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CONTENTS

Page

FIGURES

FIGURES (Continued)

Page

FIGURES (Continued)

Page

TABLES

1. PURPOSE

The objective of this calculation is to predict the temperatures of the ventilating air, waste package surface, concrete pipe walls, and insulation that will be developed during the ventilation tests involving various test conditions. The results will be used as input to the following three areas:

- Decisions regarding testing set-up and performance.
- Assessing how best to scale the test phenomena measured.
- Validating numerical approach for modeling continuous ventilation.

The scope of the calculation is to identify the physical mechanisms and parameters related to thermal response in the ventilation tests, and develop and describe numerical methods that can be used to calculate the effects of continuous ventilation. Sensitivity studies to assess the impact of variation of linear power densities (linear heat loads) and ventilation air flow rates are included. The calculation is limited to thermal effect only.

This engineering work activity has been evaluated in accordance with the AP-2.21Q procedure, and is subject to QA controls (CRWMS M&O 2000a). The calculation is developed in accordance with the AP-3.12Q procedure, *Calculations*, Revision 0, ICN 3, and prepared in accordance with the *Development Plan for Ventilation Pretest Predictive Calculation* (CRWMS M&O 2000a).

2. METHOD

The calculation uses the numerical code ANSYS Version 5.2 to predict the temperatures of the air, the carbon steel waste package, the concrete pipe simulating the emplacement drift, and the insulation around the pipe to control heat loss for the ventilation tests. The code applies the following scientific laws in predicting temperature distributions: 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.

Primary data were selected from the Technical Information Center (TIC), Document Control (DC), and input transmittal in accordance with the AP-3.14Q procedure, *Transmittal of Input*. The use or control of electronic media for data is not required. There is no variance in the method used from that planned (CRWMS M&O 2000a, Section 2). Details of the approach used in the calculation are provided in Section 5.

3. ASSUMPTIONS

The following assumptions are made in the calculations:

3.1 The temperature of the intake air for ventilation is assumed to be 25°C. The tests will be conducted indoor, and the indoor air temperature is expected to be controlled and measured. Any difference between the measured intake air temperature and the assumed will be considered in the adjustment of inputs to the posttest calculations. Further confirmation of this assumption is not required. Used throughout.

3.2 The temperature of the air outside the insulation is assumed to remain constant at 25°C. The rationale for this assumption is the same as for Assumption 3.1. Further confirmation of this assumption is not required. Used throughout.

3.3 Natural convection is dominant outside the insulation, and forced convection is negligible because the air flow outside the test set-up or insulation is minimal. Further confirmation of this assumption is not required. Used throughout.

3.4 The initial temperature of the whole system is assumed to be 25°C. The rationale for this assumption is the same for Assumption 3.1. Further confirmation of this assumption is not required. Used throughout.

3.5 The waste package and drift are sufficiently long compared to the diameters that two-dimensional analyses will be satisfactory. This assumption may be confirmed by agreement between the test results and those calculated from this report. Used throughout.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 ANSYS COMPUTER SOFTWARE

A commercially available computer program, ANSYS Version 5.2, is 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) and Sun Microsystems workstations with the Unix operating system. ANSYS Version 5.2 has been verified and validated (CSCI#: 30013 V5.2SGI, CRWMS M&O 1997) according to the AP-SI.1Q procedure, *Software Management*. The input and output files generated by ANSYS were archived and submitted to the Technical Data Management System (TDMS) and the Records Processing Center (RPC) (DTN: MO0101MWDPPV13.006). The results are presented and described throughout Section 6.0. A detailed discussion of the general features and fields of application of the ANSYS code is presented in the User's Manual (Swanson Analysis Systems 1995).

The ANSYS Version 5.2 software (CSCI#: 30013 V5.2SGI) was obtained from the software Configuration Management (CM) in accordance with the AP-SI.1Q procedure. The software was appropriate for the applications used in this analysis. The software was used within the range of validation as specified in the software qualification report (CRWMS M&O 1997).

4.2 SPREADSHEET SOFTWARE

Microsoft Excel 97 spreadsheet software was used in displaying some of the ANSYS results graphically. The results from ANSYS analyses were used as inputs, and the outputs are presented in the forms of figures in Section 6. User-defined formulas and/or algorithms are displayed where used. No additional information governing the use of Microsoft Excel 97 in this calculation is required by the AP-SI.1Q procedure.

5. CALCULATIONS

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, *Managing Technical Product Inputs*.

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 Waste package

The physical and thermal properties for the waste package used in the calculation are listed in Table 5-1. These values are for carbon steel material, based on the *Fundamentals of Heat and Mass Transfer* (Incropera and DeWitt 1985, Tables A.1 and A.11). According to the *Conceptual Arrangement Simulated Emplacement Ventilation Test* (CRWMS M&O 2000c), the designed diameter of the waste package is 0.4064 m (16 inches).

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

Parameter	Value
Density (kg/m^3)	7854[a]
Thermal Conductivity (W/m·K)	60.5[a]
Specific Heat (J/kg·K)	434[a]
Emissivity	0.8[b]

Note: [a] Incropera and DeWitt 1985, Table A.1.
[b] Incropera and DeWitt 1985, Table A.11.

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. These values are obtained based on the *Heat Transfer* (Holman 1997, Table A-3) and the *Fundamentals of Heat and Mass Transfer* (Incropera and DeWitt, Table A.11). The designed inner and outer diameters of the concrete pipe are 1.3716 m and 1.651 m, respectively (CRWMS M&O 2000c).

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

Parameter	Value
Density (kg/m^3)	2100[a]
Thermal Conductivity (W/m·K)	1.37[a]
Specific Heat (J/kg·K)	880[a]
Emissivity	0.93[b]

Note: [a] Holman 1997, Table A-3.
[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). 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 (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. These values are obtained based on the *Thermal and Physical Properties of Granular Materials* (CRWMS M&O 2000b, Tables 4 and 6) and 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	0.95[c]

Note: [a] CRWMS M&O 2000b, Table 4, a mean value for fine crushed tuff.
[b] CRWMS M&O 2000b, 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 (carbon steel) used in the calculation are listed in Table 5-1.

5.1.7 Physical and Thermal Properties for Air

The physical and thermal properties for air used in the calculation are listed in Table 5-5. These values are obtained based on *Heat Transfer* (Holman 1997, Table A-5).

Table 5-5. Physical and Thermal Properties for Ventilation Air at 298 K (25°C), 310.5 K (37.5°C), and 350 K (77°C)

Parameter	At 298 K	At 310.5 K	At 350 K
Density (kg/m^3)	1.1868	1.1397	0.9980
Thermal Conductivity (W/m·K)	0.0261	0.0270	0.03003
Specific Heat (J/kg·K)	1,005.7	1,006.4	1,009.0
Dynamic Viscosity (kg/m·s)	1.8363×10^{-5}	1.8942×10^{-5}	2.075×10^{-5}
Prandtl Number (dimensionless)	0.709	0.706	0.697

Source: Holman 1997, Table A-5.

5.1.8 Effective Length of Test Section

The effective length of test section used in the calculation is about 33.528 m (110 feet). This information is obtained based on the *Conceptual Arrangement Simulated Emplacement Ventilation Test* (CRWMS M&O 2000c).

5.2 THEORETICAL BACKGROUND

Heat transfer mechanisms in the ventilation tests involve conduction, convection, and radiation. Conductive heat flow occurs within the waste package, 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 surface and the drift wall. The radiation can transfer heat between two surfaces with thermal gradient without going through a medium.

Based on the balance of thermal energy, the general three-dimensional, heat conduction equation (Fourier's law of heat conduction) can be expressed in Cartesian coordinates as (Holman 1997, Equation 1-3, p. 5):

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

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

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):

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

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

The heat from the waste packages to the concrete wall is transferred mainly through thermal radiation. In the ANSYS model, the waste packages are completely enclosed by the concrete pipe, 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):

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

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

5.3 MODELING APPROACH

5.3.1 Model Configurations

The model configuration used in ANSYS thermal calculations is illustrated in Figure 5-1. The model contains a waste package, waste package support, invert, concrete pipe, and insulation. Materials for both the waste package and its support are carbon steel. The invert is composed of crushed tuff. Material for the insulation is fiber glass (see Section 5.1.4). Based on Assumption 3.5, a two-dimensional model is used in the calculation.

5.3.2 Boundary Conditions

Two types of boundary conditions, convection and radiation, are used in the calculation. The radiation boundary exists on the surface of the waste package. All other boundaries are set as convection boundaries. The air temperature within the test section is time-dependent, while the air temperature outside the insulation is prescribed to be 25°C (Section 3.2).

5.3.3 Approach

As stated, conduction, convection, and radiation heat exchanges are involved in the ventilation tests. Conduction and radiation are modeled by ANSYS using Equations 5-1 and 5-3, respectively. Details on the approach can be found in the *ANSYS User's Manual for Revision 5.2* (Swanson Analysis Systems 1995, Volume I, Chapter 4). For convection heat transfer associated with the continuous ventilation, the solutions from ANSYS analyses cannot directly give the result of air temperatures. Additional process is required to take into account the coupled fluid flow and heat transfer effects. The approach used is discussed below.

5.3.3.1 Modeling of Continuous Ventilation

Determination of heat exchange in a ventilation test is a complex three-dimensional and time-dependent coupled fluid flow and heat transfer problem. To simplify the solution, an approximate numerical approach using the ANSYS computer code is employed. A description of the approach follows.

First, the entire test section, subjected to continuous ventilation, with a length of L is divided into an integral number of segments of equal length Δl, so the total number of segments, m, will be equal to $L/\Delta l$. During modeling, 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 wall and waste package temperatures at a specific modeling time are assumed to be constant over the length of a segment. Theoretically, the length of segments should be selected as short as possible so that the changing air, wall, and waste package surface temperatures along a segment can be reasonably represented by their averaged constants.

The computation of temperatures is performed for every segment sequentially over a prespecified ventilation time or duration, t_{vent}, so the total number of computational runs for each case is the same as that of the number of segments, m. In this calculation, the 110-foot-long test section (33.528-meter-long) (Section 5.1.8) was divided into four (4) segments, with a length of 8.382 meters for each segment.

Second, the ventilation time, t_{vent}, is partitioned into a number of time-steps, n, for each computational run. In this calculation, the size of time-steps selected varies from 1 hour to 72 hours for a modeling time of up to 360 hours.

Third, after the selection of segment length and time-step size, the ANSYS program is executed sequentially for a total number of m times for each case. Resulting wall temperature and waste package surface temperature and the heat flow rate for the currently modeled segment are utilized to calculate the average exhaust air temperature of the segment by means of Newton's cooling law (Equation 5-2). This exhaust air temperature is then used as input for the ventilating intake air temperature of the computational run for the subsequent segment as described below in detail. This process is repeated until the computational run for the last segment is completed.

The following outlines the process of using Newton's cooling law (Equation 5-2) and energy balance (Fourier's law of heat conduction) (Equation 5-1) to calculate the exhaust air temperatures in a segment.

The rates of heat removed from wall and waste package surface in a segment by ventilation are determined by:

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

and

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

Where	q_w	=	rate of heat removed from concrete wall, W
	q_p	=	rate of heat removed from waste package surface, W
	h	=	convection heat transfer coefficient, W/m^2·K
	A_w	=	concrete wall area, m^2
	A_p	=	waste package surface area, m^2
	T_{wa}	=	average concrete wall temperature, K
	T_{pa}	=	average waste package surface temperature, K
	T_{ain}	=	intake air temperature, K

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

$$T_{aout} = T_{ain} + \frac{q_w + q_p}{Q\rho c_p} \qquad \text{(Eq. 5-6)}$$

Where	T_{aout}	=	exhaust air temperature, K
	T_{ain}	=	intake air temperature, K
	q_w	=	rate of heat removed from concrete wall, W
	q_p	=	rate of heat removed from waste package surface, W
	Q	=	ventilation air flow rate, m^3/s

ρ	=	density of air, kg/m^3
c_p	=	specific heat of air, J/kg·K

Then substitute the average of the intake and exhaust air temperatures for the intake air temperature, T_{ain}, in Equations (5-4) and (5-5), to calculate q_{rm} the rate of heat removed by ventilation at a given time step, that is,

$$q_{rm} = q_w + q_p = hA_w(T_{wa} - T_{aa}) + hA_p(T_{pa} - T_{aa}) \qquad \text{(Eq. 5-7)}$$

Where T_{aa} = average of intake and exhaust air temperature in a segment at a given time step, K, defined as

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

Where
T_{ain} = intake air temperature, K
T_{aout} = exhaust air temperature, K

5.3.3.2 Calculation of Convection Heat Transfer Coefficients

5.3.3.2.1 Convection Within Test Section

Mixed natural and forced convection within the test section is considered in evaluation of the convection heat transfer coefficient.

