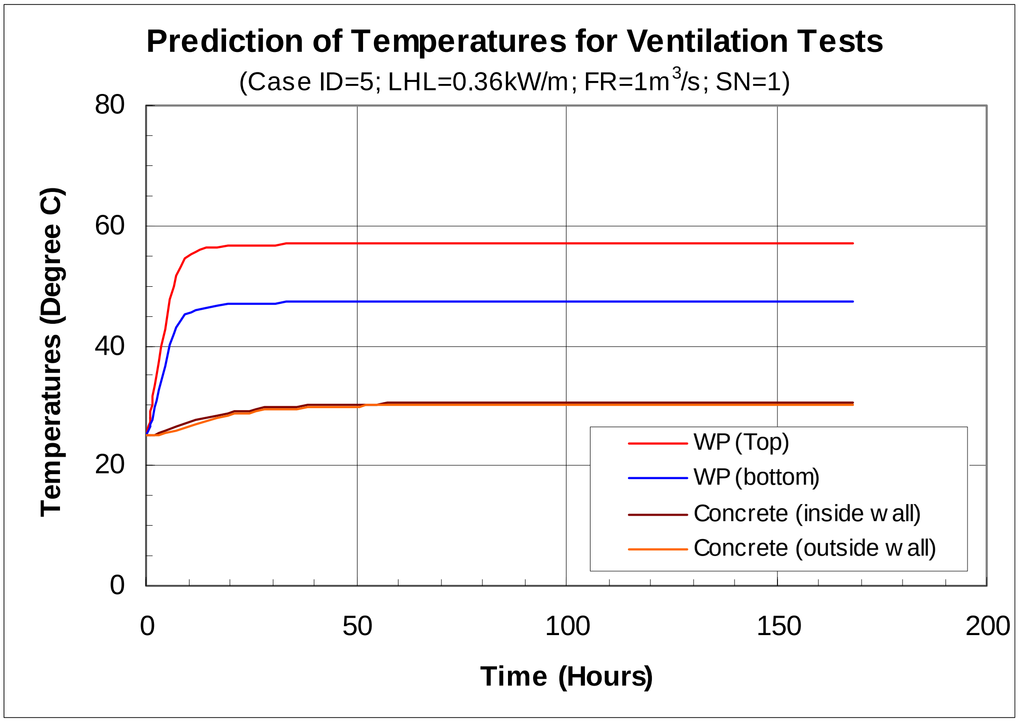
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
1.0	27.26	27.28	27.28	27.28
24.0	50.96	51.56	52.12	52.65
48.0	51.33	52.66	53.91	55.08
72.0	51.41	52.96	54.43	55.85
96.0	51.43	53.03	54.58	56.09
120.0	51.44	53.06	54.64	56.18
144.0	51.45	53.07	54.66	56.22
168.0	51.45	53.07	54.67	56.23

Source: DTN: MO0108MWDPPP18.012

Table IV-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #5

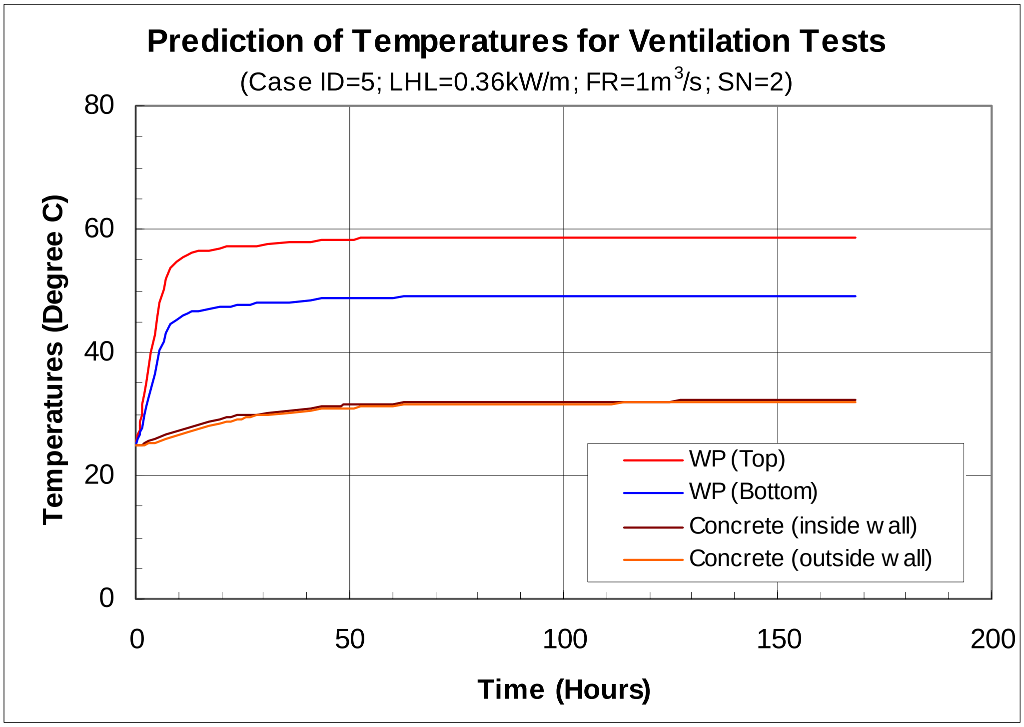
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
1.0	25.05	25.05	25.05	25.05
24.0	29.07	29.53	29.94	30.33
48.0	30.01	31.17	32.26	33.29
72.0	30.19	31.72	33.18	34.57
96.0	30.24	31.87	33.44	34.97
120.0	30.26	31.92	33.54	35.11
144.0	30.26	31.94	33.57	35.17
168.0	30.27	31.94	33.59	35.20

Source: DTN: MO0108MWDPPP18.012



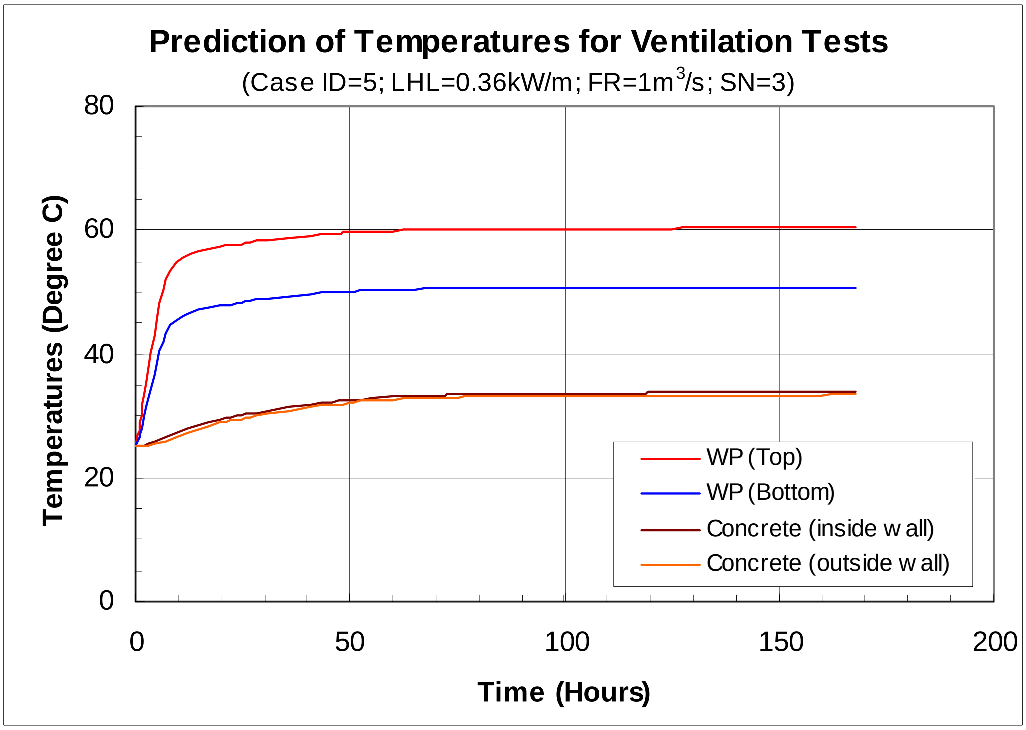
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IV-1. Predicted Average Temperatures in Segment No. 1 for Case #5



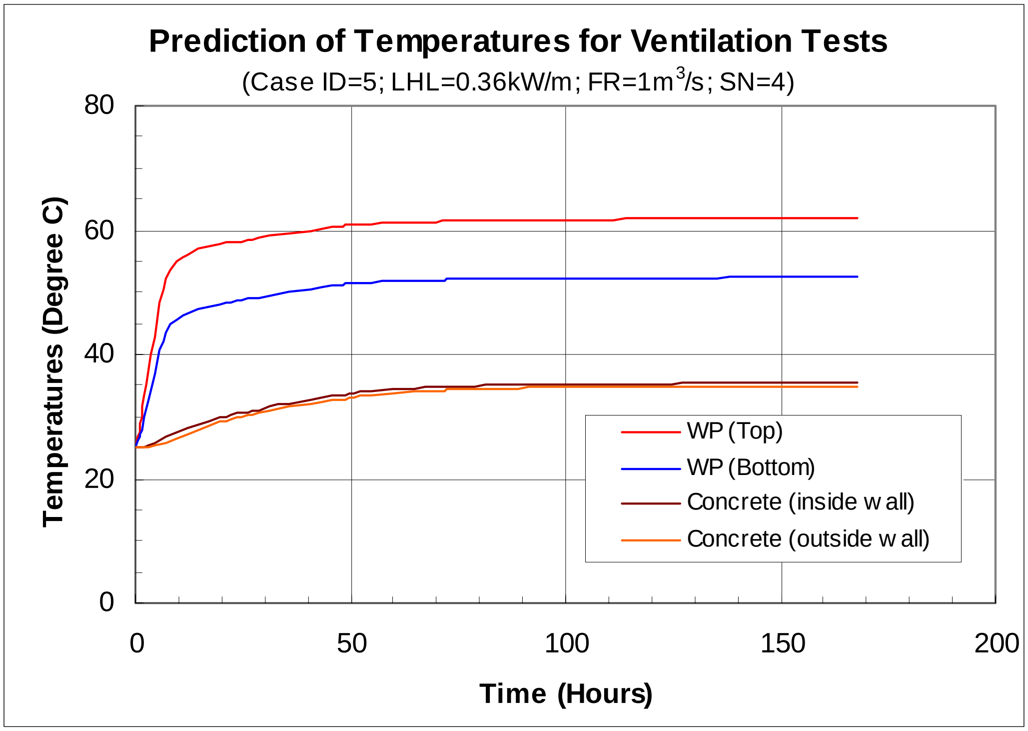
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IV-2. Predicted Average Temperatures in Segment No. 2 for Case #5



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IV-3. Predicted Average Temperatures in Segment No. 3 for Case #5



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IV-4. Predicted Average Temperatures in Segment No. 4 for Case #5

ATTACHMENT V TEMPERATURES FOR CASE #6

This attachment provides the results of calculations of temperatures for the Case #6: a linear heat load of 0.36 kW/m, an intake air volume of 1.0 m^3/s, an intake air temperature of 35°C with a relative humidity of 17 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table V-1. Average Air Temperatures (°C) at Different Time and Locations for Case #6

Time (Hours)	**Location Measured from Air-intake End (m)**				
	0.0	8.49	16.97	25.46	33.95
0	35.00	35.00	35.00	35.00	35.00
1.0	35.00	35.41	35.42	35.42	35.42
24.0	35.00	36.04	36.10	36.10	36.10
48.0	35.00	36.59	36.74	36.75	36.75
72.0	35.00	36.70	36.91	36.93	36.94
96.0	35.00	36.72	36.97	37.00	37.00
120.0	35.00	36.73	36.98	37.02	37.02
144.0	35.00	36.74	36.99	37.03	37.03
168.0	35.00	36.74	37.00	37.03	37.04

Source: DTN: MO0108MWDPPP18.012

Table V-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #6

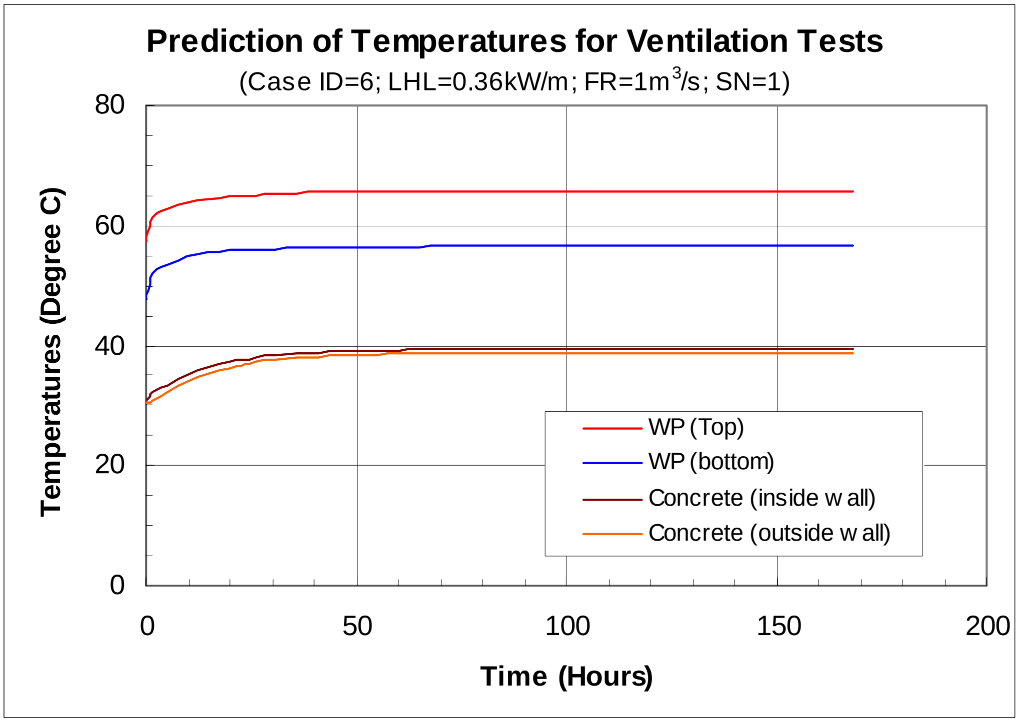
Time (Hours)	**Location Measured from Air-intake End (m)**			
	8.49	16.97	25.46	33.95
0	51.72	51.72	51.72	51.72
1.0	55.17	55.31	55.31	55.31
24.0	59.60	60.33	60.37	60.37
48.0	60.14	61.36	61.47	61.48
72.0	60.27	61.68	61.84	61.86
96.0	60.32	61.78	61.98	62.01
120.0	60.34	61.82	62.03	62.07
144.0	60.35	61.85	62.06	62.09
168.0	60.36	61.86	62.08	62.11

Source: DTN: MO0108MWDPPP18.012

Table V-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #6

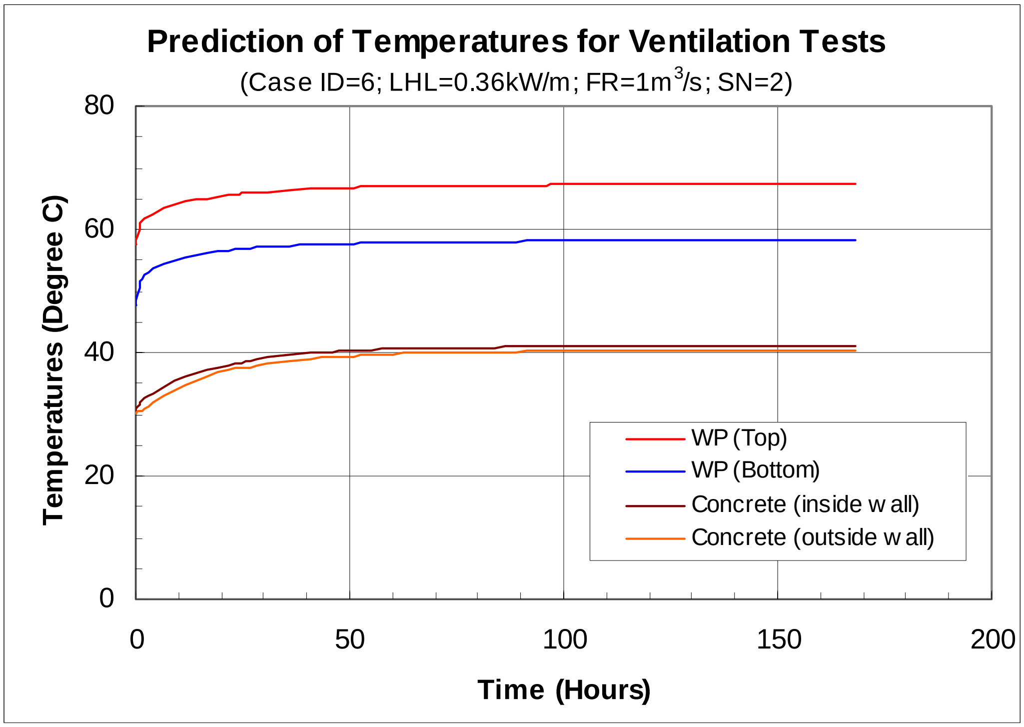
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	30.40	30.40	30.40	30.40
1.0	31.75	31.80	31.80	31.80
24.0	37.64	38.24	38.27	38.27
48.0	38.89	40.01	40.11	40.11
72.0	39.17	40.57	40.72	40.74
96.0	39.25	40.75	40.95	40.97
120.0	39.29	40.82	41.03	41.06
144.0	39.31	40.85	41.07	41.11
168.0	39.32	40.87	41.10	41.13

Source: DTN: MO0108MWDPPP18.012



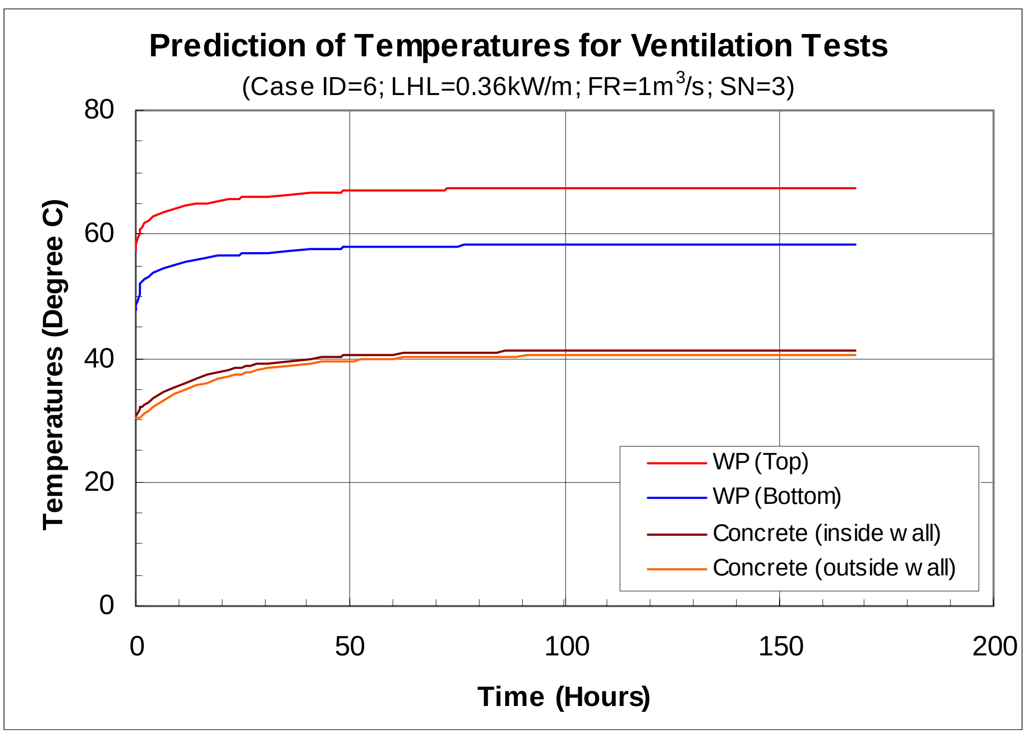
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure V-1. Predicted Average Temperatures in Segment No. 1 for Case #6



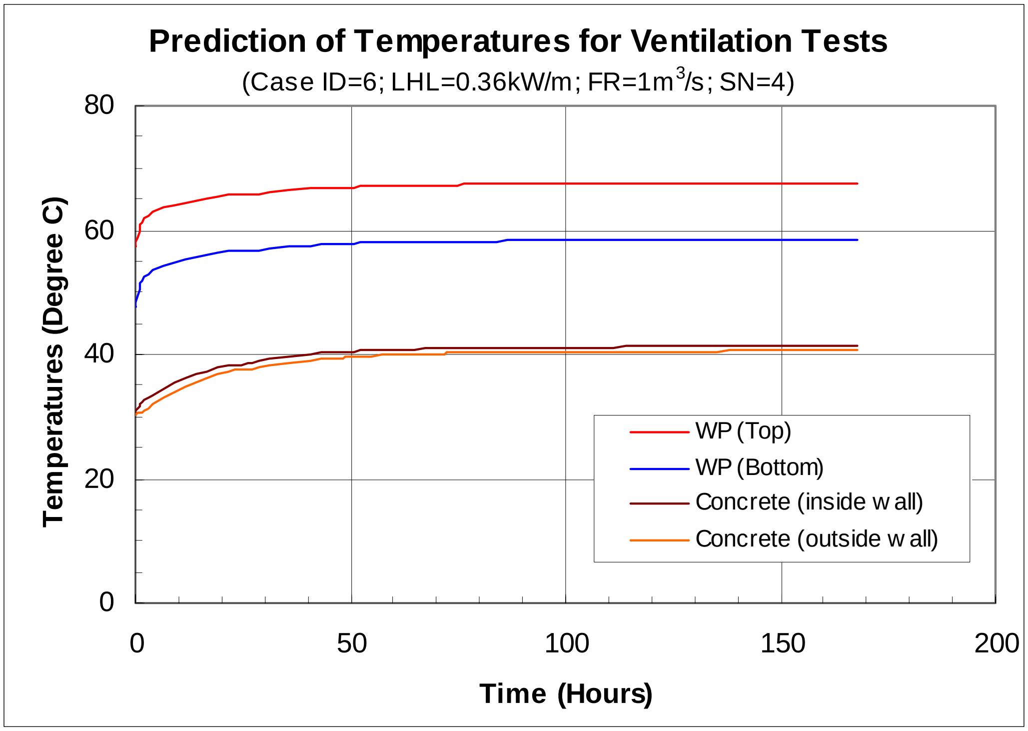
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure V-2. Predicted Average Temperatures in Segment No. 2 for Case #6



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure V-3. Predicted Average Temperatures in Segment No. 3 for Case #6



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure V-4. Predicted Average Temperatures in Segment No. 4 for Case #6

ATTACHMENT VI TEMPERATURES FOR CASE #7

This attachment provides the results of calculations of temperatures for the Case #7: a linear heat load of 0.36 kW/m, an intake air volume of 1.0 m^3/s, an intake air temperature of 45°C with a relative humidity of 10 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table VI-1. Average Air Temperatures (°C) at Different Time and Locations for Case #7

Time (Hours)	**Location Measured from Air-intake End (m)**				
	0.0	8.49	16.97	25.46	33.95
0	45.00	45.00	45.00	45.00	45.00
1.0	45.00	45.23	45.24	45.24	45.24
24.0	45.00	45.87	45.91	45.91	45.91
48.0	45.00	46.42	46.55	46.56	46.56
72.0	45.00	46.53	46.73	46.75	46.75
96.0	45.00	46.56	46.78	46.81	46.81
120.0	45.00	46.57	46.80	46.83	46.84
144.0	45.00	46.58	46.81	46.84	46.85
168.0	45.00	46.58	46.82	46.85	46.85

Source: DTN: MO0108MWDPPP18.012

Table VI-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #7

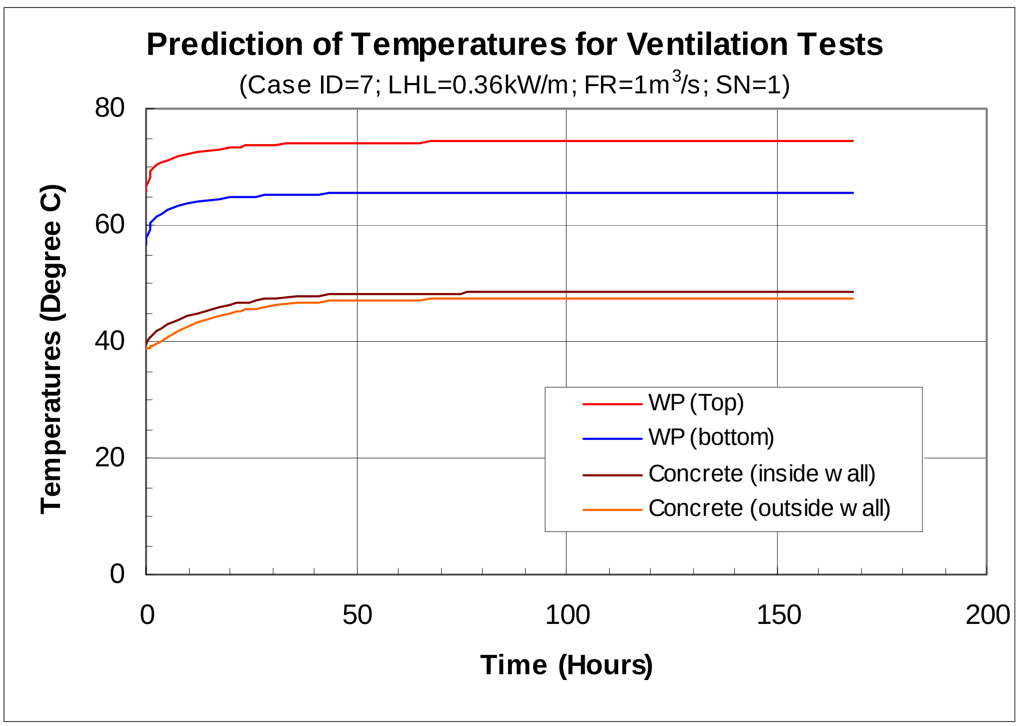
Time (Hours)	**Location Measured from Air-intake End (m)**			
	8.49	16.97	25.46	33.95
0	60.55	60.55	60.55	60.55
1.0	63.89	63.96	63.97	63.97
24.0	68.37	68.95	68.98	68.98
48.0	68.93	69.99	70.08	70.09
72.0	69.06	70.32	70.47	70.49
96.0	69.11	70.43	70.61	70.64
120.0	69.14	70.48	70.67	70.70
144.0	69.15	70.51	70.70	70.73
168.0	69.16	70.52	70.72	70.75

Source: DTN: MO0108MWDPPP18.012

Table VI-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #7

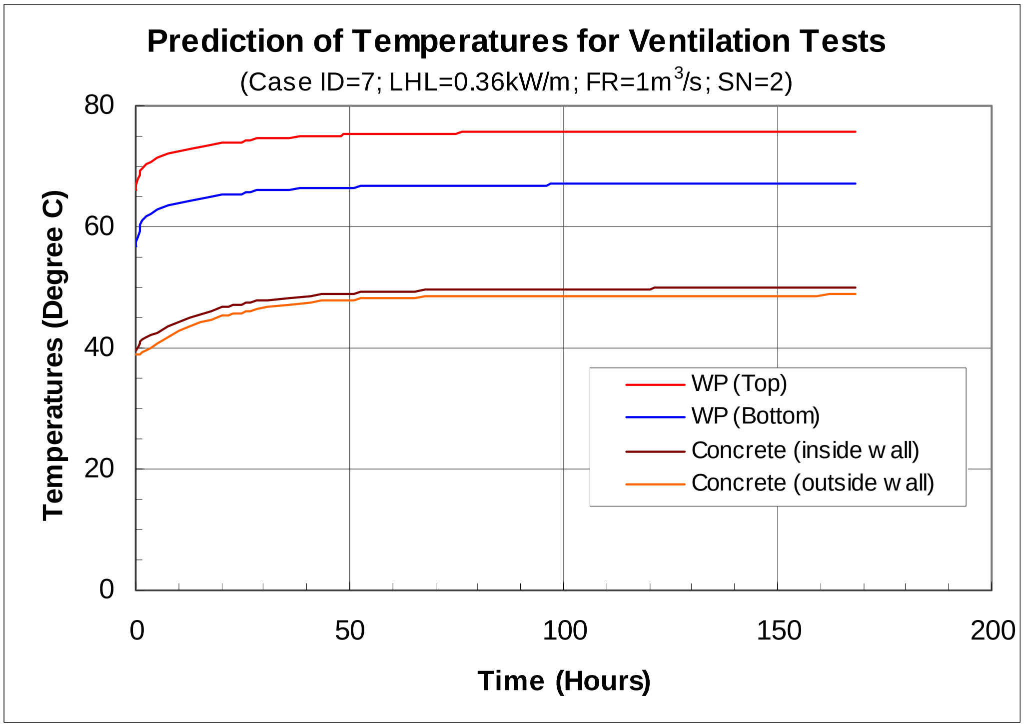
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	39.40	39.40	39.40	39.40
1.0	40.73	40.76	40.76	40.76
24.0	46.63	47.10	47.12	47.12
48.0	47.88	48.85	48.93	48.93
72.0	48.16	49.41	49.55	49.56
96.0	48.25	49.59	49.77	49.79
120.0	48.28	49.67	49.86	49.89
144.0	48.30	49.70	49.91	49.93
168.0	48.32	49.72	49.93	49.96