(a) Natural Convection

Convection heat transfer coefficients for natural convection within the test section were evaluated using the empirical equations for the Nusselt Number developed by Kuehn and Goldstein for natural convection heat transfer in concentric horizontal cylindrical annuli (Gebhart et al. 1988, Equation 14.4.16). These equations are expressed as follows:

$$Nu_i = \frac{2}{\ln\left\{1 + \dfrac{2}{\left[\left(0.5Ra_{D_i}{}^{1/4}\right)^{15} + \left(0.12Ra_{D_i}{}^{1/3}\right)^{15}\right]^{1/15}}\right\}} \qquad \text{(Eq. 5-9)}$$

and

$$Nu_o = \frac{-2}{\ln\left\{1 - \dfrac{2}{\left[\left(Ra_{D_o}{}^{1/4}\right)^{15} + \left(0.12Ra_{Do}{}^{1/3}\right)^{15}\right]^{1/15}}\right\}} \qquad \text{(Eq. 5-10)}$$

Where	Nu_i	=	Nusselt number for natural convection from waste package to air, dimensionless
	Nu_o	=	Nusselt number for natural convection from concrete wall to air, dimensionless
	Ra_{Di}	=	Rayleigh number for inner cylinder (waste package), dimensionless
	Ra_{Do}	=	Rayleigh number for outer cylinder (concrete wall), dimensionless, and defined as (Incropera, F.P. and Dewitt, D.P. 1985, Equation 9.23):

$$Ra_{D_i} = \frac{g\beta\rho^2 c_p D_i^3}{\mu k}\Delta T \qquad \text{(Eq. 5-11)}$$

and

$$Ra_{D_o} = \frac{g\beta\rho^2 c_p D_o^3}{\mu k}\Delta T \qquad \text{(Eq. 5-12)}$$

Where	g	=	gravitational acceleration, m/s^2
	β	=	thermal coefficient of volumetric expansion, 1/K
	c_p	=	specific heat of air, J/kg·K
	D_i	=	diameter of inner cylinder (waste package), m
	D_o	=	diameter of outer cylinder (concrete wall), m
	ΔT	=	temperature difference between cylinder surface and air, K

As indicated in Equations 5-9 through 5-12, the Rayleigh number, and thus the Nusselt number is dependent on the temperature difference between the cylinder surface and the air. Because this temperature difference varies with time so does the Rayleigh number and the Nusselt number. For simplicity, the temperature difference is assumed to be constant over the segment length in evaluating the Nusselt numbers for pure natural convection. The average Nusselt number (Nu_{conv}) for the natural convection is estimated using the following expression (Gebhart et al. 1988, Equation 14.4.16):

$$Nu_{conv} = \left(\frac{1}{Nu_i} + \frac{1}{Nu_o}\right)^{-1} \qquad \text{(Eq. 5-13)}$$

Table 5-6 summarizes the results of calculation of the Nusselt numbers for pure natural convection. The values of air properties at a temperature of 310.5K, such as density, thermal conductivity, specific heat, dynamic viscosity, and Prandtl number, used to calculate the convection heat transfer coefficients are given in Table 5-5, Section 5.1.7.

The Nusselt number is used to compute convection heat transfer coefficient for natural convection using Equation 5-17, as discussed in the following section.

(b) Forced Convection

The following equations were employed in calculating the convection heat transfer coefficients for forced convection:

Table 5-6. Nusselt Numbers for Pure Natural Convection

Parameter	Pure Natural Convection	
Cylinder Identification	Waste Package	Concrete Pipe
Surface Temperature (°C)	50	50
Air Temperature (°C)	25	25
Diameter (m)	0.4064	1.3716
Rayleigh No.	1.35×10^8	5.20×10^9
Nusselt No.	63.13	267.95
Average Nusselt No.	51.09	

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

$$v = \frac{Q}{A} \tag{Eq. 5-14}$$

Where Q = ventilation air flow rate, m^3/s
A = cross-sectional area, m^2

Reynolds No., Re (Holman 1997, Basic Heat Transfer Relations, inside front cover):

$$Re = \frac{\rho v D_h}{\mu} \tag{Eq. 5-15}$$

Where ρ = density of air, kg/m^3
v = air flow velocity, m/s
D_h = hydraulic diameter of the cross section, m, defined as

$$D_h = \frac{4A}{P} = \frac{4\frac{\pi}{4}\left(D_c^2 - D_w^2\right)}{\pi\left(D_c + D_w\right)} = D_c - D_w$$

P = wetted perimeter, m
D_w = diameter of the waste package, m
D_c = inside diameter of the concrete pipe, m
μ = dynamic viscosity of air, kg/m·s

Nusselt No., Nu (Holman 1997, Equation 6-4a, p. 286; n=0.4 for heating, p. 286):

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad \text{(Eq. 5-16)}$$

Where Re = Reynolds number, dimensionless
Pr = Prandtl number, dimensionless

The expression (5-16) is for calculation of heat transfer in fully developed turbulent flow in smooth tubes, and is applicable for this calculation, as the surface roughness of the concrete and the waste package is negligible.

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

$$h = \frac{kNu}{D_h} \quad \text{(Eq. 5-17)}$$

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

Table 5-7 summarizes the results of calculation of the convection heat transfer coefficients for pure forced convection for the air flow rates of 0.5, 1, 2 and 3 m^3/s. The values of air properties at a temperature of 310.5K, such as density, thermal conductivity, specific heat, dynamic viscosity, and Prandtl number, used to calculate the convection heat transfer coefficients are given in Table 5-5, Section 5.1.7.

Table 5-7. Convection Heat Transfer Coefficients for Pure Forced Convection

Parameter	Pure Forced Convection			
Air Flow Rate (m^3/s)	0.5	1	2	3
Hydraulic Diameter (m)	0.8627	0.8627	0.8627	0.8627
Cross-sectional Area (m^2)	1.20	1.20	1.20	1.20
Air Flow Velocity (m/s)	0.42	0.83	1.66	2.49
Reynolds No.	2.31×10^4	4.63×10^4	9.26×10^4	13.88×10^4
Nusselt No.	62.16	108.22	188.43	260.62
Convection Heat Transfer Coefficient ($W/m^2 \cdot K$)	1.88	3.27	5.70	7.89

(c) Mixed Natural and Forced Convection

The effects of mixed natural and forced convection can be estimated using the following correlation developed by Morgan (Gebhart et al. 1988, Section 10.4.1) for the average heat transfer from horizontal cyliners in the various flow regimes and for various directions:

Aiding flow (Gebhart et al. 1988, Equation 10.4.7):

$$\frac{Nu_{mixed}}{Nu_f} = \left[1 + \frac{C_3(Gr)^m}{Re}\right]^n \quad \text{(Eq. 5-18)}$$

Opposing flow (Gebhart et al. 1988, Equation 10.4.8):

$$\frac{Nu_{mixed}}{Nu_f} = \left[1 - \frac{C_3(Gr)^m}{Re}\right]^n \quad \text{(Eq. 5-19)}$$

Cross flow (Gebhart et al. 1988, Equation 10.4.9):

$$\frac{Nu_{mixed}}{Nu_f} = \left[1 + \frac{C_3^2(Gr)^{2m}}{Re^2}\right]^{n/2} \quad \text{(Eq. 5-20)}$$

Where Nu_{mixed} = Nusselt number for mixed convection, dimensionless
Gr = Grashof number, dimensionless, and defined as (Incropera, F.P. and Dewitt, D.P. 1985, Equation 9.12)

$$Gr = \frac{g\beta\rho^2 D^3}{\mu^2}\Delta T$$

C_3, m, and n = empirical constants dependent on Gr and Re and various flow directions, dimensionless
Nu_f = Nusselt number for forced convection, dimensionless, and is given by (Gebhart et al. 1988, Equation 10.4.10)

$$Nu_f = C_4(Re)^n \quad \text{(Eq. 5-21)}$$

Where C_4 and n = dimensionless empirical constants, dependent on Re.

Table 5-8 summarizes the results of calculation of the convection heat transfer coefficients for mixed natural and forced convection within the test section. These values are calculated using Equations 5-17, 5-18 through 5-21 and the Nusselt numbers for pure natural convection given in Table 5-6 and forced convection given in Table 5-7. The empirical constants, C_3, C_4, m, and n, in Equations 5-18 and 5-21 are obtained from Tables 10.4.1 and 10.4.2 of *Buoyancy-Induced Flows and Transport* (Gebhart et al. 1988). The range of air flow rates of 0.5 m^3/s to 3 m^3/s was chosen as part of a sensitivity study for this calculation.

It is noted that the correlation developed by Morgan is based on the mixed natural and forced convection perpendicular to a cylinder (in cross-flow, not flow along the axis) in external flow (not within an annulus). It is not directly applicable to the geometry and flow orientation of the ventilation tests. Nevertheless, the methodology of estimating the Reynolds number for natural convection and then the effective Reynolds number for mixed convection is applicable. The values of the convection heat transfer coefficients listed in Table 5-8 for mixed natural and forced convection are used as part of a sensitivity study for this calculation.

Table 5-8. Convection Heat Transfer Coefficients for Mixed Natural and Forced Convection Based on Morgan's Correlation (Gebhart et al. 1988)

Parameter	Mixed Natural and Forced Convection							
Air Flow Rate (m^3/s)	0.5		1		2		3	
Constant C_3	0.635							
Constant C_4	0.148							
Constant m	0.526							
Constant n	0.633							
Cylinder Identification	Waste Package	Concrete Pipe	Waste Package	Concrete Pipe	Waste Package	Concrete Pipe	Waste Package	Concrete Pipe
Nusselt No. for Pure Forced Convection	50.98	110.11	78.86	170.31	122.29	264.11	158.07	341.40
Nusselt No. for Mixed Natural and Forced Convection	89.13	258.99	110.80	299.31	148.27	372.09	180.87	437.37
Convection Heat Transfer Coefficient ($W/m^2 \cdot K$)	5.93	5.11	7.37	5.90	9.86	7.33	12.03	8.62

To properly evaluate the effects of mixed natural and forced convection for the geometry and flow orientation of the ventilation tests, a modified approach is used based on Equations 5-9 and 5-10 for natural convection and Equation 5-16 for forced convection, and is presented below.

Using Equation 5-16, Reynolds number for either natural or forced convection can be estimated as

$$Re = \left(\frac{Nu}{0.023 Pr^{0.4}} \right)^{1.25} \quad \text{(Eq. 5-22)}$$

or

$$Re_{NC} = \left(\frac{Nu_{NC}}{0.023 Pr^{0.4}} \right)^{1.25} \quad \text{(Eq. 5-22)}$$

and

$$Re_{FC} = \left(\frac{\bar{N}u_{FC}}{0.023 Pr^{0.4}} \right)^{1.25} \quad \text{(Eq. 5-23)}.$$

Where Re_{NC} = Reynolds number for natural convection, dimensionless
Re_{FC} = Reynolds number for forced convection, dimensionless
Nu_{NC} = Nusselt number for natural convection, dimensionless
Nu_{FC} = Nusselt number for forced convection, dimensionless

The effective Reynolds Re_{eff} number for mixed natural and forced convection can be estimated as

$$Re_{eff}^2 = Re_{NC}^2 + Re_{FC}^2 \qquad \text{(Eq. 5-24)}$$

For a flow within an annulus, the effective Nusselt number Nu_{eff} for mixed natural and forced convection can be estimated as

$$\frac{Nu_{mixed}}{Nu_{FC}} = \left(\frac{Re_{eff}^2}{Re_{FC}^2}\right)^{0.4} \qquad \text{(Eq. 5-25)}$$

Substituting Equation 5-24 into Equation 5-25 yields

$$\frac{Nu_{mixed}}{Nu_{FC}} = \left(1 + \frac{Re_{NC}^2}{Re_{FC}^2}\right)^{0.4} \qquad \text{(Eq. 5-26)}$$

Equation 5-26 can be used to evaluate the Nusselt number for mixed natural and forced convection in the flow of the ventilation tests. Once the Nusselt number is determined, the corresponding convection heat transfer coefficients can be evaluated using the following expressions

$$h_w = \frac{kNu_w}{D_w} \qquad \text{(Eq. 5-27)}$$

and

$$h_c = \frac{kNu_c}{D_c} \qquad \text{(Eq. 5-28)}$$

Where h_w = convection heat transfer coefficient for waste package, $W/m^2 \cdot K$
h_c = convection heat transfer coefficient for concrete pipe, $W/m^2 \cdot K$
Nu_w = Nusselt Number for waste package, dimensionless
Nu_c = Nusselt Number for concrete pipe, dimensionless
D_w = diameter of waste package, m
D_c = inside diameter of concrete pipe, m
k = thermal conductivity of air, W/m·K.

Table 5-9 summarizes the results of calculation of the convection heat transfer coefficients for mixed natural and forced convection within the test section. These values are calculated using

Equations 5-22 through 5-28, and the Nusselt numbers for pure natural convection given in Table 5-6 and those for pure forced convection given in Table 5-7.

Table 5-9. Convection Heat Transfer Coefficients for Mixed Convection Using Modified Approach Based on Morgan and Kuehn and Goldstein

Parameter	Mixed Convection			
Air Flow Rate (m^3/s)	1		2	
Cylinder Identification	Waste Package	Concrete Pipe	Waste Package	Concrete Pipe
Nusselt No. for Pure Natural Convection	63.13	267.95	63.13	267.95
Nusselt No. for Pure Forced Convection	108.22	108.22	188.43	188.43
Reynolds No. for Pure Natural Convection	2.36×10^4	1.44×10^5	2.36×10^4	1.44×10^5
Reynolds No. For Pure Forced Convection	4.31×10^4	4.31×10^4	8.62×10^4	8.62×10^4
Nusselt No. for Mixed Natural and Forced Convection	120.19	293.98	193.96	321.10
Convection Heat Transfer Coefficient ($W/m^2 \cdot K$)	7.99	5.79	12.89	6.32

5.3.3.2.2 Convection Heat Transfer Coefficient for Outside the Insulation

Only natural convection is considered outside the insulation. The Nusselt number for natural convection outside the insulation is evaluated using the expression developed by Churchill and Chu for horizontal cylinders as (Holman 1997, Equation 7-36):

$$Nu^{1/2} = 0.60 + 0.387\left\{\frac{GrPr}{\left[1+(0.559/Pr)^{9/16}\right]^{16/9}}\right\}^{1/6} \quad \text{(Eq. 5-29)}$$

Where $GrPr$ = Rayleigh number for natural convection, dimensionless

By using the insulation surface and air temperatures of 40°C and 25°C, respectively, the convection heat transfer coefficient for natural convection is calculated to be 3.28 $W/m^2 \cdot K$. It is noted that the insulation surface temperature is unknown and calculated from ANSYS runs. To have a better evaluation of this convection heat coefficient, iterations and results from the measurements are desirable.