Source: DTN: MO0108MWDPPP18.012



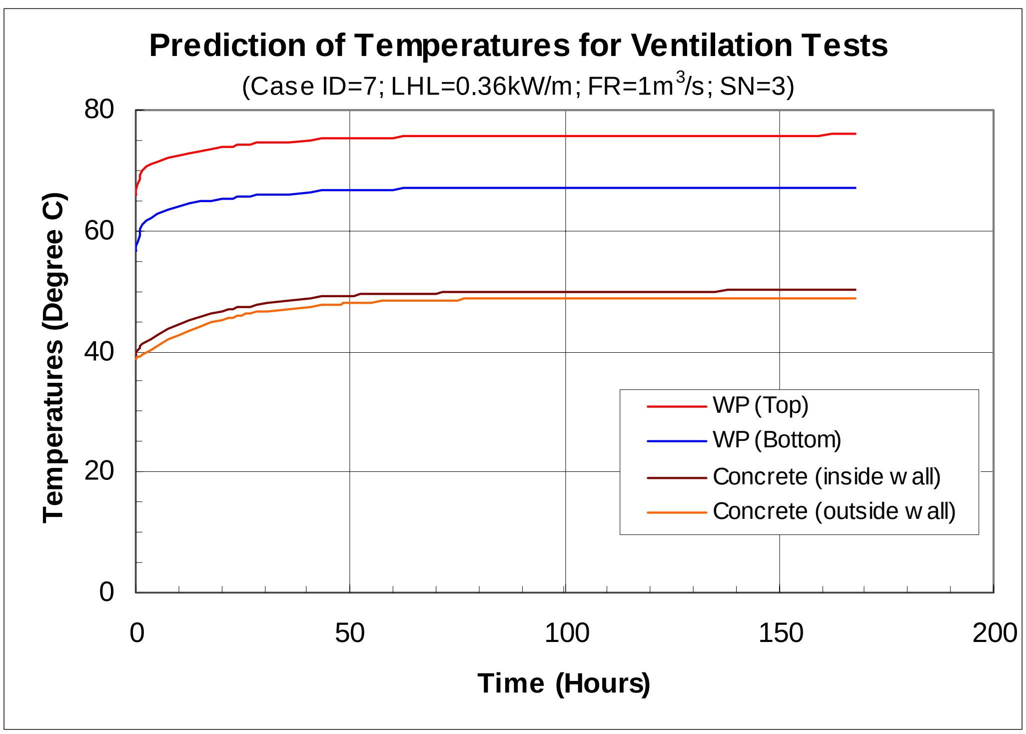
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VI-1. Predicted Average Temperatures in Segment No. 1 for Case #7



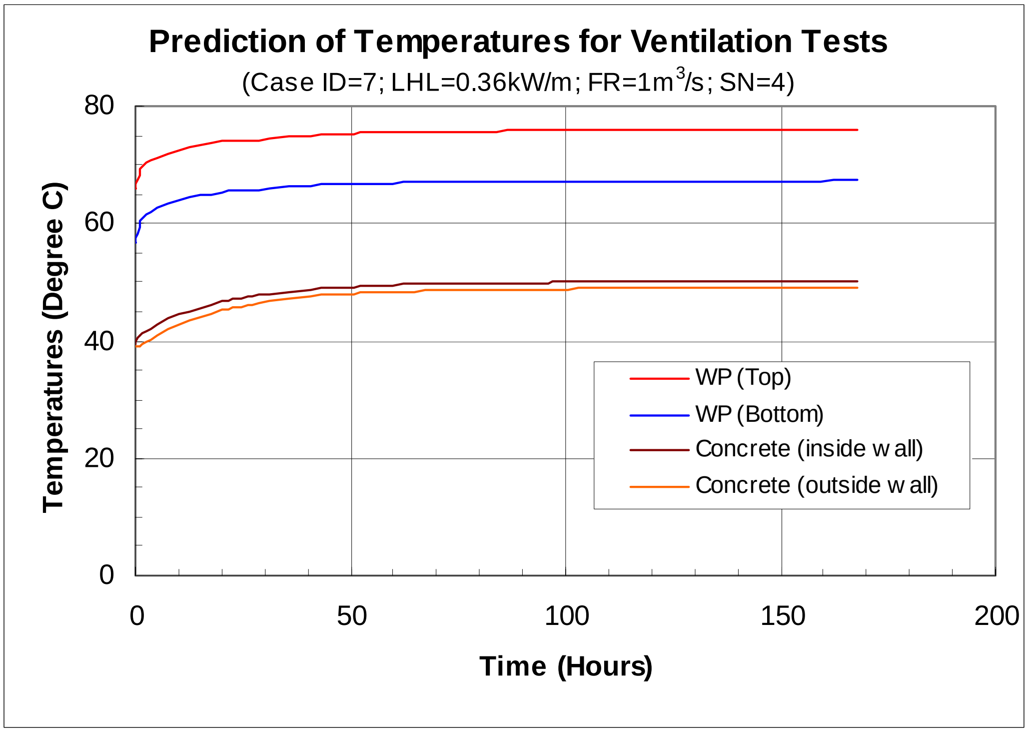
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VI-2. Predicted Average Temperatures in Segment No. 2 for Case #7



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VI-3. Predicted Average Temperatures in Segment No. 3 for Case #7



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VI-4. Predicted Average Temperatures in Segment No. 4 for Case #7

ATTACHMENT VII TEMPERATURES FOR CASE #9

This attachment provides the results of calculations of temperatures for the Case #9: a linear heat load of 0.18 kW/m, an intake air volume of 0.5 m^3/s, an intake air temperature of 25°C with a relative humidity of 30 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table VII-1. Average Air Temperatures (°C) at Different Time and Locations for Case #9

Time (Hours)	**Location Measured from Air-intake End (m)**				
	0.0	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00	25.00
1.0	25.00	25.03	25.03	25.03	25.03
24.0	25.00	25.70	26.35	26.93	27.47
48.0	25.00	26.44	27.76	28.97	30.07
72.0	25.00	26.58	28.05	29.42	30.68
96.0	25.00	26.63	28.17	29.64	31.02
120.0	25.00	26.65	28.23	29.74	31.18
144.0	25.00	26.65	28.25	29.78	31.25
168.0	25.00	26.66	28.26	29.80	31.29

Source: DTN: MO0108MWDPPP18.012

Table VII-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #9

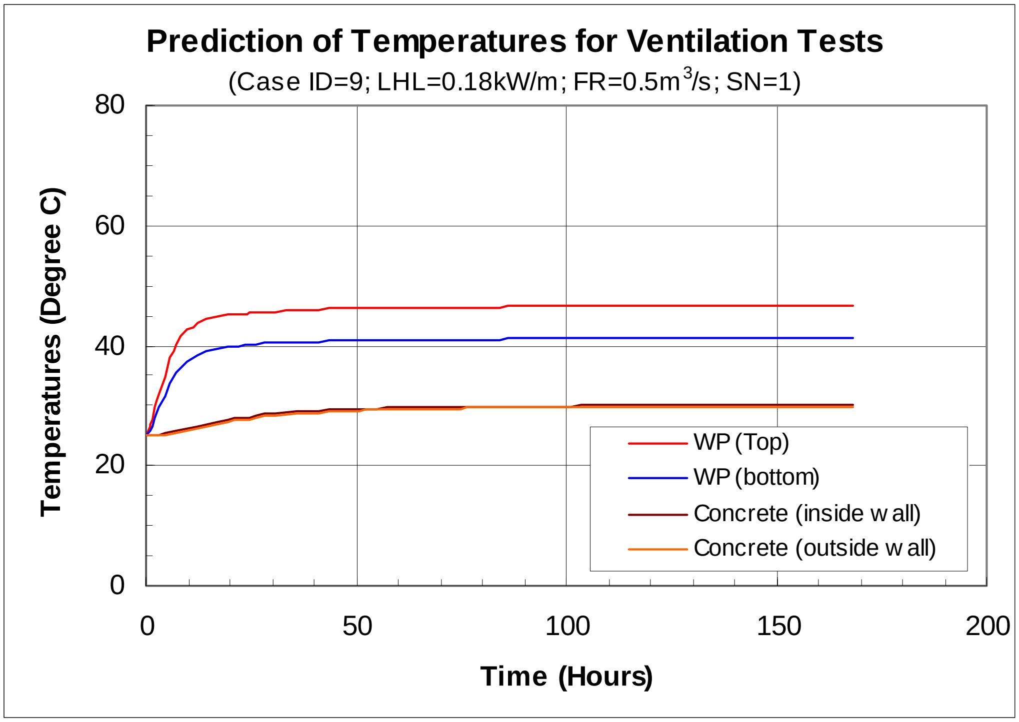
Time (Hours)	**Location Measured from Air-intake End (m)**			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
1.0	26.15	26.16	26.16	26.16
24.0	42.26	42.63	42.96	43.26
48.0	43.01	43.91	44.74	45.49
72.0	43.24	44.41	45.51	46.52
96.0	43.32	44.62	45.83	46.98
120.0	43.36	44.71	45.99	47.21
144.0	43.38	44.75	46.07	47.33
168.0	43.39	44.78	46.11	47.39

Source: DTN: MO0108MWDPPP18.012

Table VII-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #9

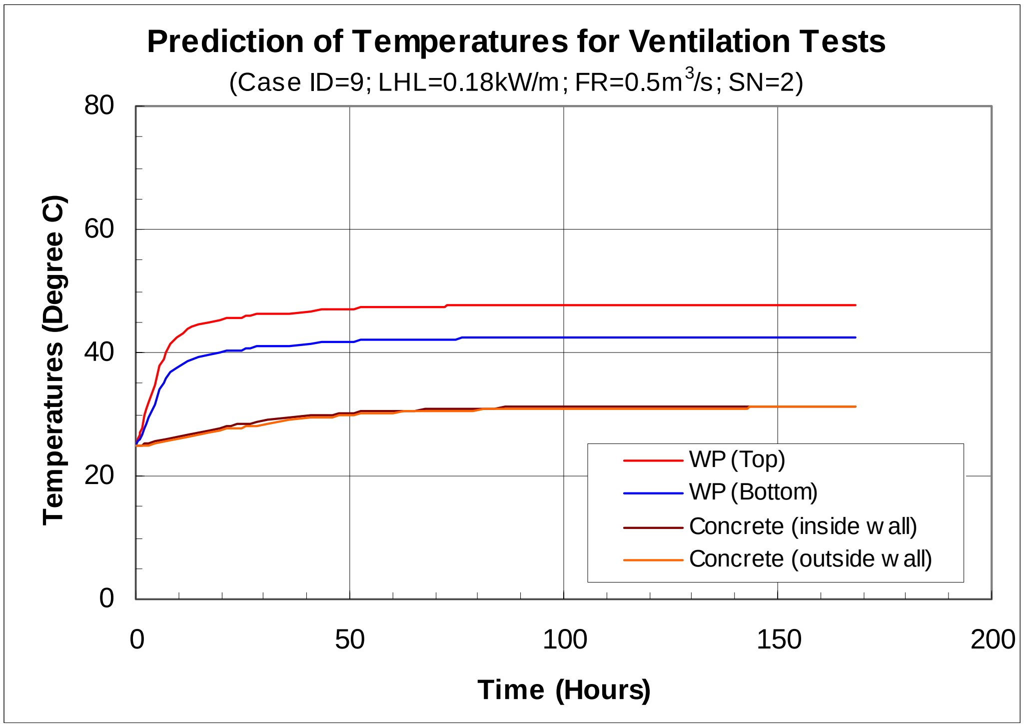
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
1.0	25.02	25.03	25.03	25.03
24.0	28.00	28.25	28.47	28.66
48.0	29.25	29.97	30.62	31.22
72.0	29.66	30.73	31.71	32.61
96.0	29.81	31.04	32.18	33.26
120.0	29.87	31.17	32.41	33.58
144.0	29.90	31.24	32.52	33.74
168.0	29.92	31.27	32.57	33.82

Source: DTN: MO0108MWDPPP18.012



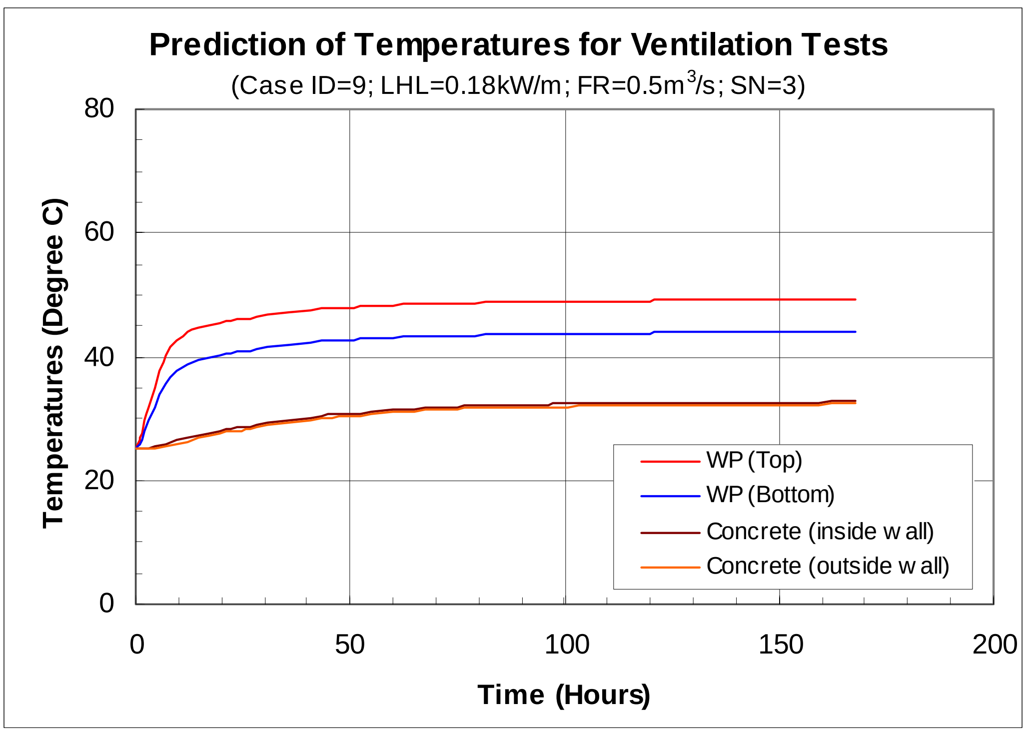
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VII-1. Predicted Average Temperatures in Segment No. 1 for Case #9



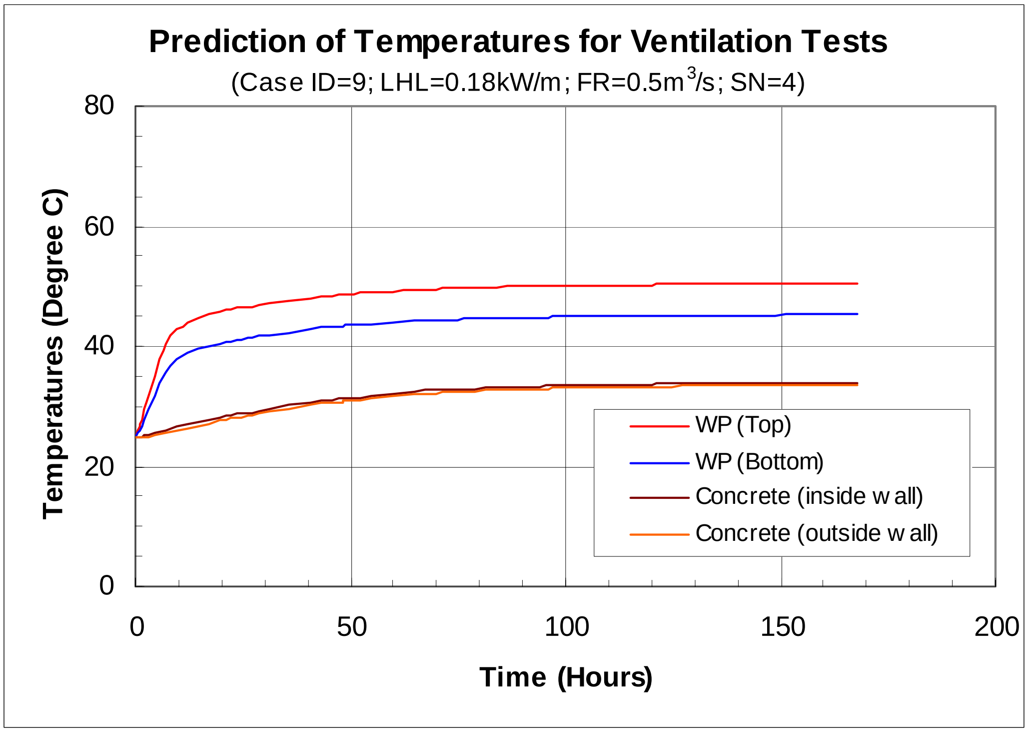
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VII-2. Predicted Average Temperatures in Segment No. 2 for Case #9



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VII-3. Predicted Average Temperatures in Segment No. 3 for Case #9



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VII-4. Predicted Average Temperatures in Segment No. 4 for Case #9

ATTACHMENT VIII TEMPERATURES FOR CASE #10

This attachment provides the results of calculations of temperatures for the Case #10: a linear heat load of 0.18 kW/m, an intake air volume of 0.5 m^3/s, an intake air temperature of 35°C with a relative humidity of 17 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table VIII-1. Average Air Temperatures (°C) at Different Time and Locations for Case #10

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	35.00	35.00	35.00	35.00	35.00
1.0	35.00	34.91	34.91	34.91	34.91
24.0	35.00	35.47	35.48	35.48	35.48
48.0	35.00	36.06	36.12	36.13	36.13
72.0	35.00	36.25	36.38	36.39	36.39
96.0	35.00	36.32	36.49	36.51	36.51
120.0	35.00	36.35	36.54	36.57	36.57
144.0	35.00	36.36	36.57	36.60	36.60
168.0	35.00	36.37	36.58	36.61	36.62

Source: DTN: MO0108MWDPPP18.012

Table VIII-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #10

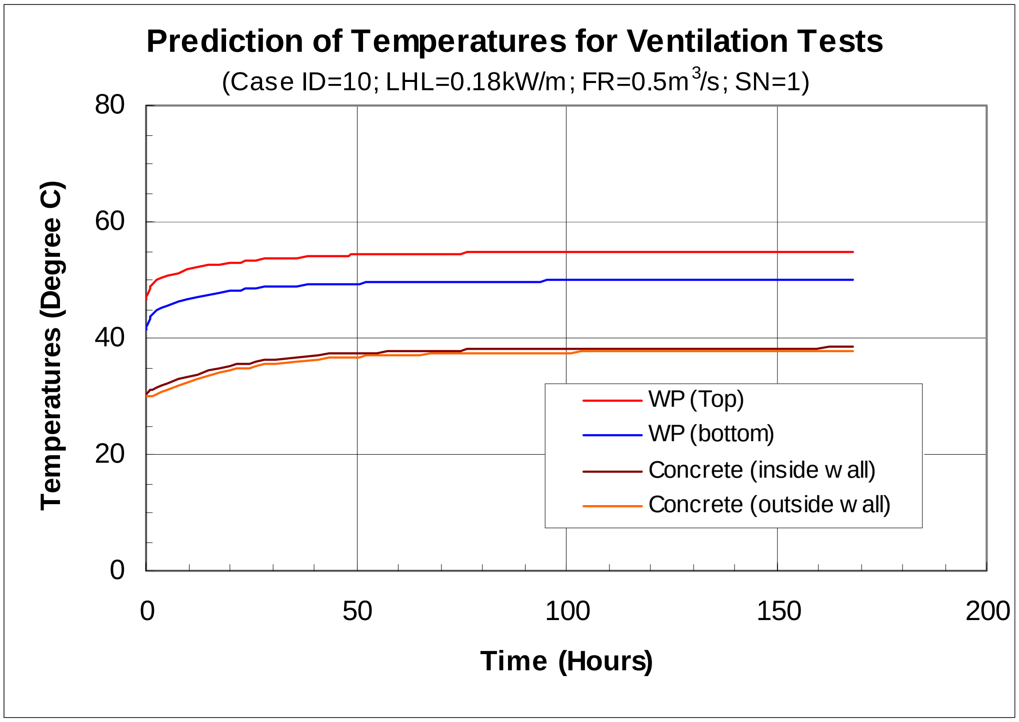
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	43.59	43.59	43.59	43.59
1.0	45.83	45.81	45.81	45.81
24.0	50.32	50.54	50.54	50.54
48.0	51.32	51.96	51.99	51.99
72.0	51.67	52.57	52.65	52.65
96.0	51.81	52.84	52.96	52.97
120.0	51.89	52.97	53.11	53.14
144.0	51.92	53.04	53.20	53.23
168.0	51.95	53.08	53.25	53.27

Source: DTN: MO0108MWDPPP18.012

Table VIII-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #10

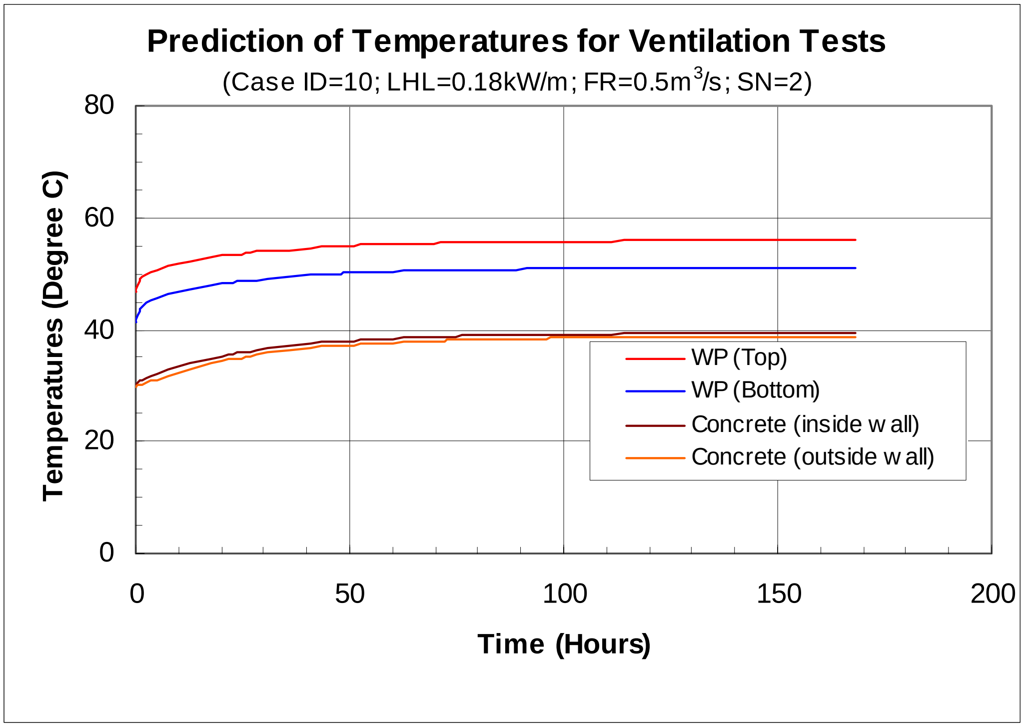
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	30.05	30.05	30.05	30.05
1.0	30.86	30.85	30.85	30.85
24.0	35.55	35.69	35.69	35.69
48.0	37.24	37.74	37.76	37.77
72.0	37.83	38.63	38.69	38.70
96.0	38.06	39.03	39.13	39.14
120.0	38.17	39.21	39.35	39.36
144.0	38.22	39.31	39.46	39.49
168.0	38.25	39.36	39.53	39.55

Source: DTN: MO0108MWDPPP18.012



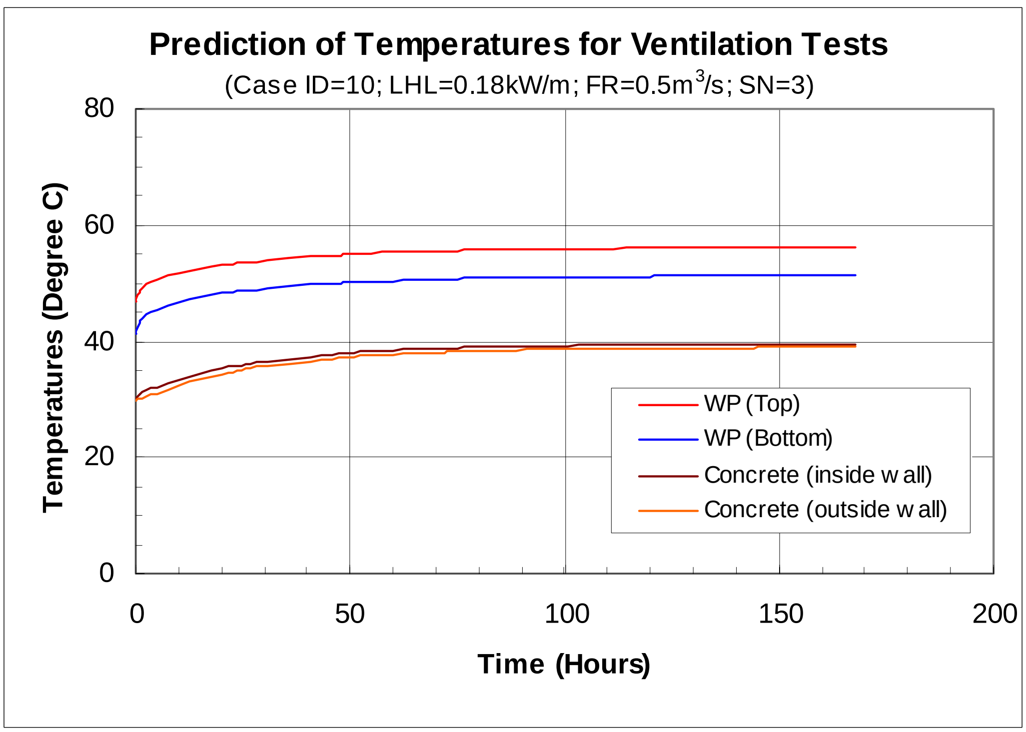
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VIII-1. Predicted Average Temperatures in Segment No. 1 for Case #10