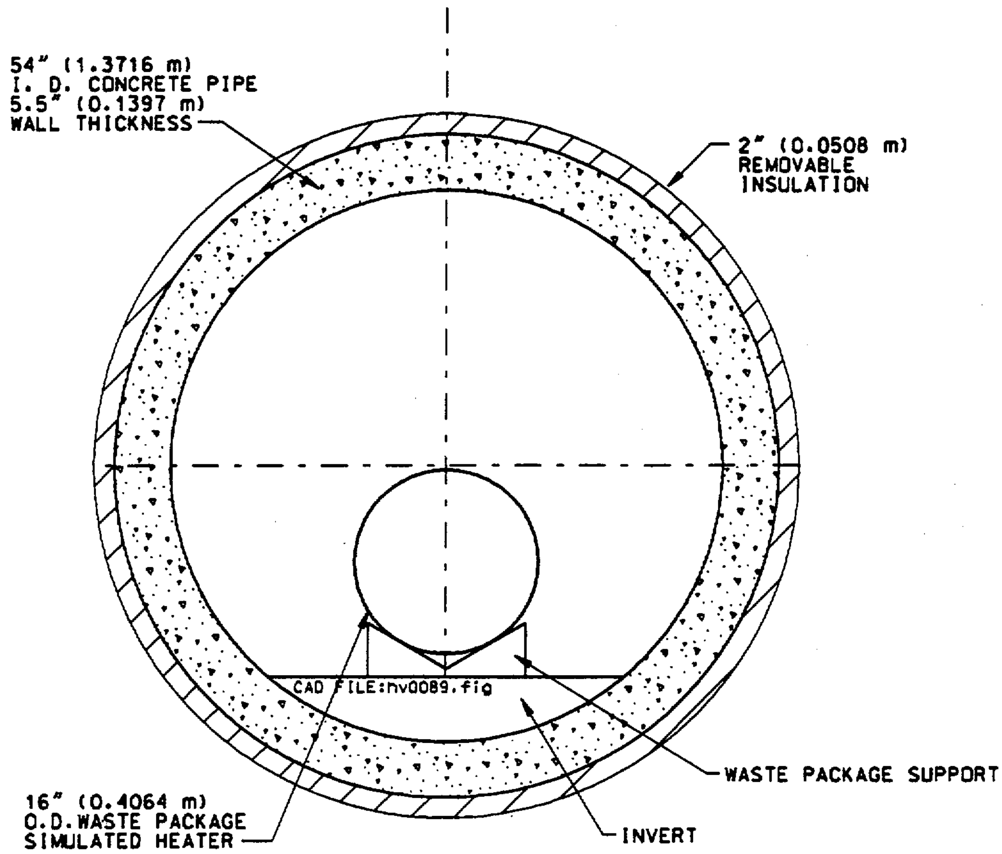


Figure 5-1. Configuration of ANSYS Model for Ventilation Test

6. RESULTS

This section summarizes the results of the calculation using the ANSYS Version 5.2 code (DTN: MO0101MWDPPV13.006).

6.1 TEMPERATURES WITHOUT VENTILATION

Temperatures were calculated for a case when no air flow was considered. Natural convection was applied to both inside the test section and outside the insulation. As stated, the convection heat transfer coefficients for natural convection are sensitive to the temperature difference between the cylinder surface and the air. Therefore, the predicted temperatures are dependent on the assumed temperatures when estimating the Nusselt numbers and convection heat transfer coefficients. Figure 6-1 shows the predicted temperatures of the waste package surface, the concrete pipe inside wall, concrete outside wall, and insulation surface based on the convection heat transfer coefficients determined in Sections 5.3.3.2.1 and 5.3.3.2.2.

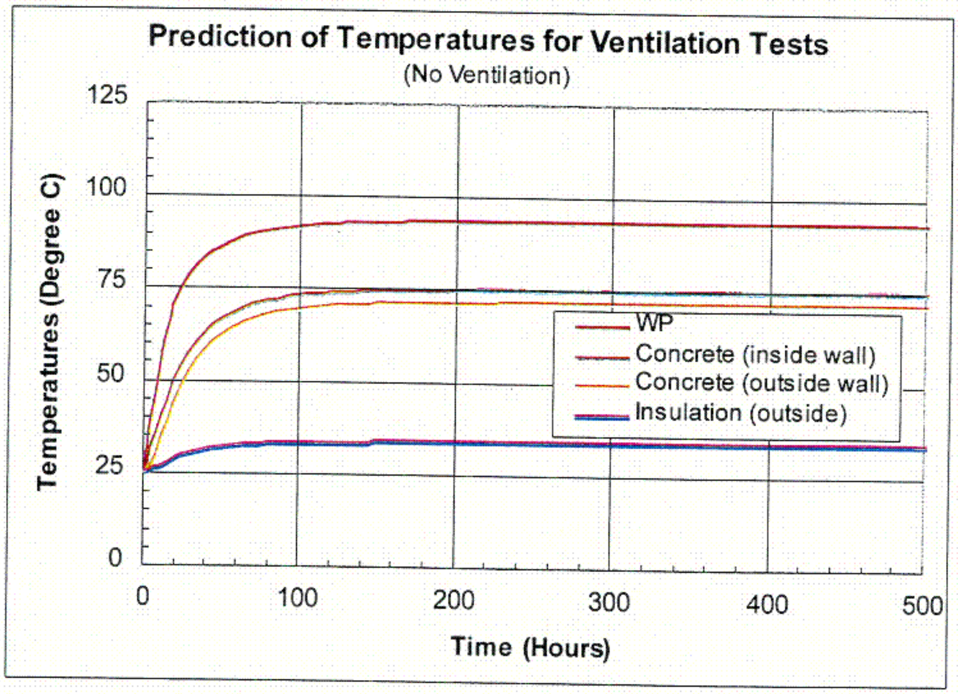


Figure 6-1. Predicted Temperatures at Zero Air Flow

6.2 TEMPERATURES WITH VENTILATION

Temperatures were calculated for the air flow rates of 0.5, 1, 2, and 3 m^3/s. Mixed natural and forced convection was considered to account for the ventilation effects inside the test section, whereas only natural convection was considered outside the insulation. The test section was divided into four segments, except for one case where the test section was divided into eight segments as part of a sensitivity study. The exhaust air temperatures of each segment were

C01

calculated using the approach discussed in Section 5.3.3.1. Table 6-1 lists all the cases considered along with a brief case description.

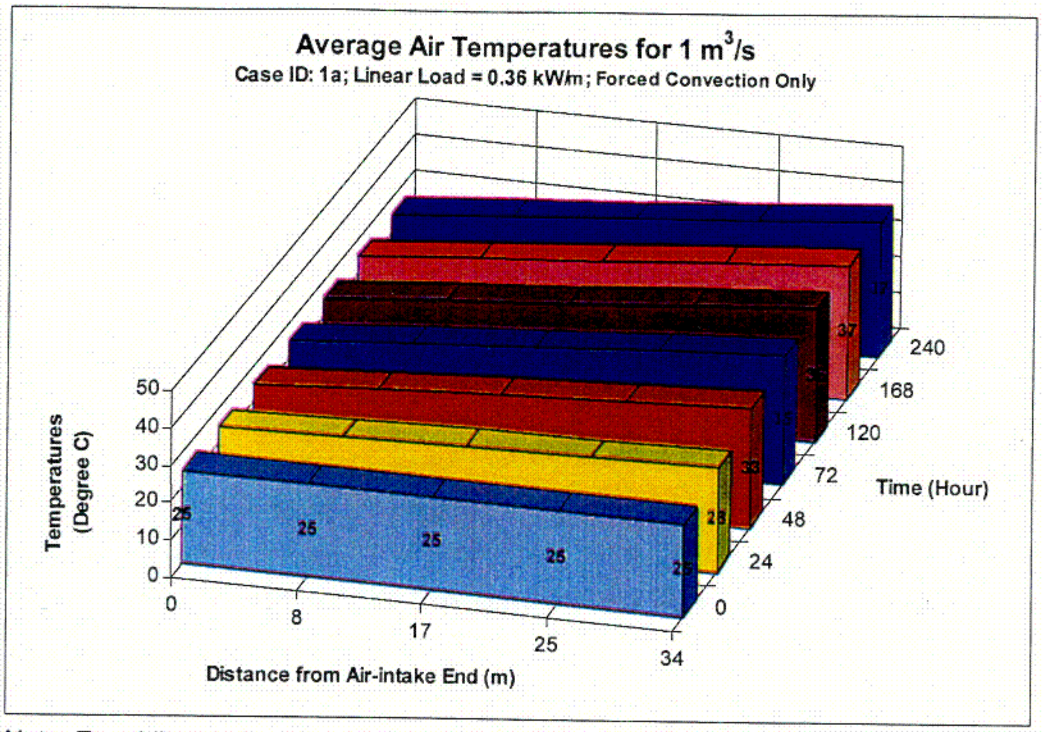
The predicted temperatures of the air, concrete inside wall, and waste package surface for all these cases are presented in Figures 6-2 through 6-99. The predicted peak temperatures for the cases considered are summarized in Table 6-2.

Table 6-1. Description of Cases Considered in Sensitivity Study

Case Identification	Case Description
1a	Forced convection only within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on both waste package and concrete pipe = 3.27 $W/m^2 \cdot K$.
1b	Forced convection only within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 8, convection heat transfer coefficient on both waste package and concrete pipe = 3.27 $W/m^2 \cdot K$.
2aa	Mixed convection (using Morgan's approach) within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 7.37 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 5.90 $W/m^2 \cdot K$.
2ab	Mixed convection (using Morgan's approach) within test section: flow rate = 2 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 9.86 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 7.33 $W/m^2 \cdot K$.
2ac	Mixed convection (using Morgan's approach) within test section: flow rate = 1 m^3/s, heat output = 0.18 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 7.37 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 5.90 $W/m^2 \cdot K$.
2ad	Mixed convection (using Morgan's approach) within test section: flow rate = 2 m^3/s, heat output = 0.18 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 9.86 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 7.33 $W/m^2 \cdot K$.
2ba	Mixed convection (using modified approach based on Morgan and Kuehn and Goldstein) within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 7.99 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 5.79 $W/m^2 \cdot K$.
2bb	Mixed convection (using modified approach based on Morgan and Kuehn and Goldstein) within test section: flow rate = 2 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 12.89 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 6.32 $W/m^2 \cdot K$.
3a	Forced convection only within test section: flow rate = 0.5 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on both waste package and concrete pipe = 1.88 $W/m^2 \cdot K$.
3aa	Mixed convection (using Morgan's approach) within test section: flow rate = 0.5 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 5.93 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 5.11 $W/m^2 \cdot K$.
4a	Forced convection only within test section: flow rate = 0.5 m^3/s, heat output = 0.18 kW/m, number of segments used = 4, convection heat transfer coefficient on both waste package and concrete pipe = 1.88 $W/m^2 \cdot K$.
4aa	Mixed convection (using Morgan's approach) within test section: flow rate = 0.5 m^3/s, heat output = 0.18 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 5.93 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 5.11 $W/m^2 \cdot K$.
5a	Forced convection only within test section: flow rate = 3.0 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on both waste package and concrete pipe = 7.89 $W/m^2 \cdot K$.
5aa	Mixed convection (using Morgan's approach) within test section: flow rate = 3.0 m^3/s, heat output = 0.36 kW/m, number of segments used = 4, convection heat transfer coefficient on waste package = 12.03 $W/m^2 \cdot K$, convection heat transfer coefficient on concrete pipe = 8.62 $W/m^2 \cdot K$.

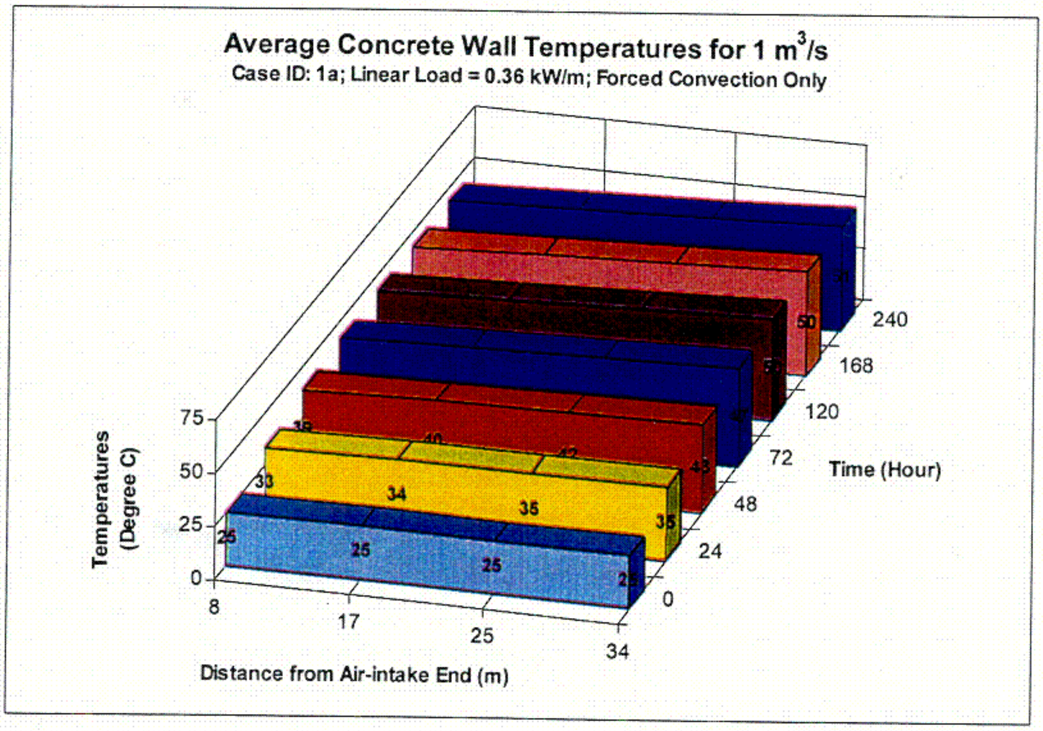
Table 6-2. Summary of Predicted Peak Temperatures