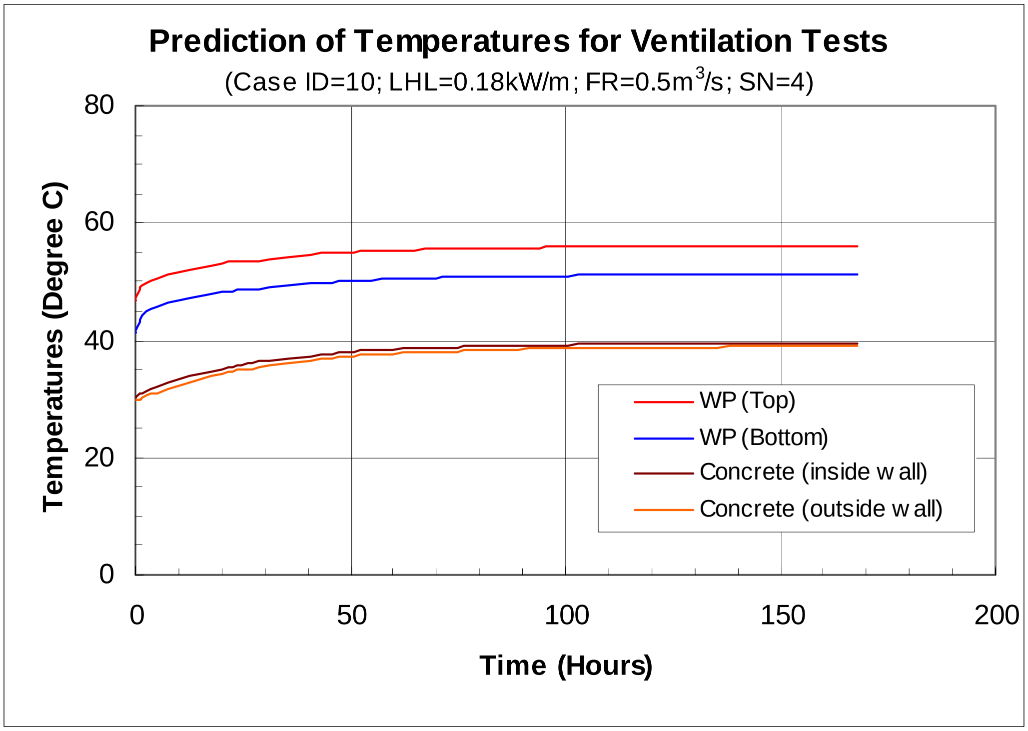
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VIII-2. Predicted Average Temperatures in Segment No. 2 for Case #10



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VIII-3. Predicted Average Temperatures in Segment No. 3 for Case #10



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure VIII-4. Predicted Average Temperatures in Segment No. 4 for Case #10

ATTACHMENT IX TEMPERATURES FOR CASE #11

This attachment provides the results of calculations of temperatures for the Case #11: a linear heat load of 0.18 kW/m, an intake air volume of 0.5 m^3/s, an intake air temperature of 45°C with a relative humidity of 10 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table IX-1. Average Air Temperatures (°C) at Different Time and Locations for Case #11

Time (Hours)	**Location Measured from Air-intake End (m)**				
	0.0	8.49	16.97	25.46	33.95
0	45.00	45.00	45.00	45.00	45.00
1.0	45.00	44.58	44.58	44.58	44.58
24.0	45.00	45.15	45.14	45.14	45.14
48.0	45.00	45.74	45.77	45.77	45.77
72.0	45.00	45.94	46.02	46.03	46.03
96.0	45.00	46.01	46.14	46.15	46.15
120.0	45.00	46.04	46.19	46.20	46.21
144.0	45.00	46.05	46.21	46.23	46.24
168.0	45.00	46.06	46.23	46.25	46.25

Source: DTN: MO0108MWDPPP18.012

Table IX-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #11

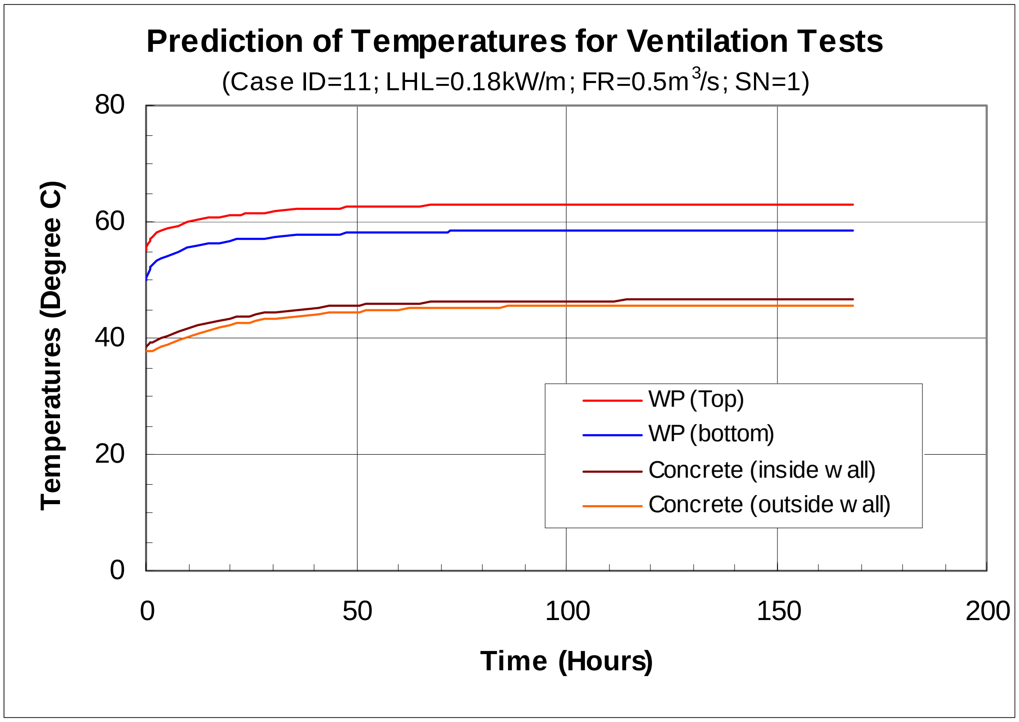
Time (Hours)	**Location Measured from Air-intake End (m)**			
	8.49	16.97	25.46	33.95
0	52.08	52.08	52.08	52.08
1.0	54.25	54.15	54.15	54.15
24.0	58.72	58.72	58.72	58.72
48.0	59.74	60.12	60.13	60.13
72.0	60.10	60.74	60.78	60.79
96.0	60.25	61.01	61.10	61.11
120.0	60.33	61.15	61.26	61.27
144.0	60.37	61.22	61.35	61.36
168.0	60.39	61.26	61.40	61.41

Source: DTN: MO0108MWDPPP18.012

Table IX-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #11

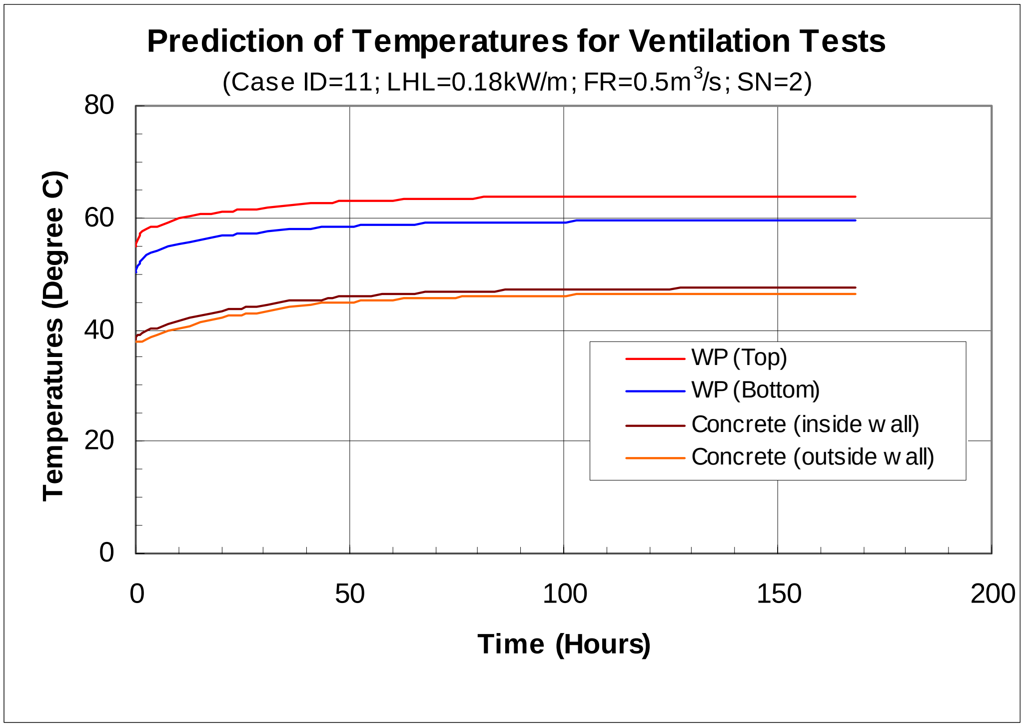
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	38.34	38.34	38.34	38.34
1.0	39.14	39.11	39.11	39.11
24.0	43.83	43.79	43.79	43.79
48.0	45.52	45.79	45.79	45.79
72.0	46.11	46.66	46.70	46.70
96.0	46.34	47.06	47.13	47.14
120.0	46.45	47.25	47.35	47.35
144.0	46.51	47.34	47.46	47.47
168.0	46.54	47.40	47.53	47.54

Source: DTN: MO0108MWDPPP18.012



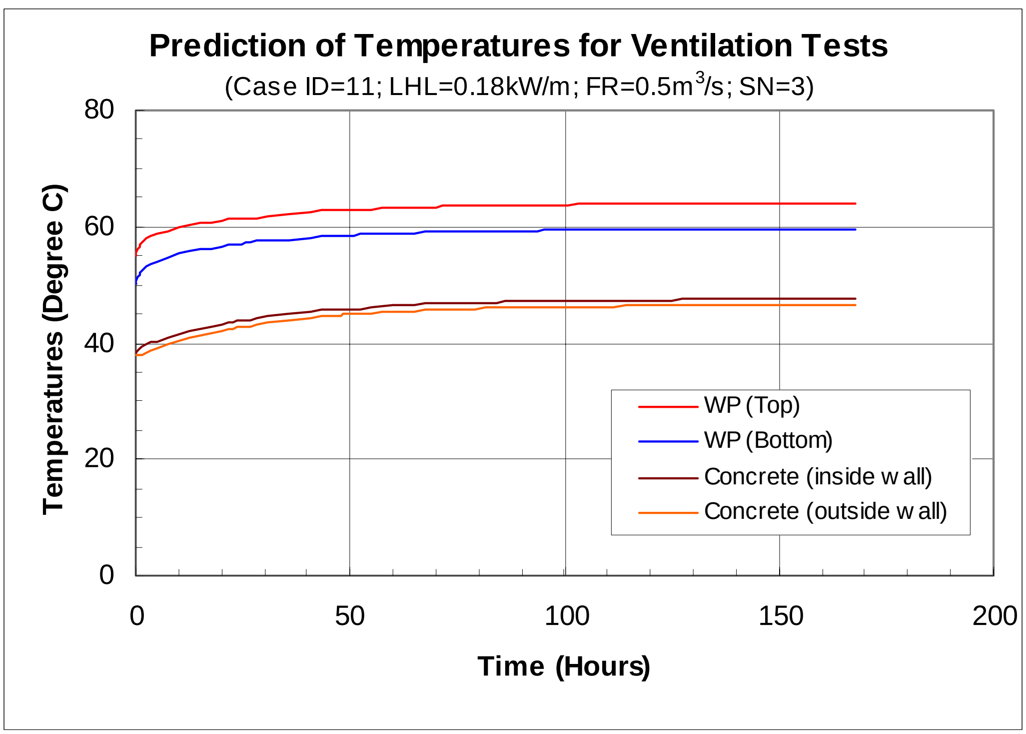
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IX-1. Predicted Average Temperatures in Segment No. 1 for Case #11



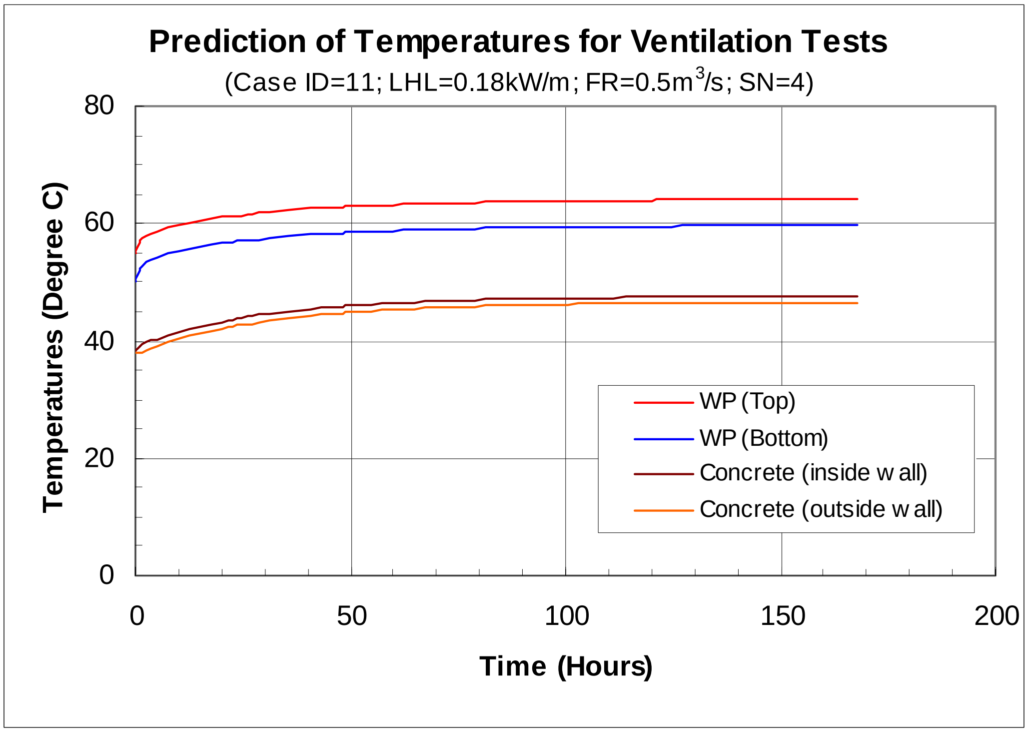
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IX-2. Predicted Average Temperatures in Segment No. 2 for Case #11



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IX-3. Predicted Average Temperatures in Segment No. 3 for Case #11



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure IX-4. Predicted Average Temperatures in Segment No. 4 for Case #11

ATTACHMENT X TEMPERATURES FOR CASE #12

This attachment provides the results of calculations of temperatures for the Case #12: a linear heat load of 0.36 kW/m, an intake air volume of 0.5 m^3/s, an intake air temperature of 25°C with a relative humidity of 30 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table X-1. Average Air Temperatures (°C) at Different Time and Locations for Case #12

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00	25.00
1.0	25.00	25.07	25.07	25.07	25.07
24.0	25.00	26.40	27.67	28.84	29.91
48.0	25.00	27.86	30.46	32.84	35.01
72.0	25.00	28.13	31.02	33.71	36.19
96.0	25.00	28.22	31.26	34.14	36.87
120.0	25.00	28.25	31.36	34.33	37.17
144.0	25.00	28.27	31.41	34.42	37.32
168.0	25.00	28.27	31.43	34.47	37.39

Source: DTN: MO0108MWDPPP18.012

Table X-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #12

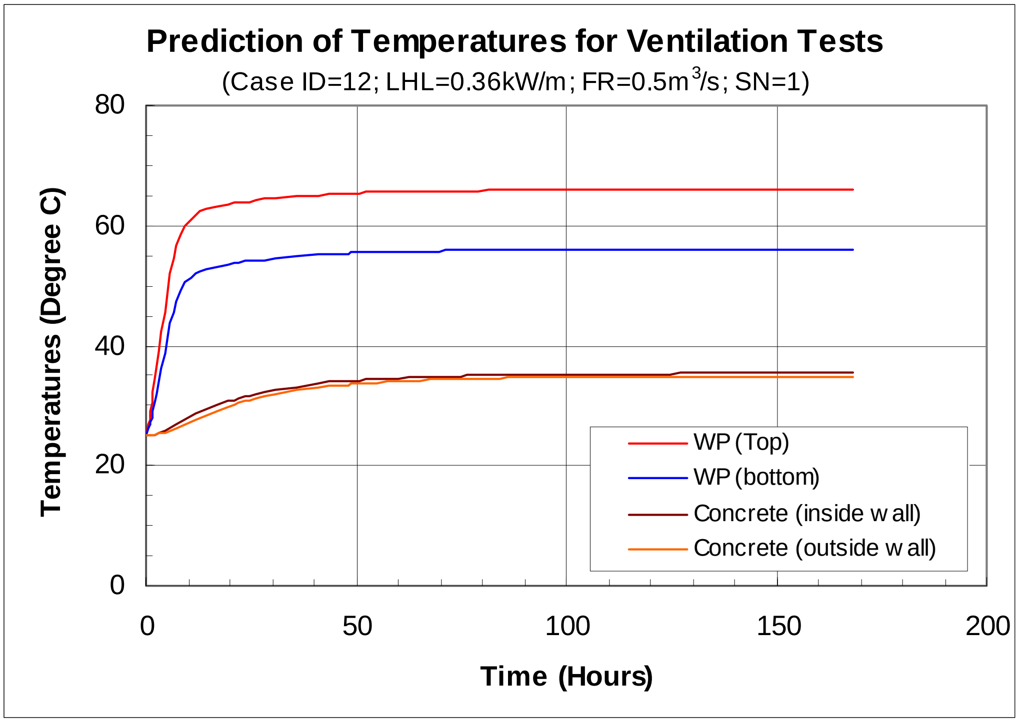
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
1.0	27.43	27.44	27.44	27.44
24.0	58.14	58.82	59.43	59.99
48.0	59.45	61.13	62.66	64.04
72.0	59.88	62.06	64.06	65.92
96.0	60.04	62.44	64.67	66.78
120.0	60.12	62.60	64.96	67.21
144.0	60.15	62.69	65.11	67.43
168.0	60.18	62.73	65.19	67.55

Source: DTN: MO0108MWDPPP18.012

Table X-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #12

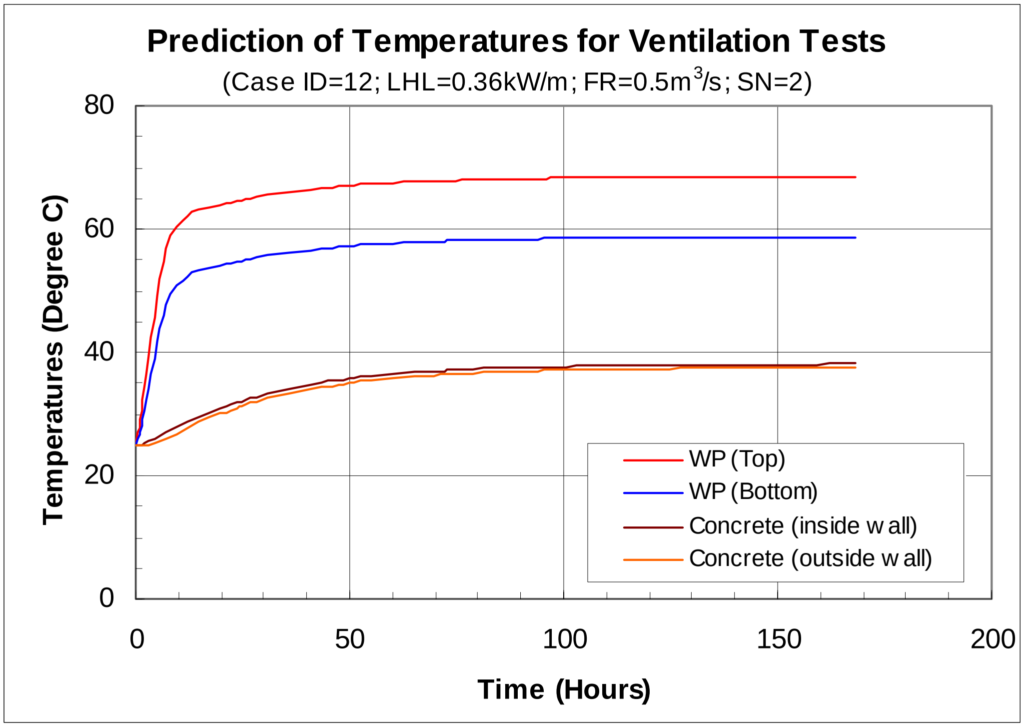
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	25.00	25.00	25.00	25.00
1.0	25.05	25.06	25.06	25.06
24.0	31.37	31.86	32.30	32.70
48.0	33.84	35.28	36.58	37.78
72.0	34.65	36.78	38.74	40.55
96.0	34.95	37.40	39.68	41.83
120.0	35.07	37.67	40.13	42.45
144.0	35.13	37.80	40.35	42.78
168.0	35.17	37.87	40.46	42.95

Source: DTN: MO0108MWDPPP18.012



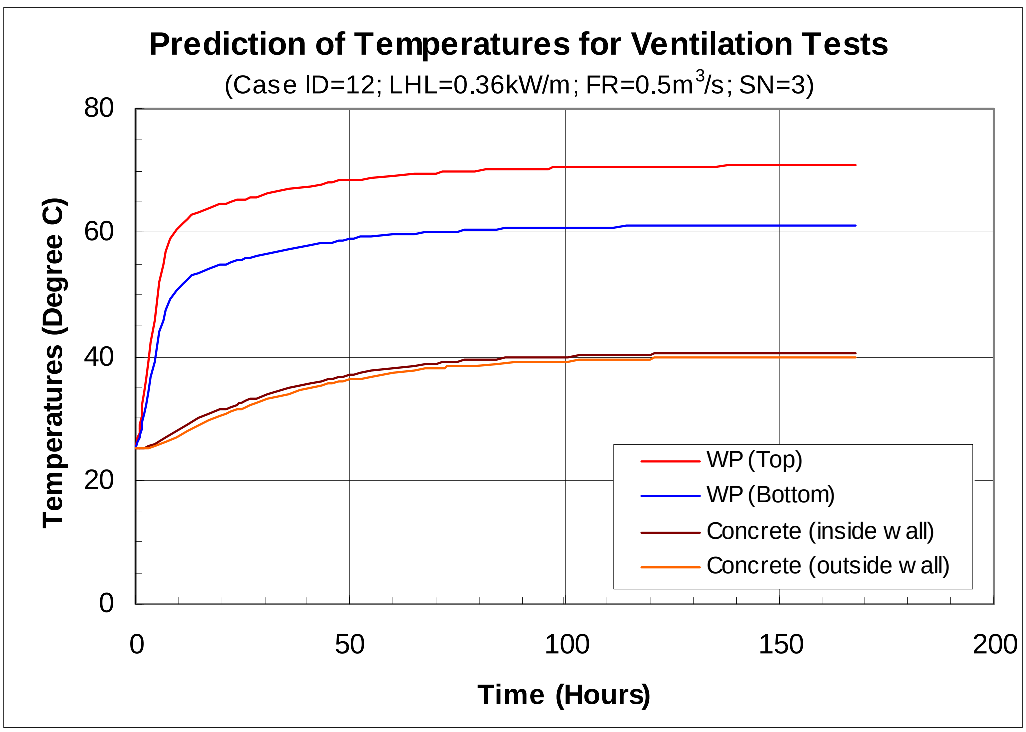
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure X-1. Predicted Average Temperatures in Segment No. 1 for Case #12



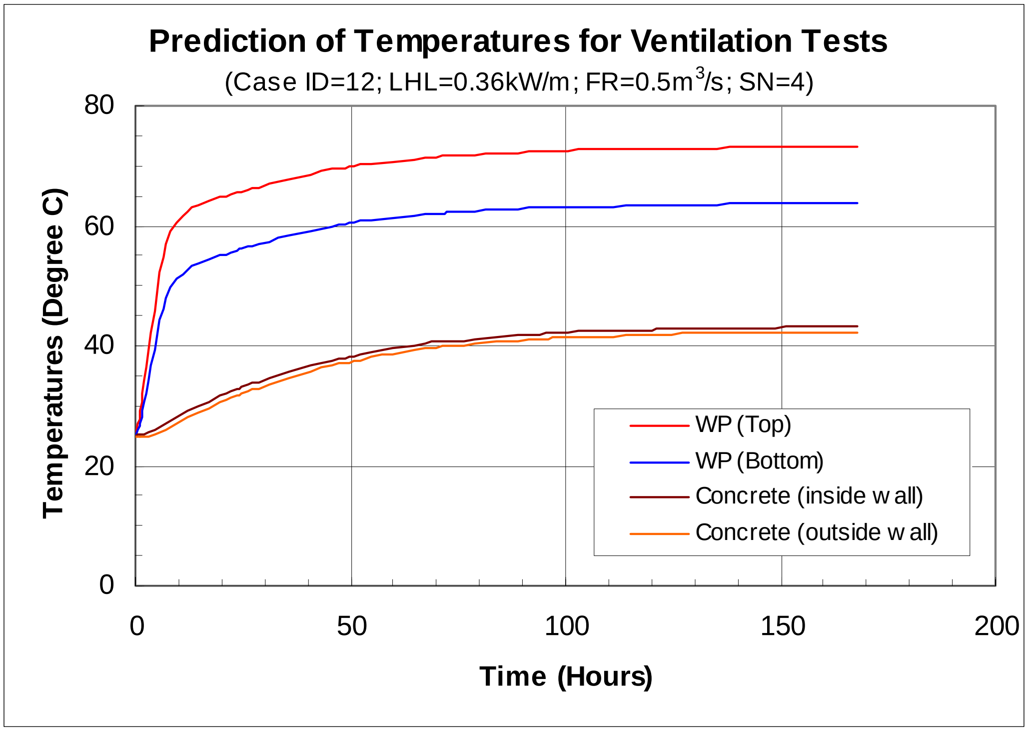
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure X-2. Predicted Average Temperatures in Segment No. 2 for Case #12



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure X-3. Predicted Average Temperatures in Segment No. 3 for Case #12



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure X-4. Predicted Average Temperatures in Segment No. 4 for Case #12

ATTACHMENT XI TEMPERATURES FOR CASE #13

This attachment provides the results of calculations of temperatures for the Case #13: a linear heat load of 0.36 kW/m, an intake air volume of 0.5 m^3/s, an intake air temperature of 35°C with a relative humidity of 17 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table XI-1. Average Air Temperatures (°C) at Different Time and Locations for Case #13

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	35.00	35.00	35.00	35.00	35.00
1.0	35.00	36.57	36.59	36.59	36.59
24.0	35.00	37.12	37.25	37.25	37.25
48.0	35.00	37.71	37.98	38.00	38.00
72.0	35.00	37.90	38.27	38.30	38.30
96.0	35.00	37.97	38.39	38.44	38.44
120.0	35.00	38.00	38.45	38.51	38.51
144.0	35.00	38.01	38.47	38.54	38.55
168.0	35.00	38.02	38.49	38.56	38.57

Source: DTN: MO0108MWDPPP18.012

Table XI-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #13

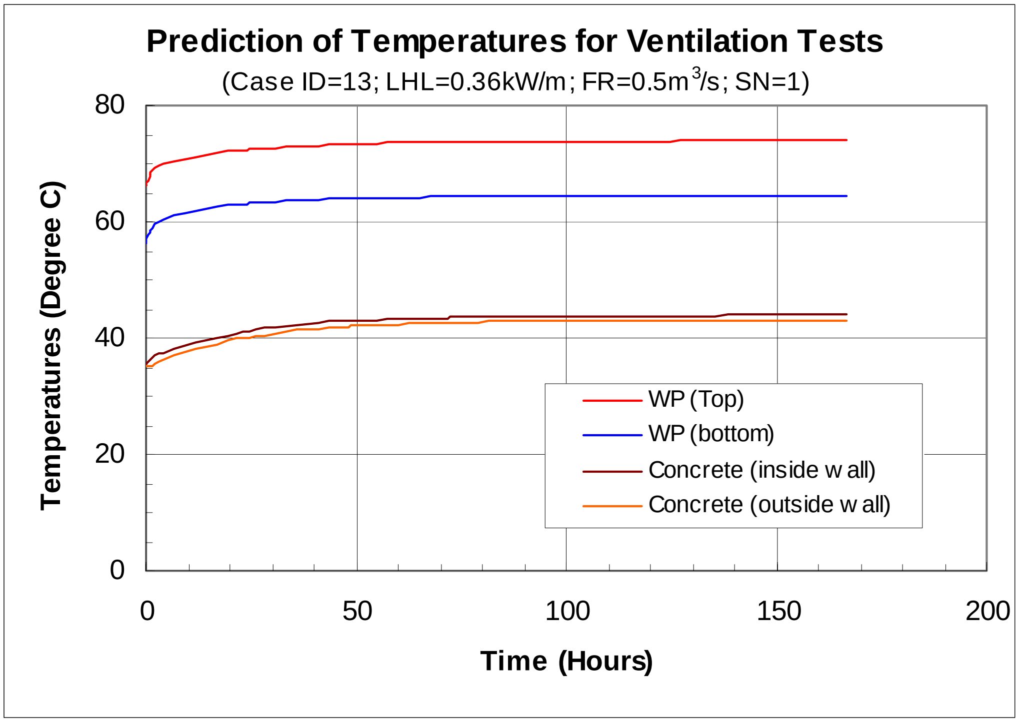
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	60.53	60.53	60.53	60.53
1.0	62.67	63.00	63.01	63.01
24.0	66.81	68.05	68.12	68.12
48.0	67.76	69.55	69.70	69.71
72.0	68.09	70.18	70.42	70.44
96.0	68.23	70.46	70.76	70.79
120.0	68.30	70.60	70.93	70.97
144.0	68.34	70.67	71.02	71.07
168.0	68.36	70.71	71.08	71.13