Case Identification and Description	Ventilating Air (°C)	WP Surface (°C)	Concrete Pipe Wall (°C)	Insulation Surface (°C)
1a - Forced convection only within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	36.8	75.8	51.6	29.7
1b - Forced convection only within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 8.	36.8	77.0	52.8	29.9
2aa - Mixed convection (using Morgan's approach) within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	36.7	58.2	40.4	27.7
2ab - Mixed convection (using Morgan's approach) within test section: flow rate = 2 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	30.9	49.2	34.0	26.6
2ac - Mixed convection (using Morgan's approach) within test section: flow rate = 1 m^3/s, heat output = 0.18 kW/m, number of segments used = 4.	30.8	41.8	32.5	26.3
2ad - Mixed convection (using Morgan's approach) within test section: flow rate = 2 m^3/s, heat output = 0.18 kW/m, number of segments used = 4.	27.9	37.2	29.4	25.8
2ba - Mixed convection (using modified approach based on Morgan and Kuehn and Goldstein) within test section: flow rate = 1 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	36.6	56.8	40.0	27.6
2bb - Mixed convection (using modified approach based on Morgan and Kuehn and Goldstein) within test section: flow rate = 2 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	30.8	45.5	33.3	26.5
3a - Forced convection only within test section: flow rate = 0.5 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	47.2	98.4	73.6	33.5
3aa - Mixed convection (using Morgan's approach) within test section: flow rate = 0.5 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	48.0	70.1	50.6	29.5
4a - Forced convection only within test section: flow rate = 0.5 m^3/s, heat output = 0.18 kW/m, number of segments used = 4.	36.0	63.5	48.3	46.7
4aa - Mixed convection (using Morgan's approach) within test section: flow rate = 0.5 m^3/s, heat output = 0.18 kW/m, number of segments used = 4.	36.4	47.9	37.4	36.5
5a - Forced convection only within test section: flow rate = 3.0 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	29.0	51.3	33.3	26.5
5aa - Mixed convection (using Morgan's approach) within test section: flow rate = 3.0 m^3/s, heat output = 0.36 kW/m, number of segments used = 4.	28.9	44.9	31.4	26.1



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

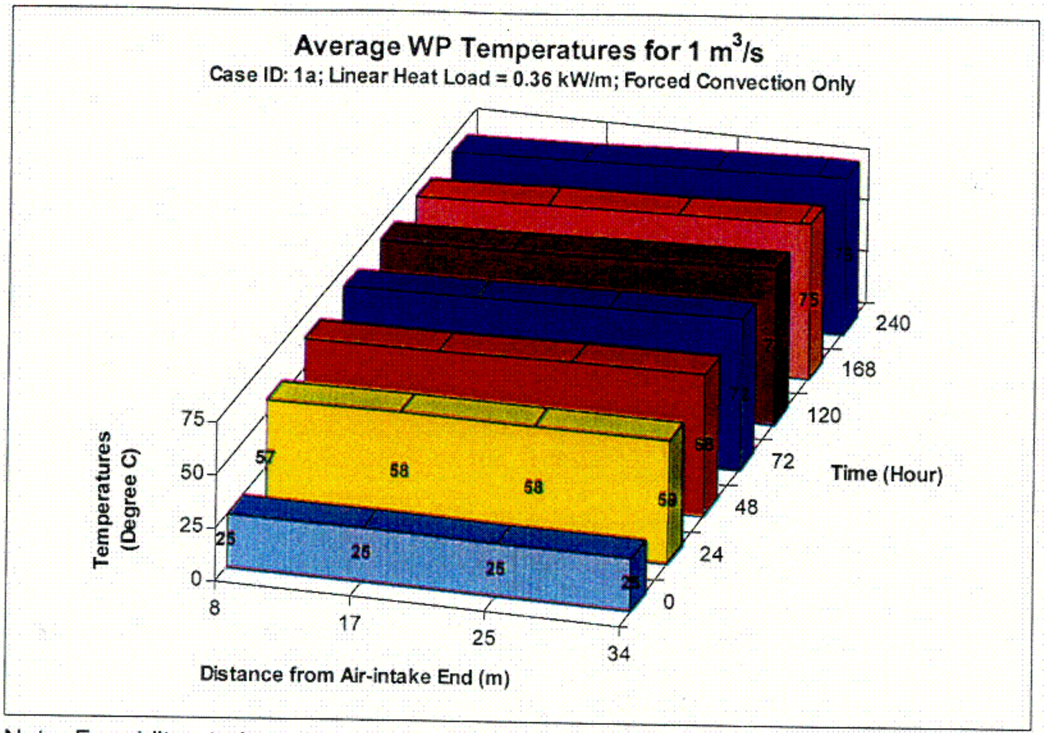
Figure 6-2. Predicted Air Temperatures for Case 1a



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

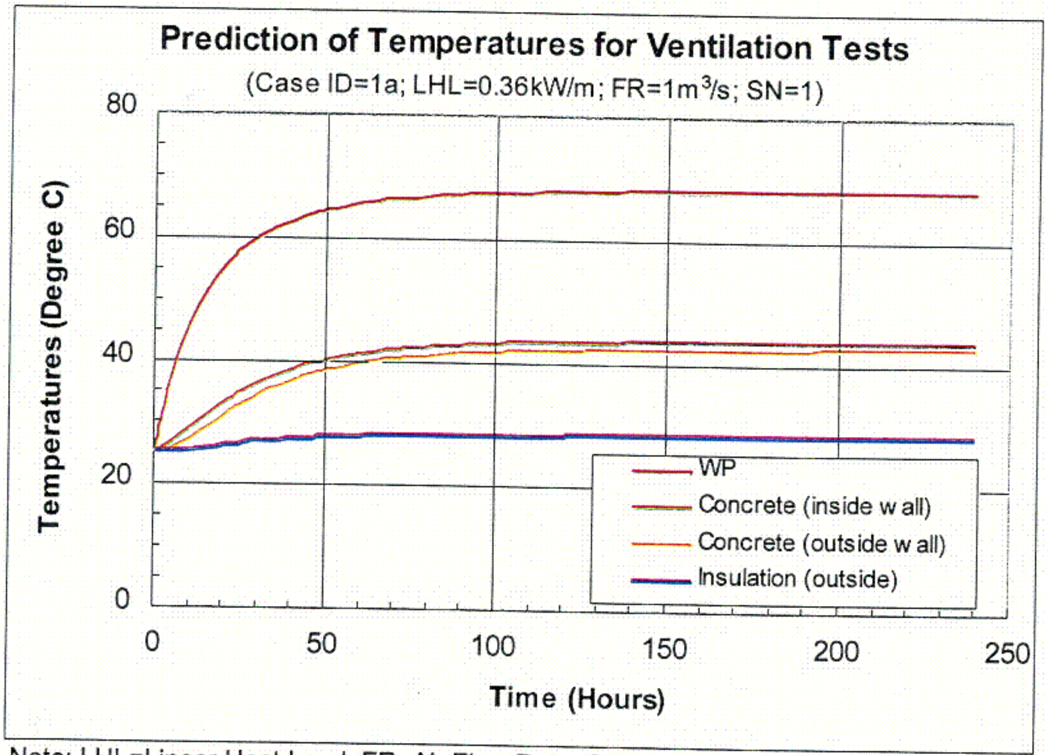
Figure 6-3. Predicted Concrete Inside Wall Temperatures for Case 1a

C02



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

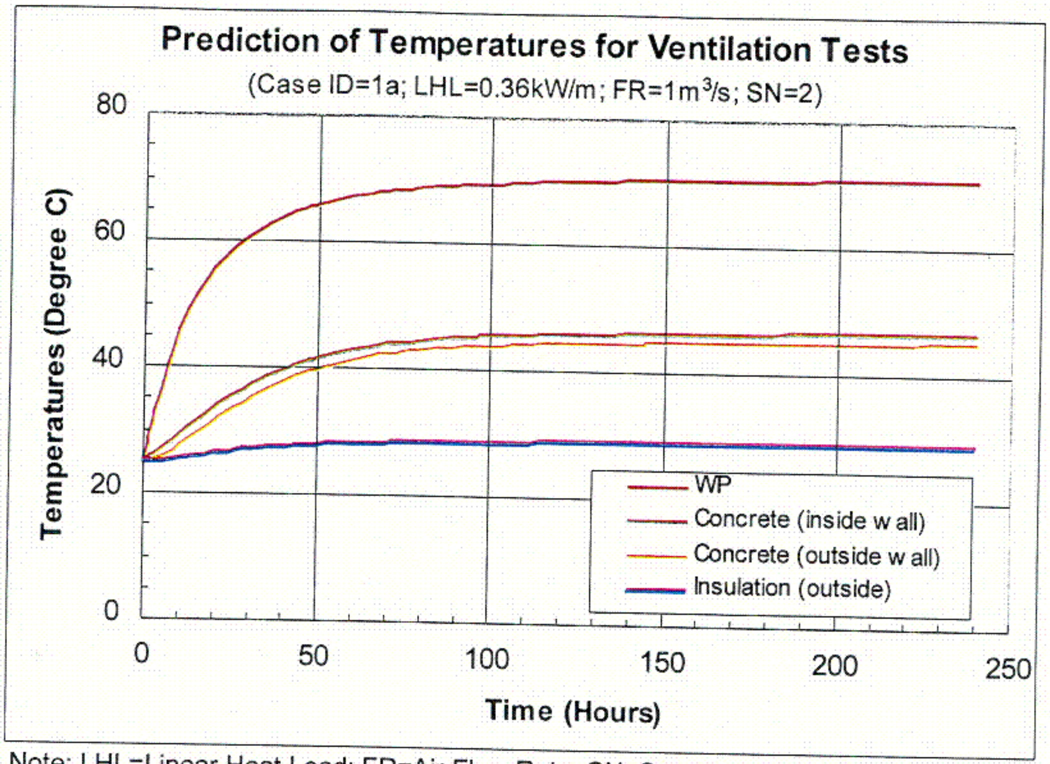
Figure 6-4. Predicted Waste Package Surface Temperatures for Case 1a



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

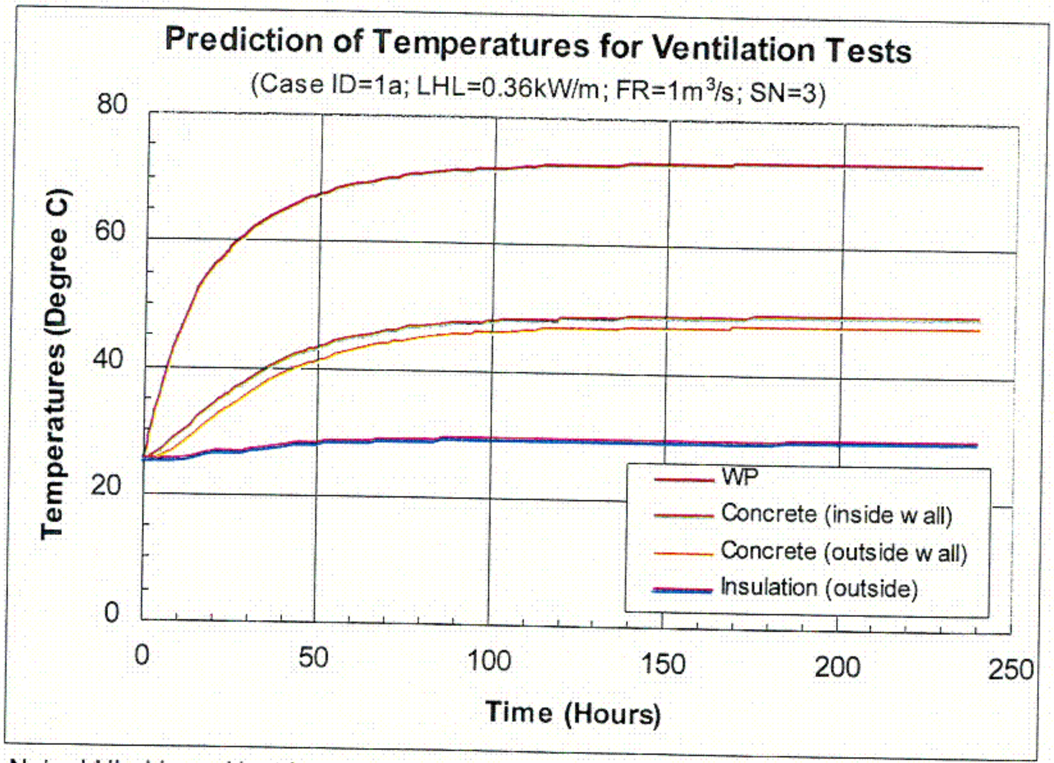
Figure 6-5. Predicted Average Temperatures in Segment No. 1 for Case 1a

C03



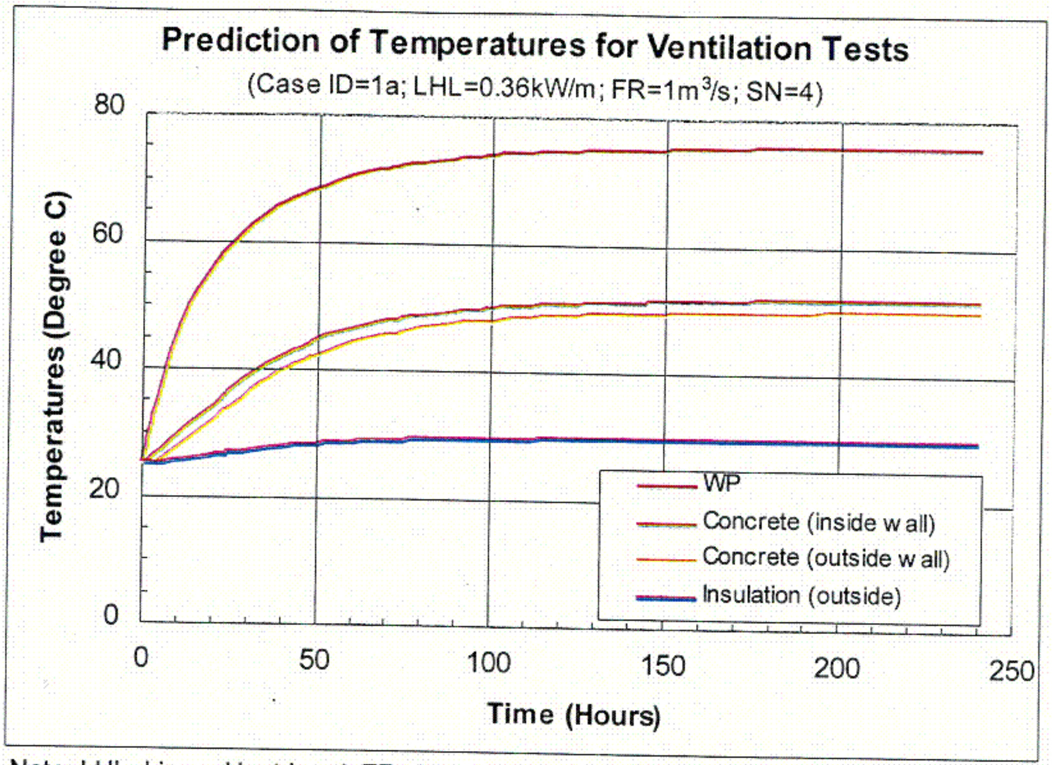
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-6. Predicted Average Temperatures in Segment No. 2 for Case 1a