Source: DTN: MO0108MWDPPP18.012

Table XI-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #13

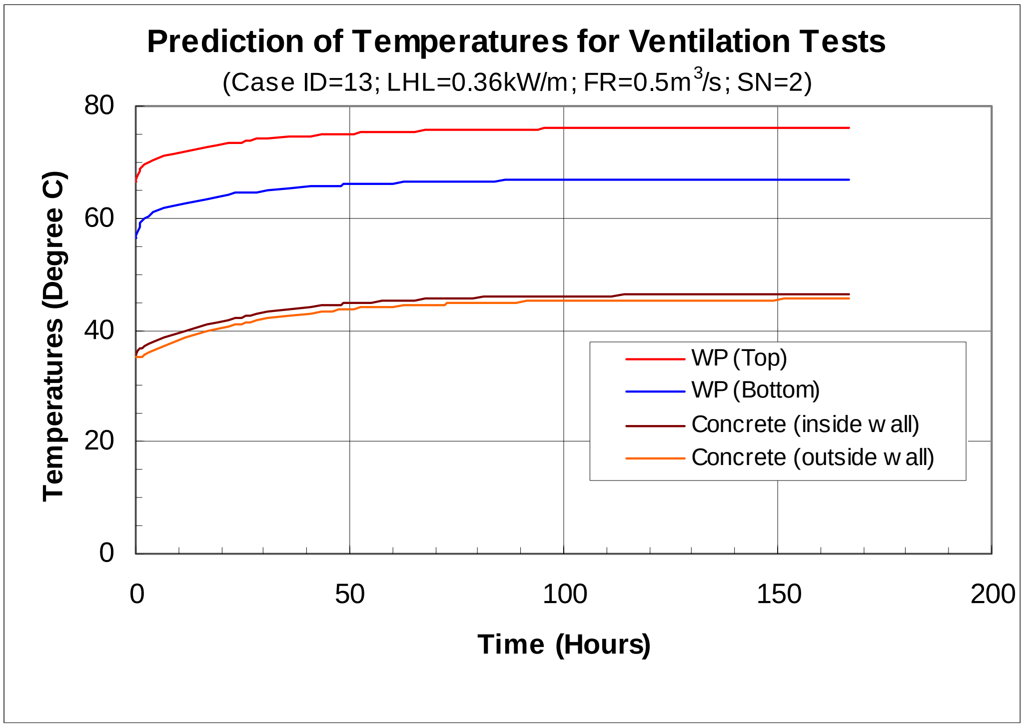
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	35.43	35.43	35.43	35.43
1.0	36.25	36.38	36.38	36.38
24.0	41.00	42.06	42.11	42.11
48.0	42.71	44.42	44.55	44.56
72.0	43.30	45.41	45.64	45.66
96.0	43.54	45.85	46.15	46.18
120.0	43.65	46.06	46.40	46.44
144.0	43.70	46.17	46.53	46.58
168.0	43.74	46.23	46.61	46.66

Source: DTN: MO0108MWDPPP18.012



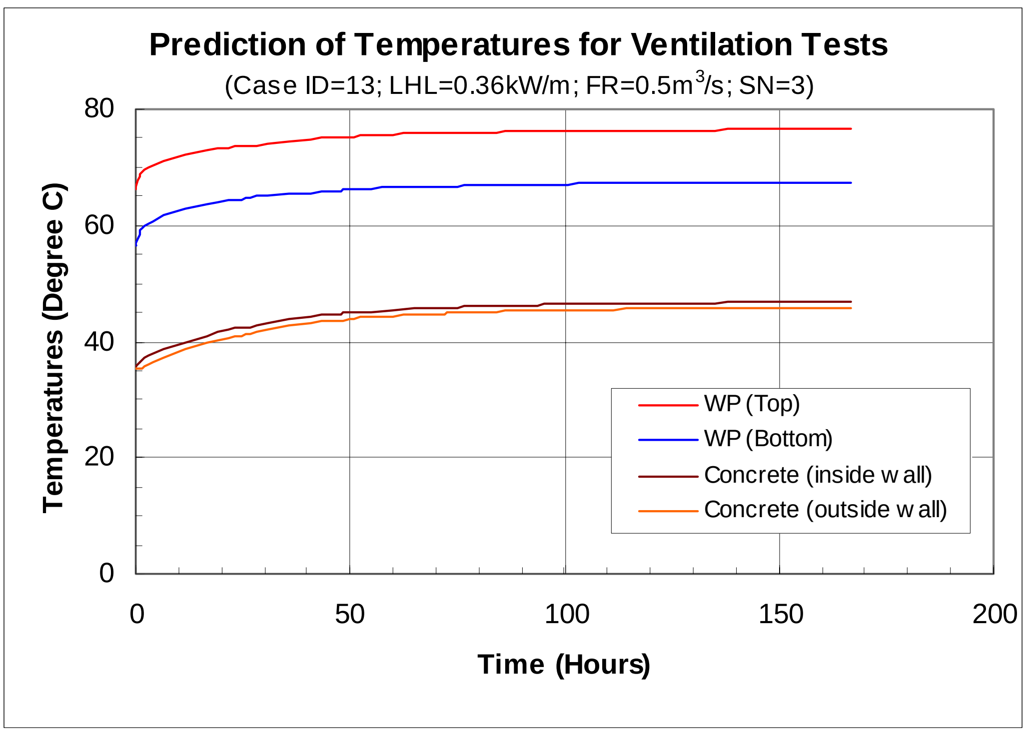
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XI-1. Predicted Average Temperatures in Segment No. 1 for Case #13



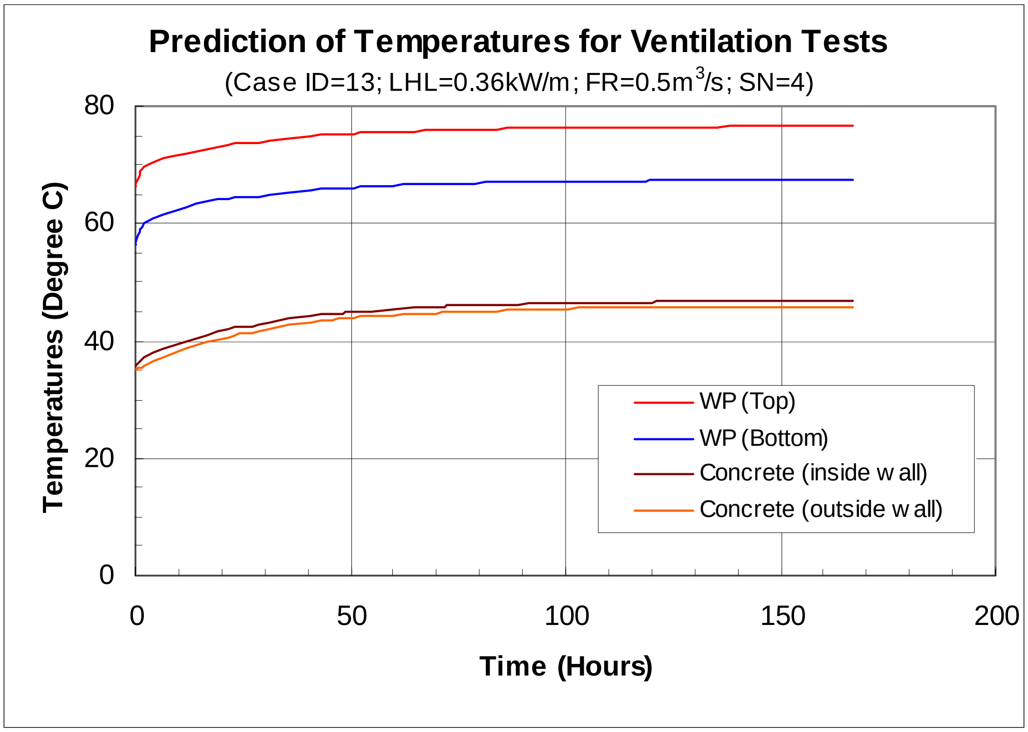
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XI-2. Predicted Average Temperatures in Segment No. 2 for Case #13



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XI-3. Predicted Average Temperatures in Segment No. 3 for Case #13



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XI-4. Predicted Average Temperatures in Segment No. 4 for Case #13

ATTACHMENT XII TEMPERATURES FOR CASE #14

This attachment provides the results of calculations of temperatures for the Case #14: a linear heat load of 0.36 kW/m, an intake air volume of 0.5 m^3/s, an intake air temperature of 45°C with a relative humidity of 10 percent. All data presented in this attachment can be found in DTN: MO0108MWDPPP18.012.

Table XII-1. Average Air Temperatures (°C) at Different Time and Locations for Case #14

Time (Hours)	Location Measured from Air-intake End (m)				
	0.0	8.49	16.97	25.46	33.95
0	45.00	45.00	45.00	45.00	45.00
1.0	45.00	46.26	46.28	46.28	46.28
24.0	45.00	46.82	46.92	46.93	46.93
48.0	45.00	47.41	47.64	47.66	47.66
72.0	45.00	47.60	47.93	47.96	47.96
96.0	45.00	47.67	48.05	48.10	48.10
120.0	45.00	47.71	48.11	48.17	48.17
144.0	45.00	47.72	48.14	48.20	48.21
168.0	45.00	47.73	48.16	48.22	48.23

Source: DTN: MO0108MWDPPP18.012

Table XII-2. Average WP Surface Temperatures (°C) at Different Time and Locations for Case #14

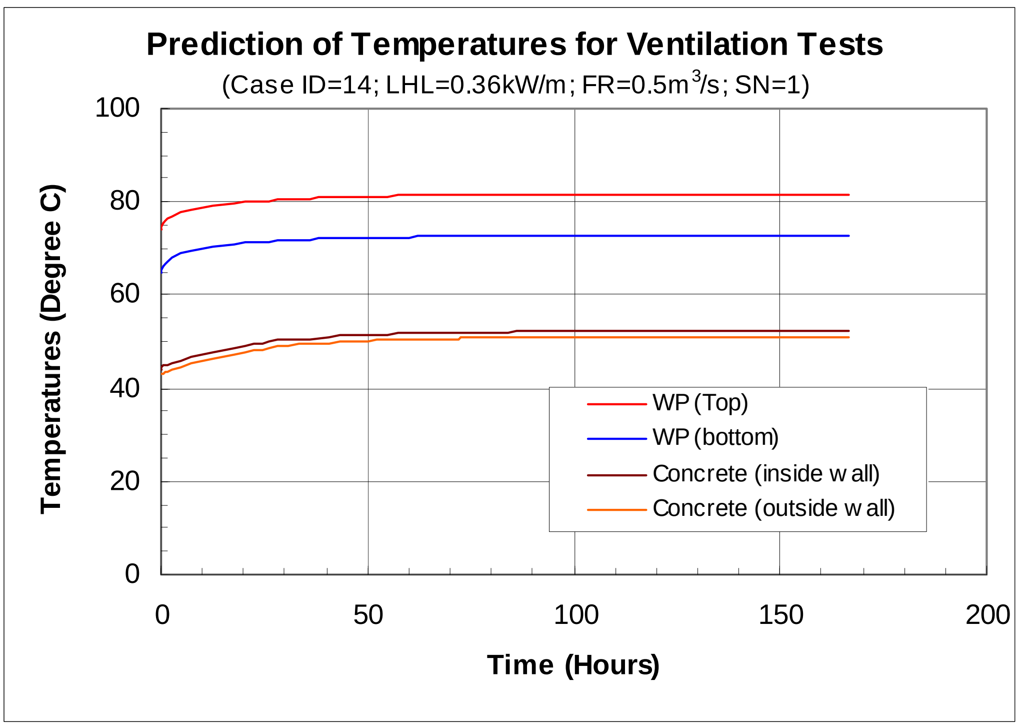
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	68.57	68.57	68.57	68.57
1.0	70.63	70.90	70.90	70.90
24.0	74.80	75.84	75.89	75.89
48.0	75.76	77.32	77.45	77.46
72.0	76.10	77.96	78.17	78.18
96.0	76.25	78.24	78.51	78.54
120.0	76.32	78.39	78.69	78.73
144.0	76.36	78.47	78.78	78.83
168.0	76.39	78.51	78.84	78.89

Source: DTN: MO0108MWDPPP18.012

Table XII-3. Average Concrete Pipe Temperatures (°C) at Different Time and Locations for Case #14

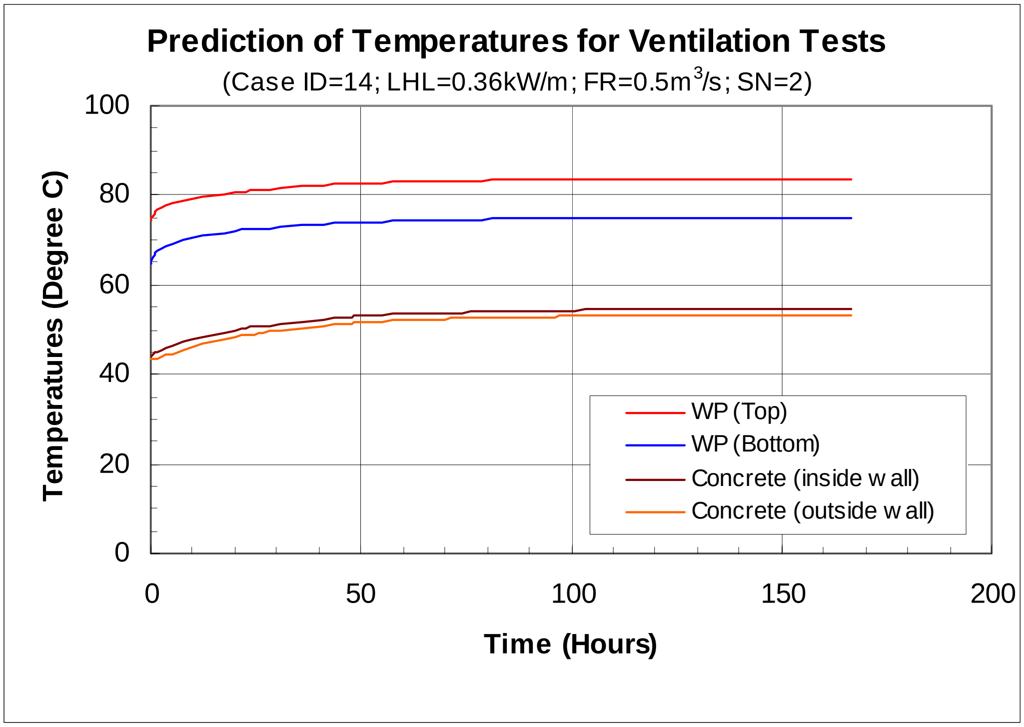
Time (Hours)	Location Measured from Air-intake End (m)			
	8.49	16.97	25.46	33.95
0	43.89	43.89	43.89	43.89
1.0	44.69	44.80	44.80	44.80
24.0	49.44	50.33	50.37	50.37
48.0	51.15	52.63	52.74	52.75
72.0	51.74	53.61	53.81	53.83
96.0	51.98	54.05	54.31	54.34
120.0	52.09	54.26	54.56	54.60
144.0	52.15	54.37	54.70	54.75
168.0	52.19	54.43	54.78	54.83

Source: DTN: MO0108MWDPPP18.012



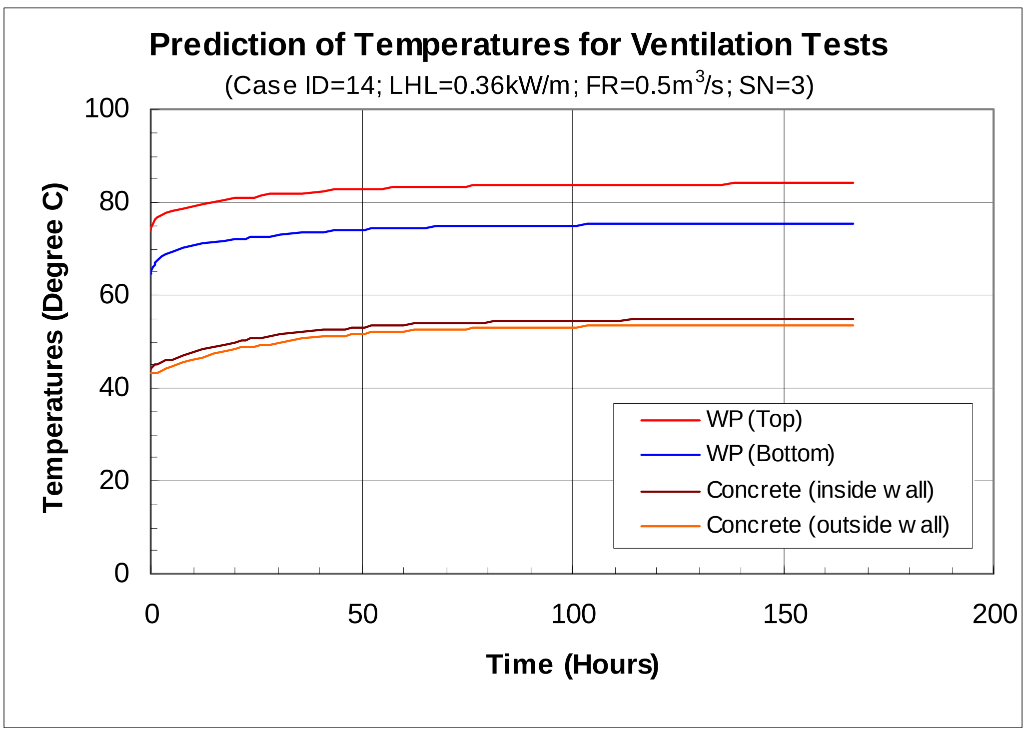
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XII-1. Predicted Average Temperatures in Segment No. 1 for Case #14



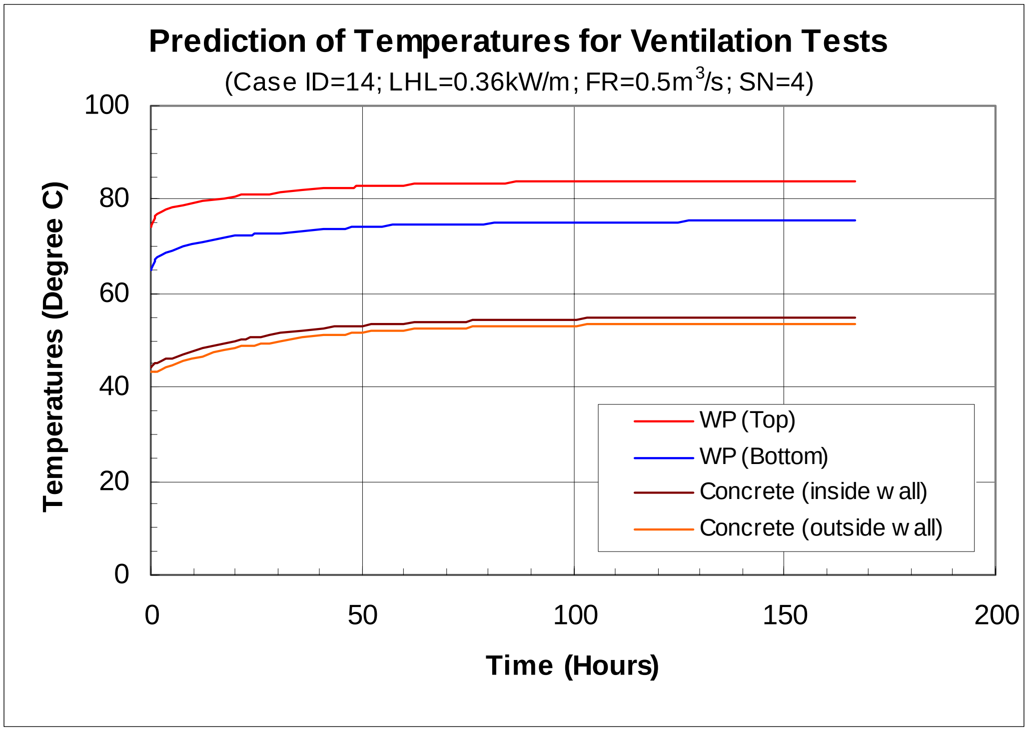
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XII-2. Predicted Average Temperatures in Segment No. 2 for Case #14



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XII-3. Predicted Average Temperatures in Segment No. 3 for Case #14



Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure XII-4. Predicted Average Temperatures in Segment No. 4 for Case #14

ATTACHMENT XIII CALCULATION OF CONVECTION HEAT TRANSFER COEFFICIENTS

This attachment presents the calculation of convection heat transfer coefficients using the equations provided in Section 5.3.3.2.

Given

π = 3.1415926	(Universal constant)
Concrete pipe diameter (D_w) = 1.3716 m	(Section 5.1.3)
Waste package steel pipe diameter (D_p) = 0.4064 m	(Section 5.1.2)
Depth of invert = 0.21 m	(Assumption 3.3)
Air flow rate (Q) = 0.5 and 1.0 m^3/s	(Section 5.3.3.2)
Intake air temperature (T) = 25, 35, and 45°C	(Section 5.3.3.2)
Air properties at 25, 35, and 45°C as follow:	(Section 5.1.7)

Parameter	At 298 K (25°C)	At 308 K (35°C)	At 318 K (45°C)
Density (kg/m^3)	1.1868	1.1487	1.1128
Thermal Conductivity (W/m·K)	0.0261	0.0269	0.0276
Specific Heat (J/kg·K)	1,005.7	1,006.2	1,006.9
Dynamic Viscosity (kg/m·s)	1.8363×10^{-5}	1.8828×10^{-5}	1.9286×10^{-5}
Prandtl Number (dimensionless)	0.709	0.706	0.704

Solution

Contained Angle:

$$\alpha = 2\arccos\left(\frac{1.3716/2 - 0.21}{1.3716/2}\right) = 92.14\,°$$

Area of invert:

$$a = \frac{1}{2}R^2(\alpha - \sin\alpha) = \frac{1}{2}\left(\frac{1.3716}{2}\right)^2\left(\frac{92.14}{180}\pi - \sin 92.14\right) = 0.1432\text{m}^2$$

Area in flow:

$$A_{flow} = \frac{\pi}{4}\left(D_w^2 - D_p^2\right) - a = \frac{\pi}{4}\left(1.3716^2 - 0.4064^2\right) - 0.14 = 1.2046\text{m}^2$$

Wetter perimeter:

$$P = \pi\left(D_w + D_p\right) = \pi(1.3716 + 0.4064) = 5.5858\,\text{m}$$

Hydraulic diameter (Eq. 5-13):

$$D_h = \frac{4A_{flow}}{P} = \frac{4\times 1.2046}{5.5858} = 0.86\text{m}$$

a) *h* at Air Flow Rate of 0.5 m^3/s

Air flow velocity (Eq. 5-11):

$$v = \frac{Q}{A_{flow}} = \frac{0.5}{1.2046} = 0.42\text{m/s}$$

a.1) Intake Air Temperature at 25°C

Reynolds No. (Eq. 5-12):

$$Re = \frac{\rho v D_h}{\mu} = \frac{1.1868\times 0.42\times 0.86}{1.8363\times 10^{-5}} = 23141.01$$

Nusselt No. (Eq. 5-14):

$$Nu = 0.020 Re^{0.8} Pr^{1/3}\left(\frac{D_w}{D_p}\right)^{0.53} = 0.020\times 23141.01^{0.8} 0.709^{1/3}\left(\frac{1.3716}{0.4064}\right)^{0.53} = 105.37$$

Convection heat transfer coefficient (Eq. 5-15):

$$h = \frac{kNu}{D_h} = \frac{0.02608\times 105.37}{0.86} = 3.19\text{W/m}^2\cdot\text{K}$$

a.2) Intake Air Temperature at 35°C

Reynolds No. (Eq. 5-12):

$$Re = \frac{\rho v D_h}{\mu} = \frac{1.1487\times 0.42\times 0.86}{1.8828\times 10^{-5}} = 21844.94$$

Nusselt No. (Eq. 5-14):

$$Nu = 0.020Re^{0.8}Pr^{1/3}\left(\frac{D_w}{D_p}\right)^{0.53} = 0.020 \times 21844.94^{0.8}0.706^{1/3}\left(\frac{1.3716}{0.4064}\right)^{0.53} = 100.48$$

Convection heat transfer coefficient (Eq. 5-15):

$$h = \frac{kNu}{D_h} = \frac{0.02685 \times 100.48}{0.86} = 3.13\text{W/m}^2 \cdot \text{K}$$

<u>a.3) Intake Air Temperature at 45°C</u>

Reynolds No. (Eq. 5-12):

$$Re = \frac{\rho v D_h}{\mu} = \frac{1.1128 \times 0.42 \times 0.86}{1.9286 \times 10^{-5}} = 20659.67$$

Nusselt No. (Eq. 5-14):

$$Nu = 0.020Re^{0.8}Pr^{1/3}\left(\frac{D_w}{D_p}\right)^{0.53} = 0.020 \times 20659.67^{0.8}0.704^{1/3}\left(\frac{1.3716}{0.4064}\right)^{0.53} = 96.01$$

Convection heat transfer coefficient (Eq. 5-15):

$$h = \frac{kNu}{D_h} = \frac{0.02760 \times 96.01}{0.86} = 3.07\text{W/m}^2 \cdot \text{K}$$

b) *h* at Air Flow Rate of 1.0 m³/s

Air flow velocity (Eq. 5-11):

$$v = \frac{Q}{A_{flow}} = \frac{1.0}{1.2046} = 0.83\text{m/s}$$

<u>b.1) Intake Air Temperature at 25°C</u>

Reynolds No. (Eq. 5-12):

$$Re = \frac{\rho v D_h}{\mu} = \frac{1.1868 \times 0.83 \times 0.86}{1.8363 \times 10^{-5}} = 46282.02$$

Nusselt No. (Eq. 5-14):

$$Nu = 0.020Re^{0.8}Pr^{1/3}\left(\frac{D_w}{D_p}\right)^{0.53} = 0.020 \times 46282.02^{0.8}0.709^{1/3}\left(\frac{1.3716}{0.4064}\right)^{0.53} = 183.47$$

Convection heat transfer coefficient (Eq. 5-15):

$$h = \frac{kNu}{D_h} = \frac{0.02608 \times 183.47}{0.86} = 5.55\,\mathrm{W/m^2 \cdot K}$$

<u>b.2) Intake Air Temperature at 35°C</u>

Reynolds No. (Eq. 5-12):

$$Re = \frac{\rho v D_h}{\mu} = \frac{1.1487 \times 0.83 \times 0.86}{1.8828 \times 10^{-5}} = 43689.87$$

Nusselt No. (Eq. 5-14):

$$Nu = 0.020 Re^{0.8} Pr^{1/3} \left(\frac{D_w}{D_p} \right)^{0.53} = 0.020 \times 43689.87^{0.8} 0.706^{1/3} \left(\frac{1.3716}{0.4064} \right)^{0.53} = 174.95$$

Convection heat transfer coefficient (Eq. 5-15):

$$h = \frac{kNu}{D_h} = \frac{0.02685 \times 174.95}{0.86} = 5.45\,\mathrm{W/m^2 \cdot K}$$

<u>b.3) Intake Air Temperature at 45°C</u>

Reynolds No. (Eq. 5-12):

$$Re = \frac{\rho v D_h}{\mu} = \frac{1.1128 \times 0.83 \times 0.86}{1.9286 \times 10^{-5}} = 41319.33$$

Nusselt No. (Eq. 5-14):

$$Nu = 0.020 Re^{0.8} Pr^{1/3} \left(\frac{D_w}{D_p} \right)^{0.53} = 0.020 \times 41319.33^{0.8} 0.704^{1/3} \left(\frac{1.3716}{0.4064} \right)^{0.53} = 167.16$$

Convection heat transfer coefficient (Eq. 5-15):

$$h = \frac{kNu}{D_h} = \frac{0.02760 \times 167.16}{0.86} = 5.35\,\mathrm{W/m^2 \cdot K}$$