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

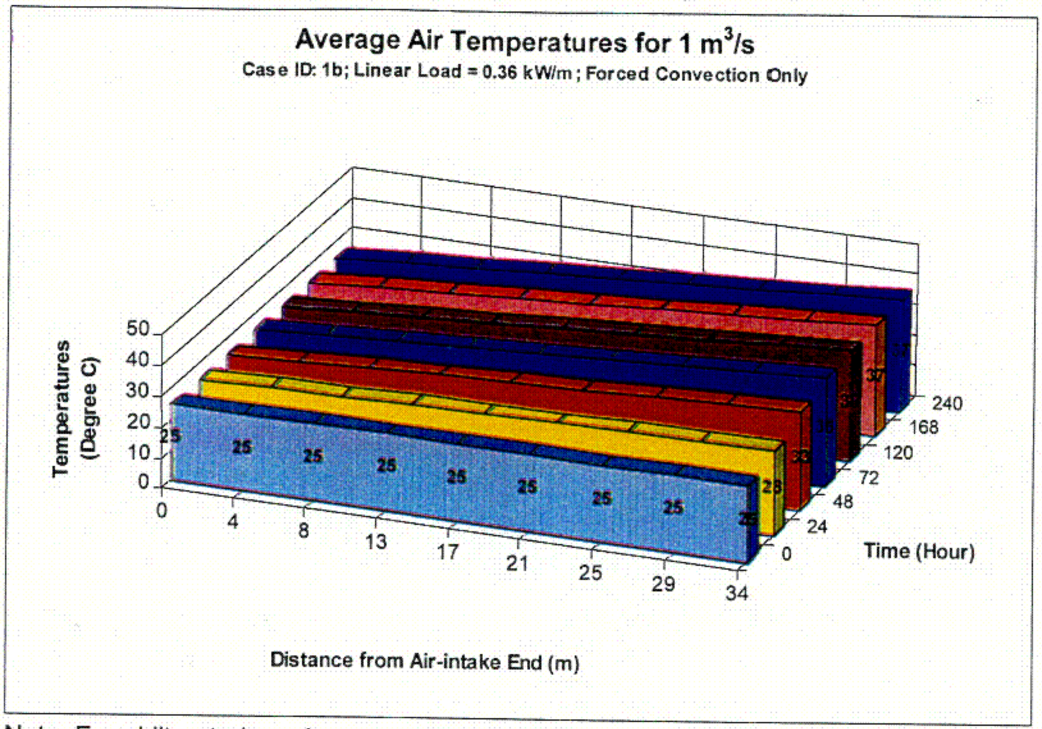
Figure 6-7. Predicted Average Temperatures in Segment No. 3 for Case 1a



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

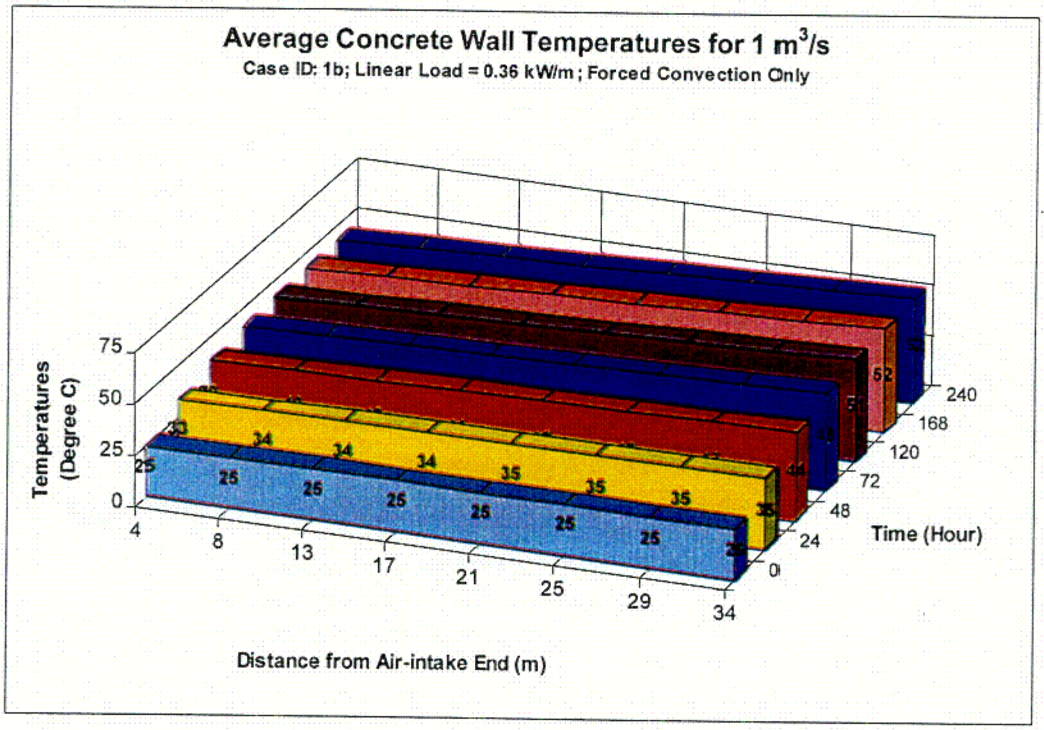
Figure 6-8. Predicted Average Temperatures in Segment No. 4 for Case 1a

C05



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

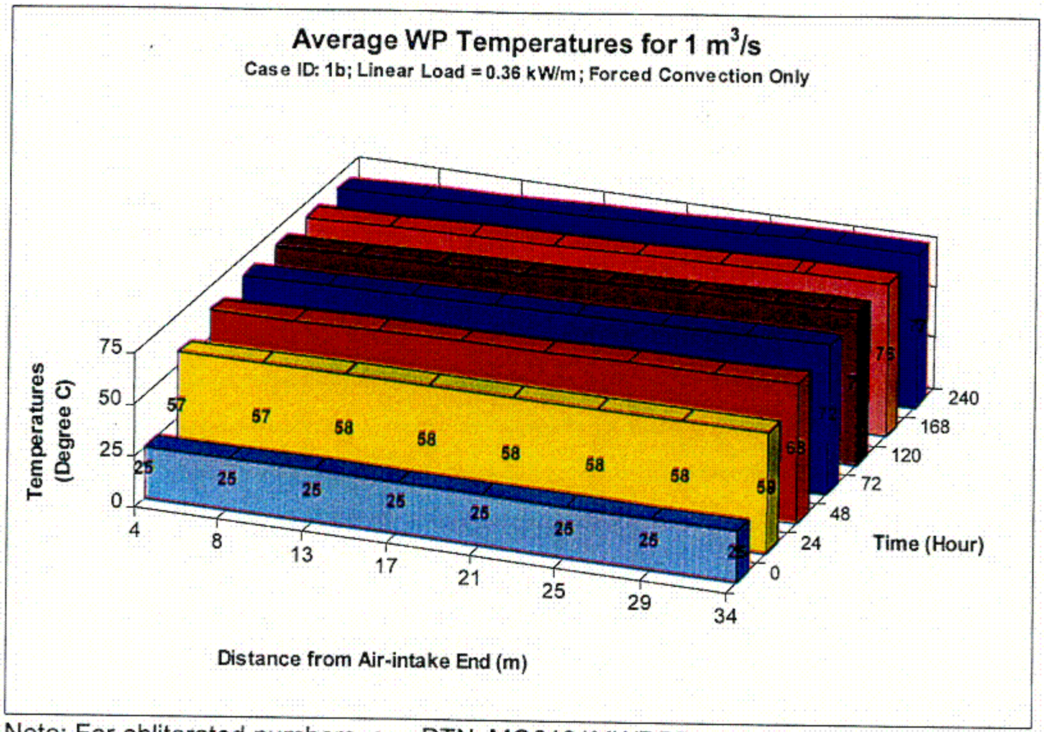
Figure 6-9. Predicted Air Temperatures for Case 1b



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

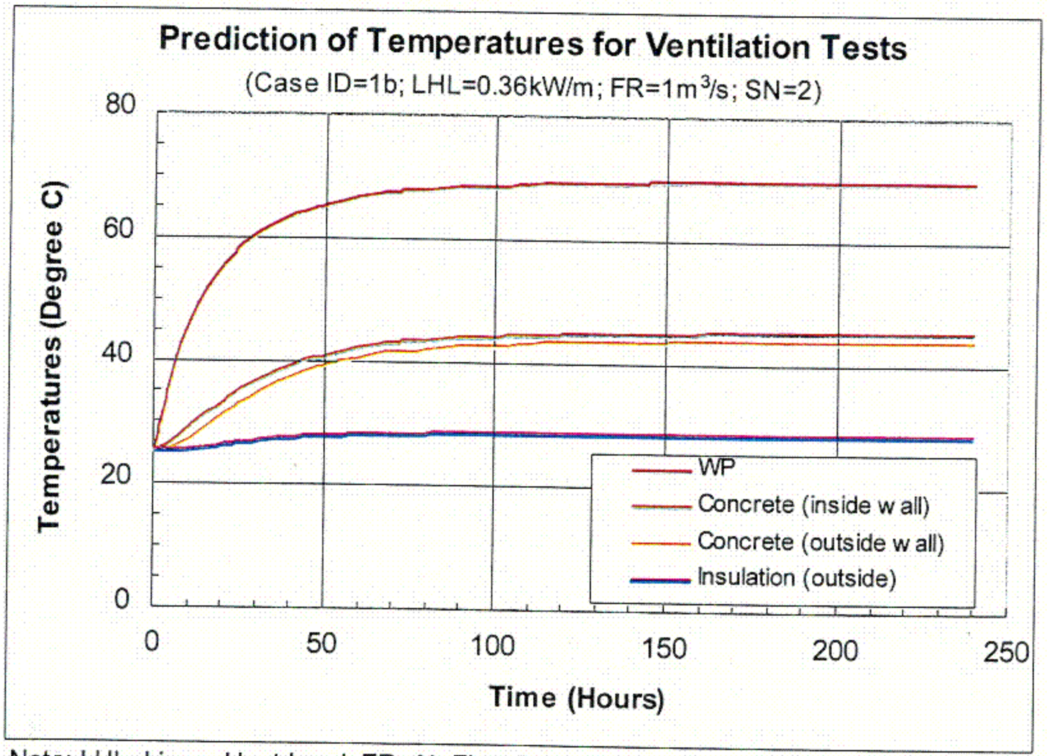
Figure 6-10. Predicted Concrete Inside Wall Temperatures for Case 1b

C06



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

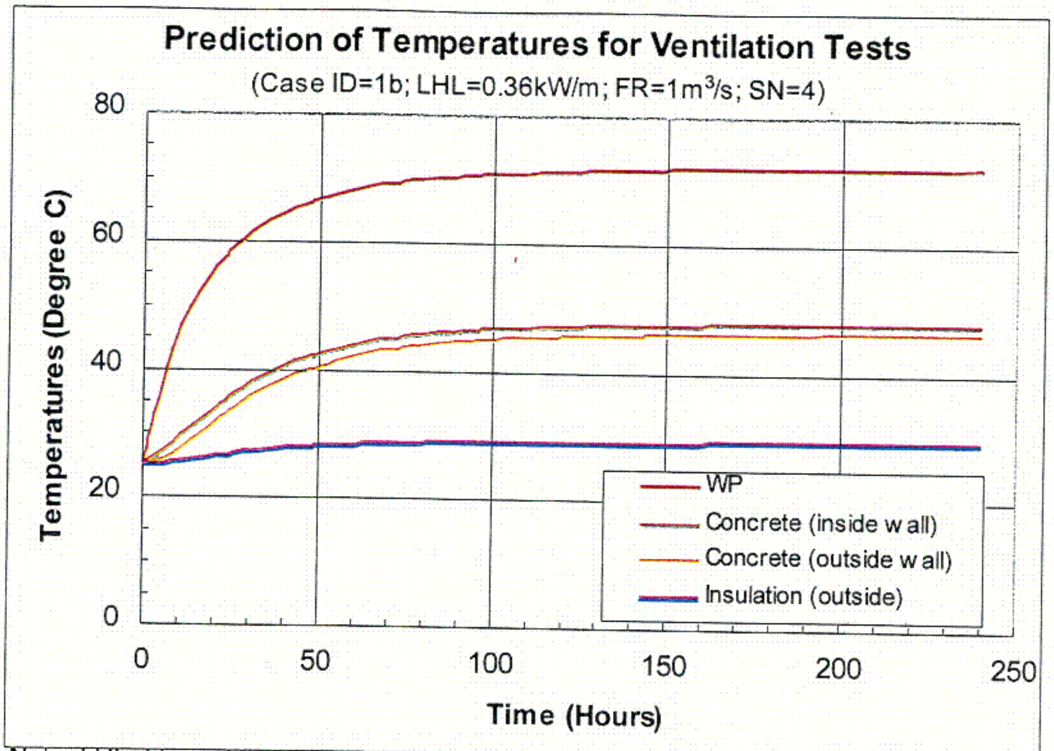
Figure 6-11. Predicted Waste Package Surface Temperatures for Case 1b



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

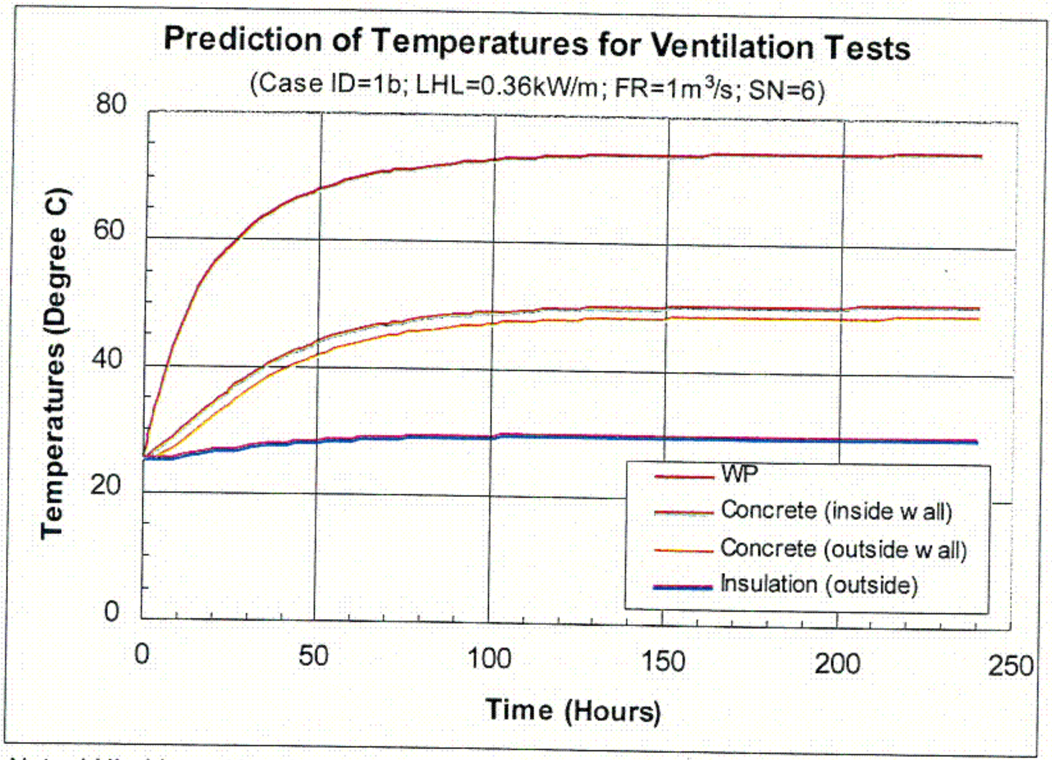
Figure 6-12. Predicted Average Temperatures in Segment No. 2 for Case 1b

C07



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

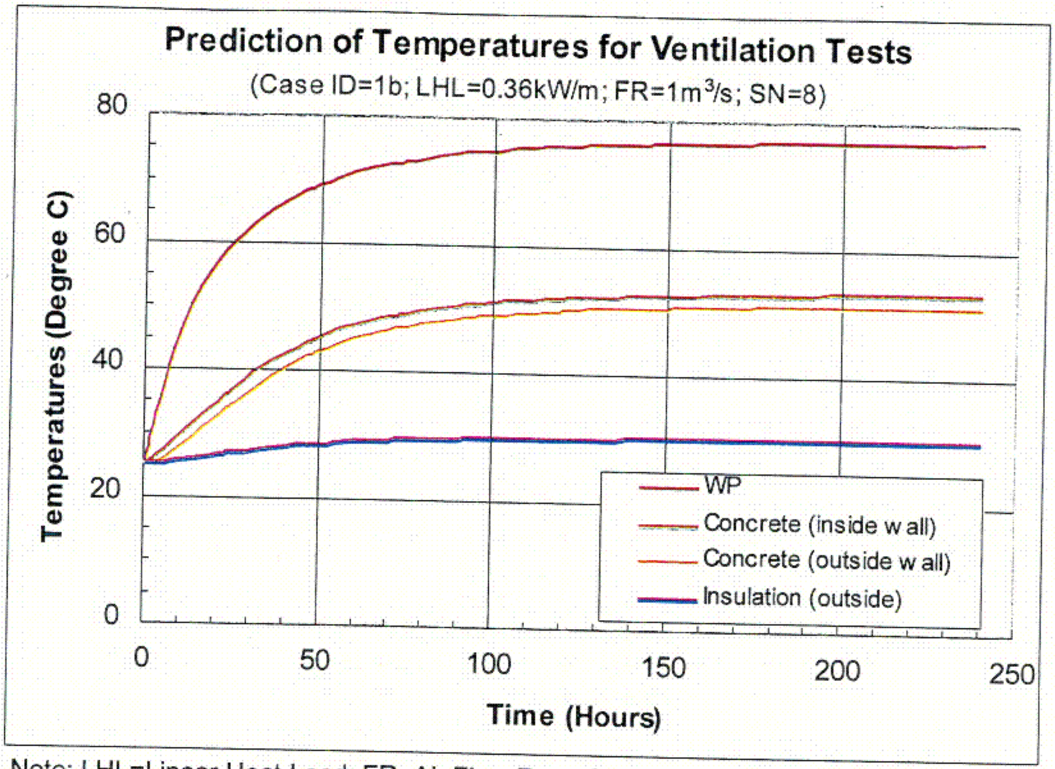
Figure 6-13. Predicted Average Temperatures in Segment No. 4 for Case 1b



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

Figure 6-14. Predicted Average Temperatures in Segment No. 6 for Case 1b

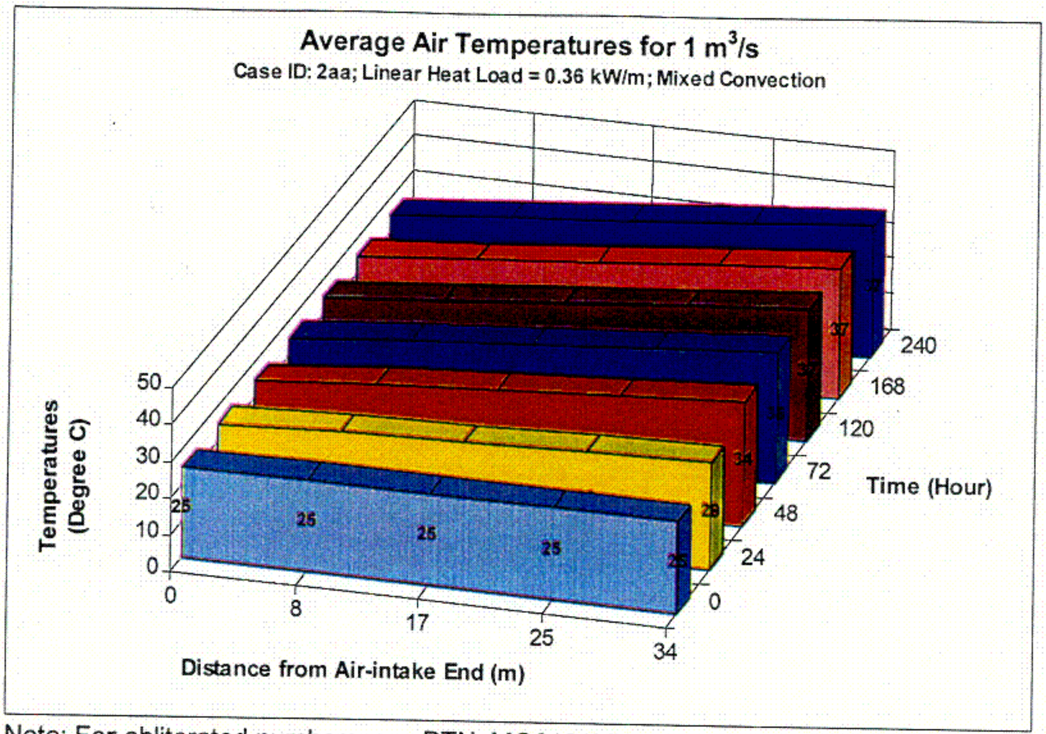
C08



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

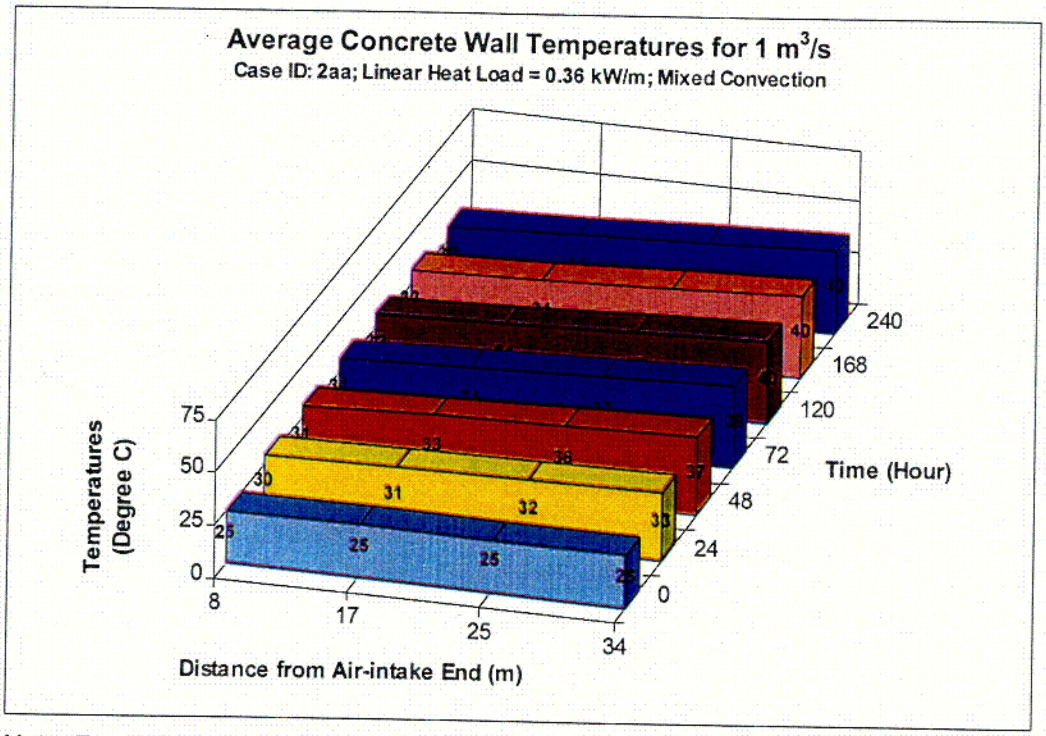
Figure 6-15. Predicted Average Temperatures in Segment No. 8 for Case 1b

C09



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

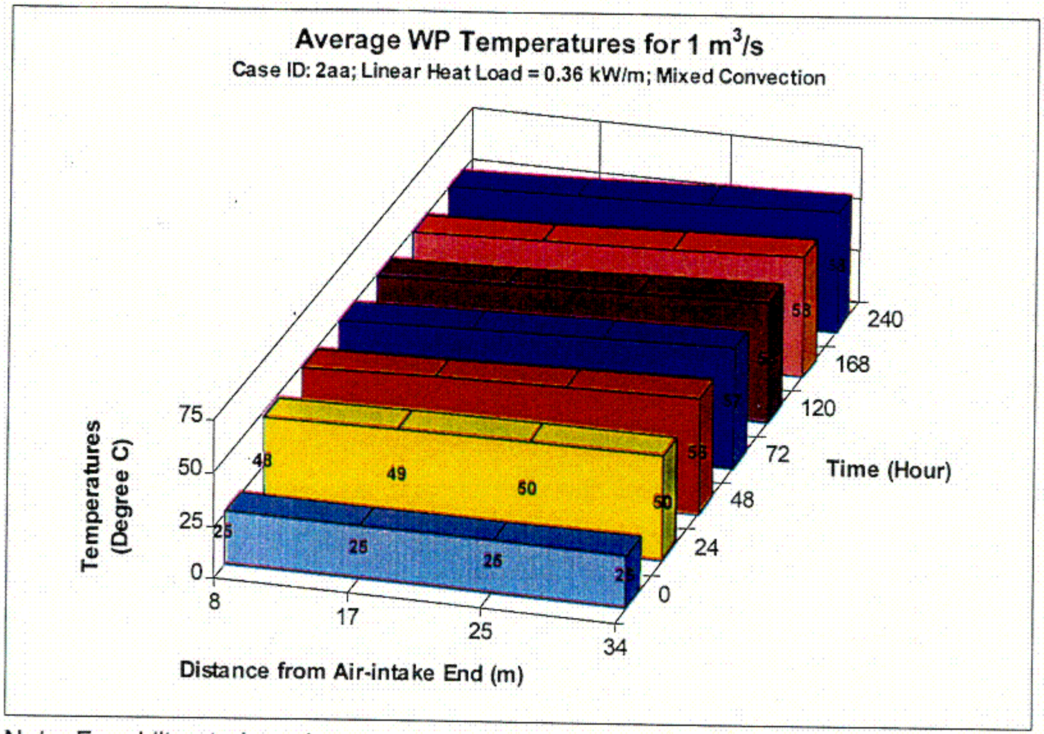
Figure 6-16. Predicted Air Temperatures for Case 2aa



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

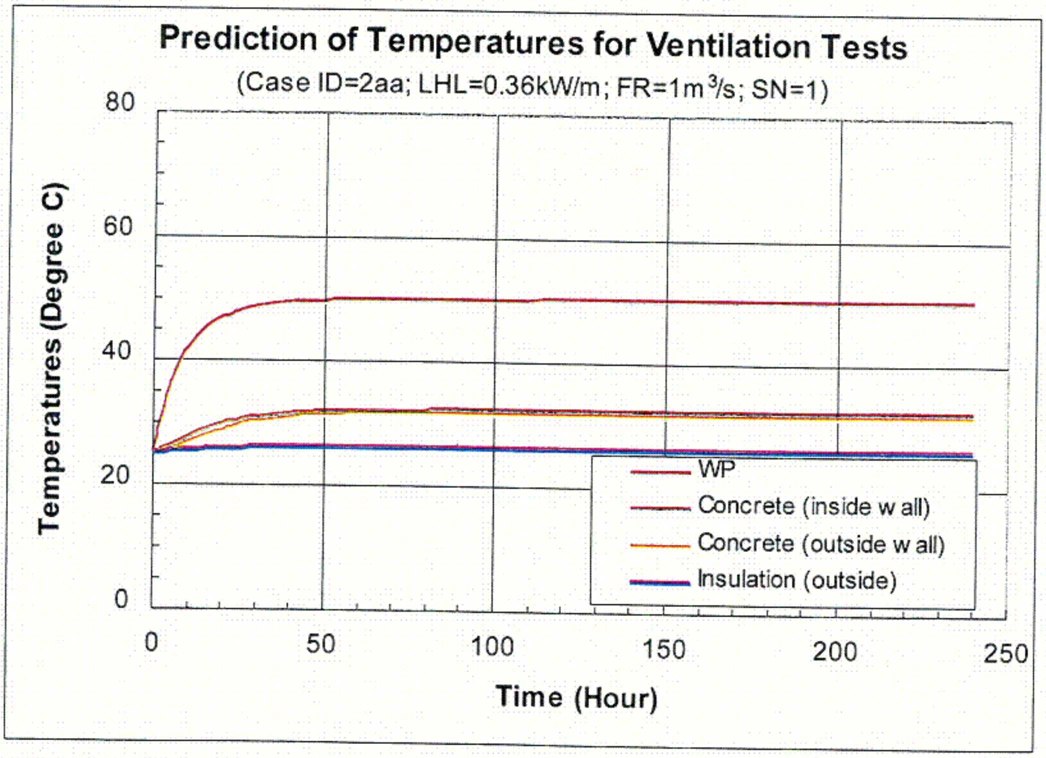
Figure 6-17. Predicted Concrete Inside Wall Temperatures for Case 2aa

C10



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

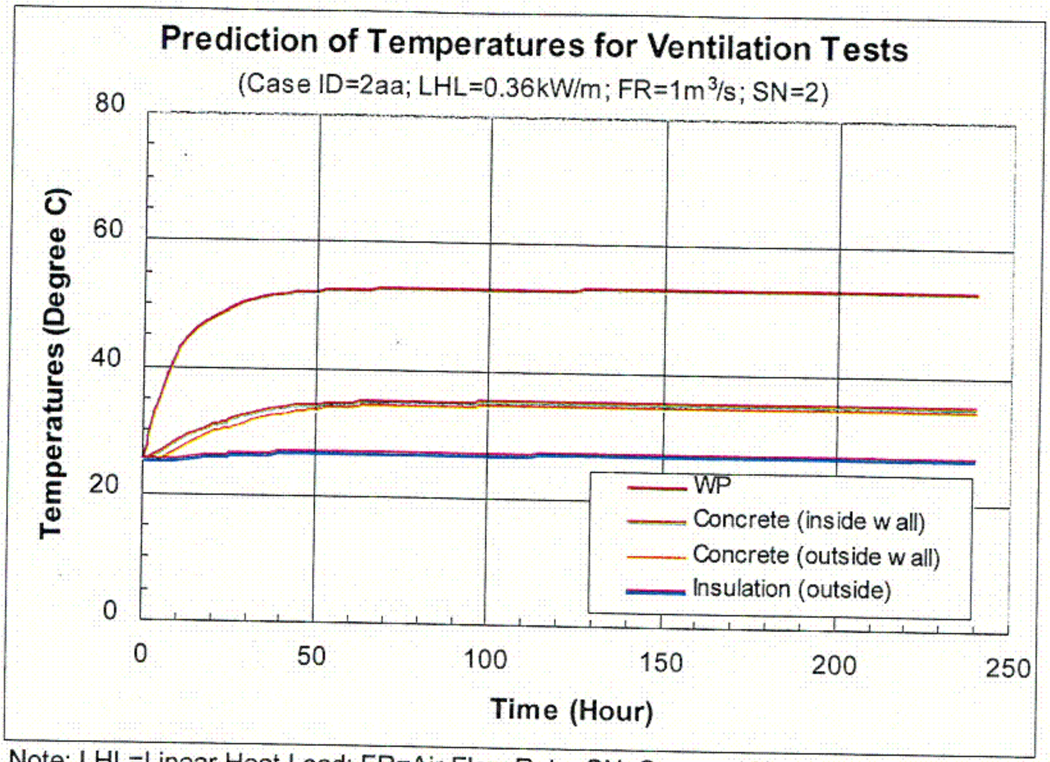
Figure 6-18. Predicted Waste Package Surface Temperatures for Case 2aa



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

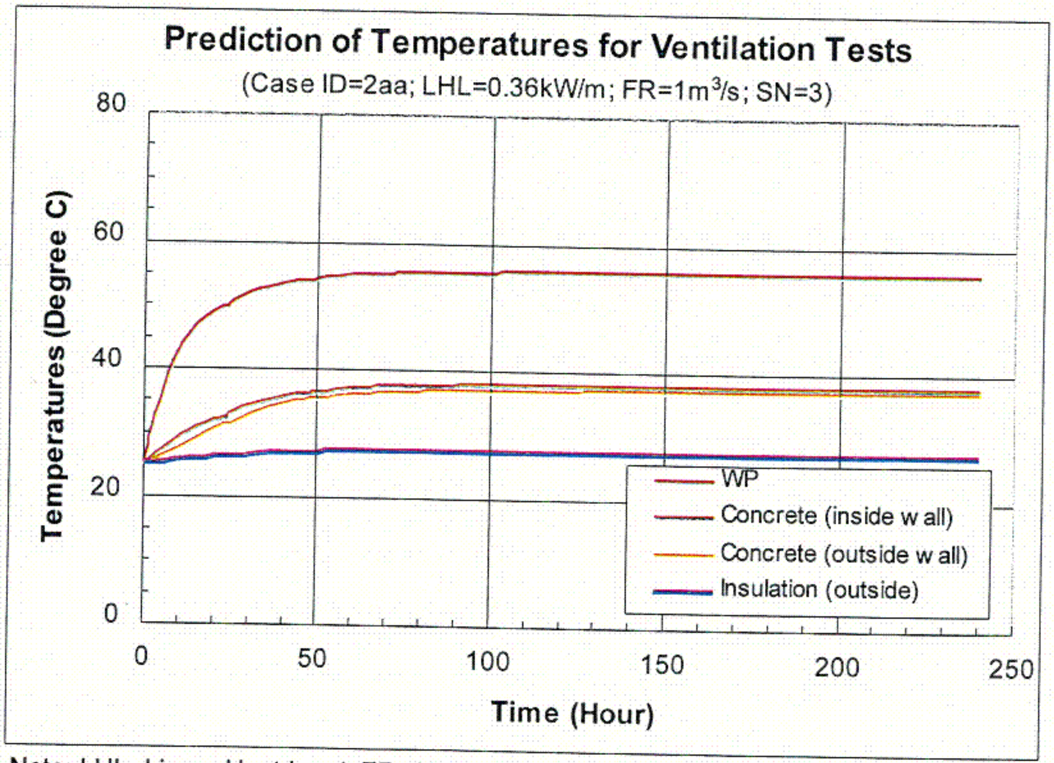
Figure 6-19. Predicted Average Temperatures in Segment No. 1 for Case 2aa

C11



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

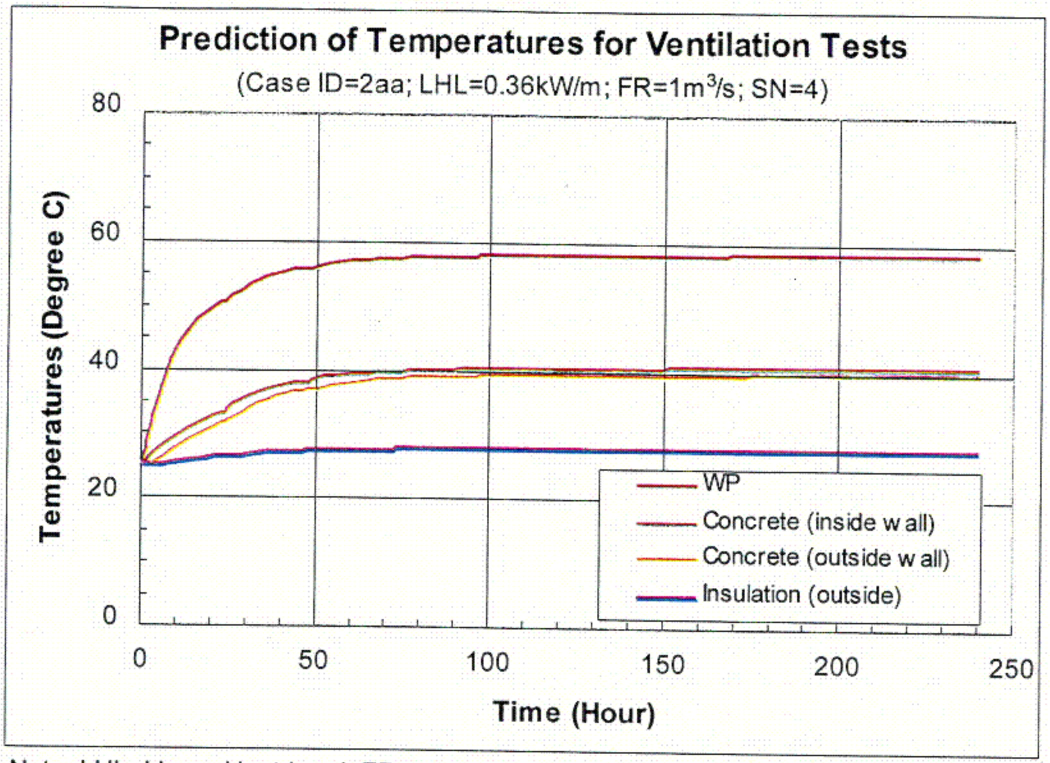
Figure 6-20. Predicted Average Temperatures in Segment No. 2 for Case 2aa



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

Figure 6-21. Predicted Average Temperatures in Segment No. 3 for Case 2aa

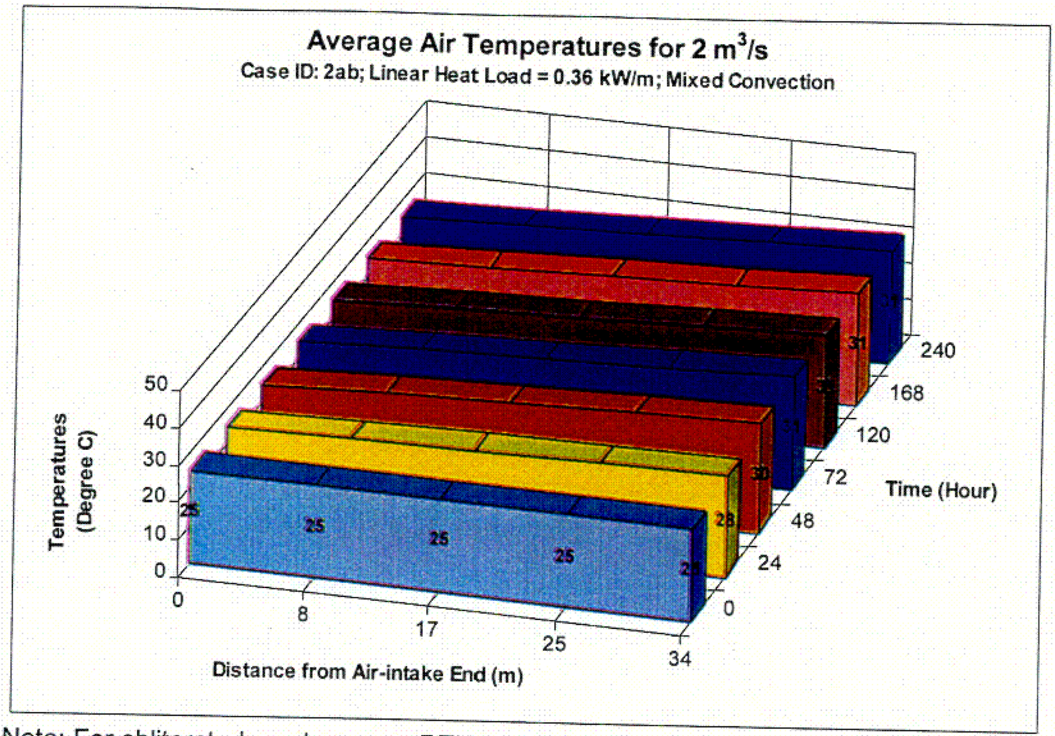
C12



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

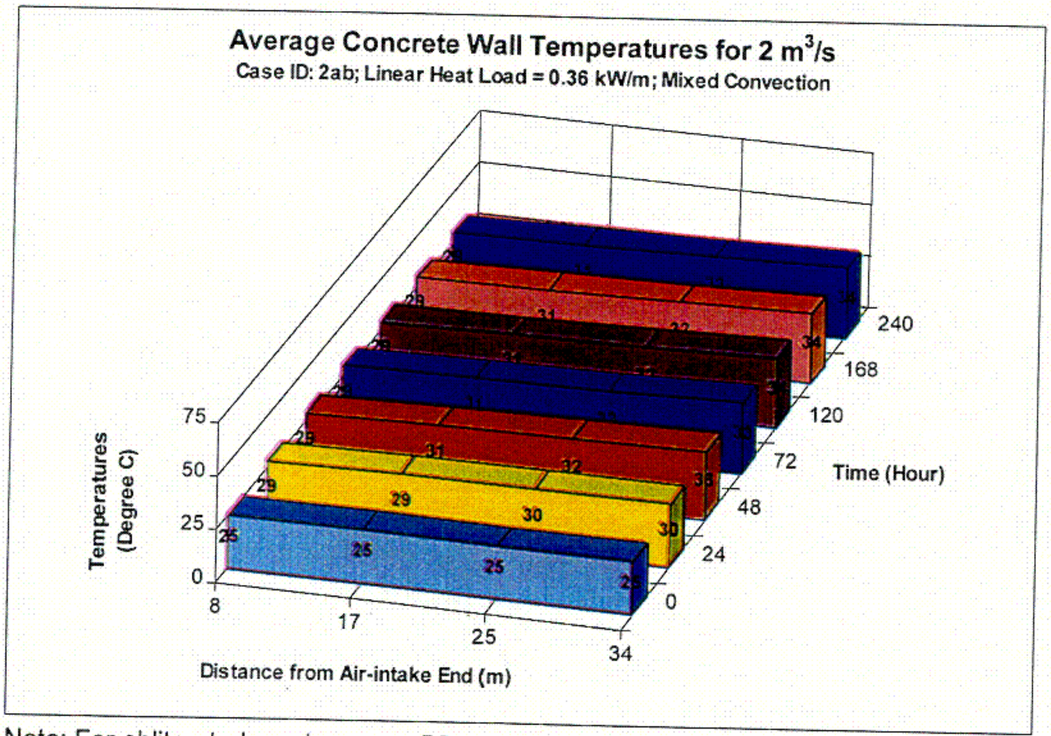
Figure 6-22. Predicted Average Temperatures in Segment No. 4 for Case 2aa

C13



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

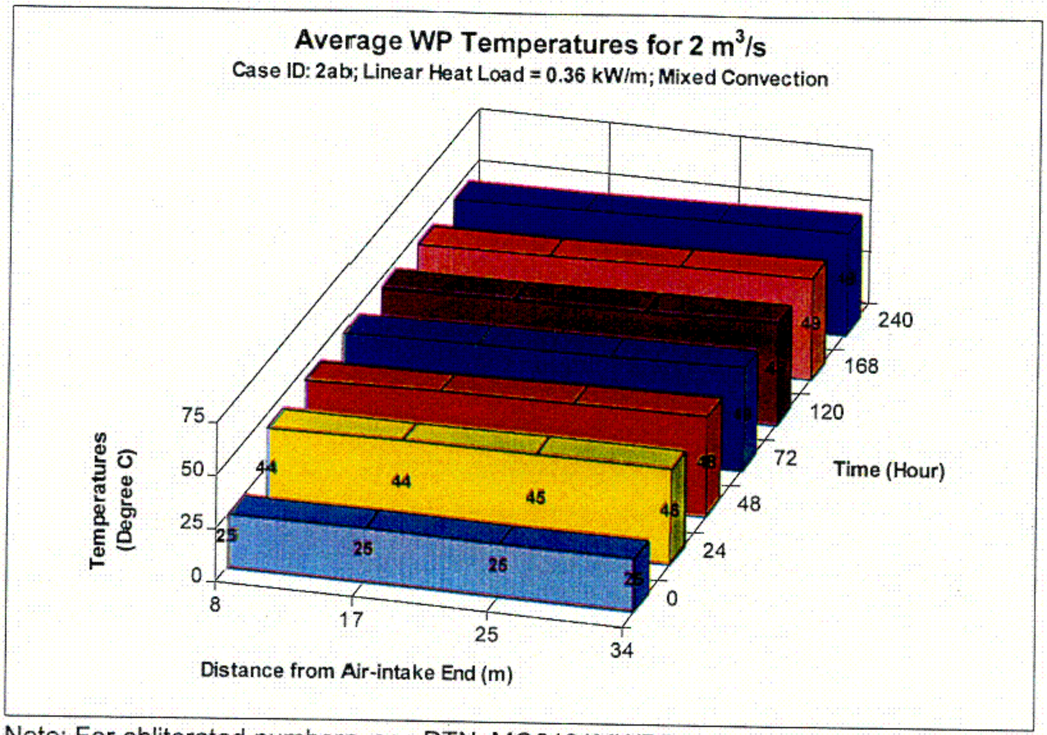
Figure 6-23. Predicted Air Temperatures for Case 2ab



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

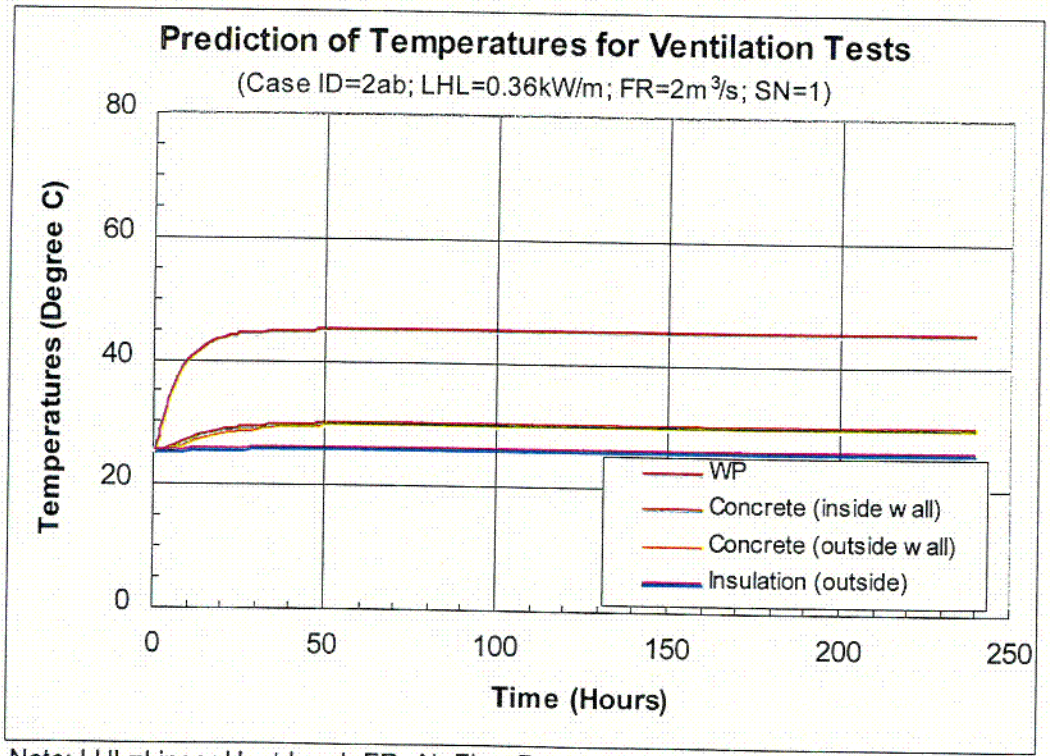
Figure 6-24. Predicted Concrete Inside Wall Temperatures for Case 2ab

C14



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

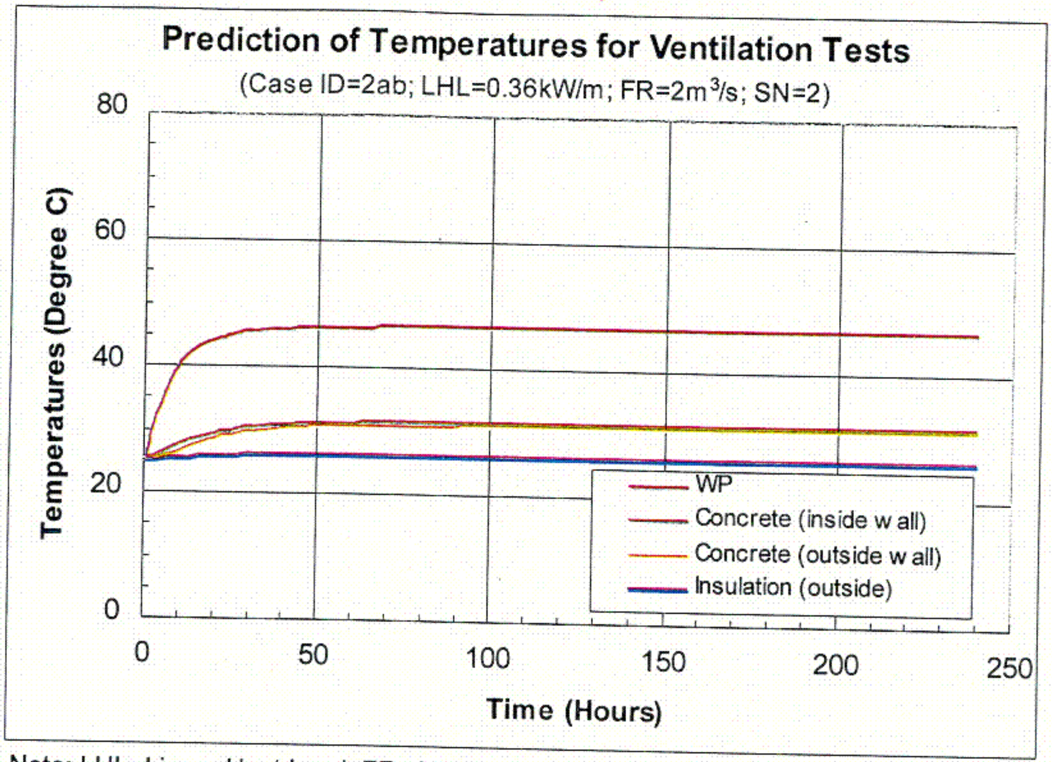
Figure 6-25. Predicted Waste Package Surface Temperatures for Case 2ab



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

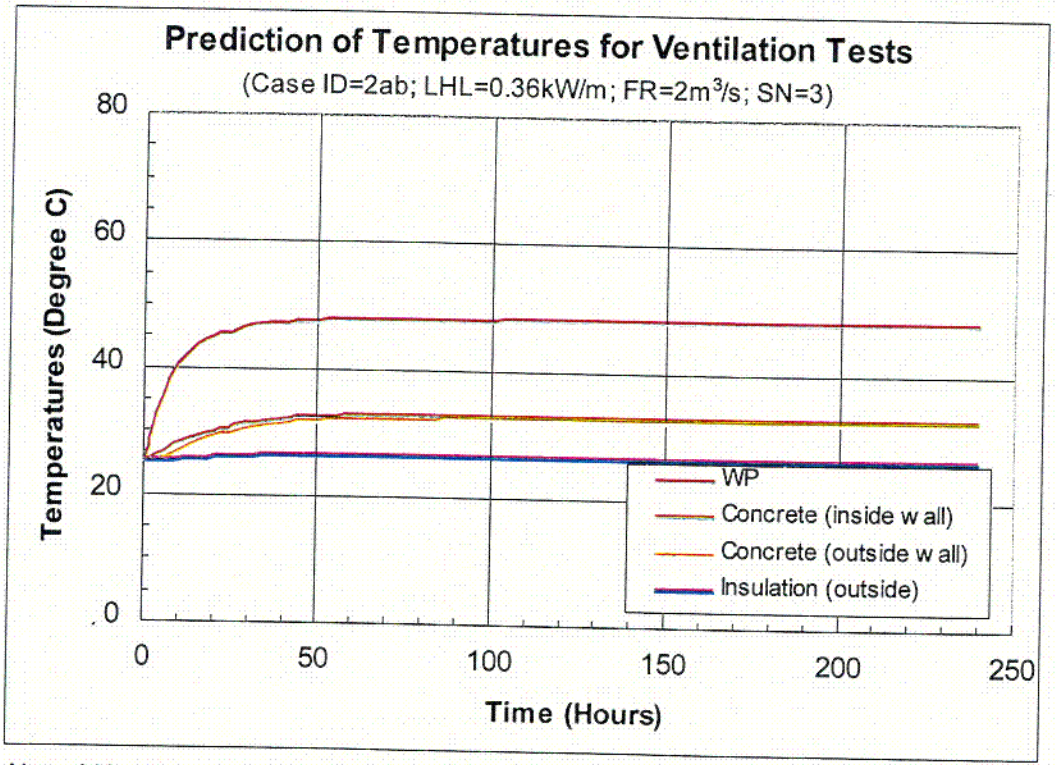
Figure 6-26. Predicted Average Temperatures in Segment No. 1 for Case 2ab

C15



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

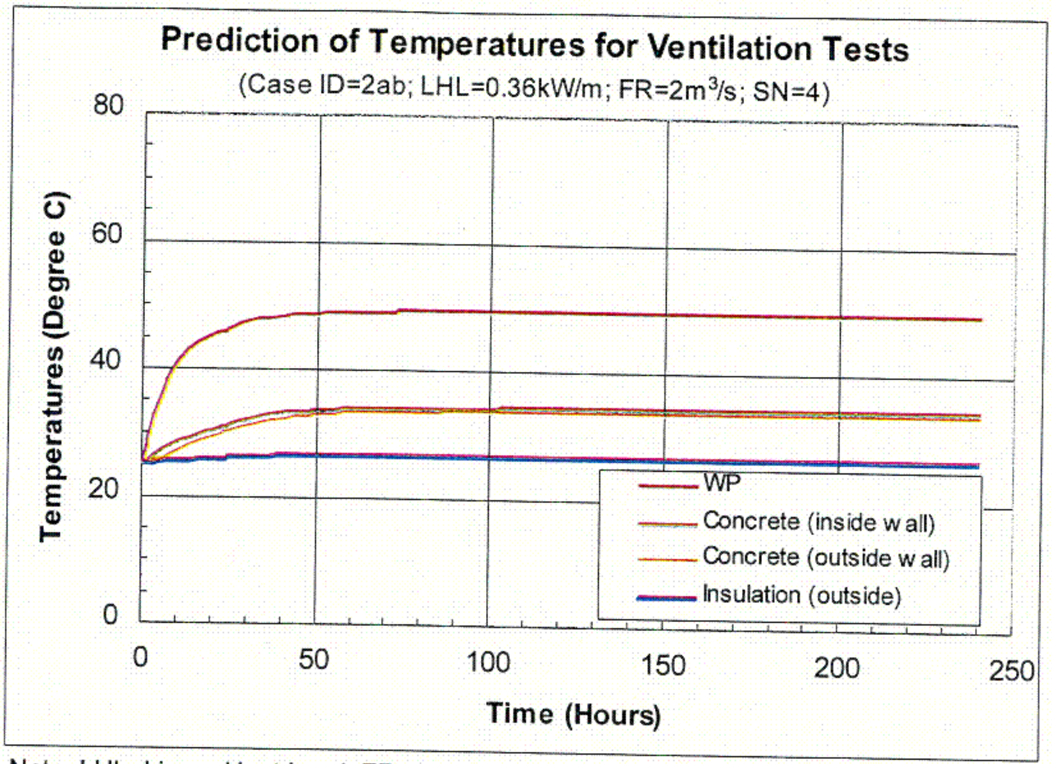
Figure 6-27. Predicted Average Temperatures in Segment No. 2 for Case 2ab



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

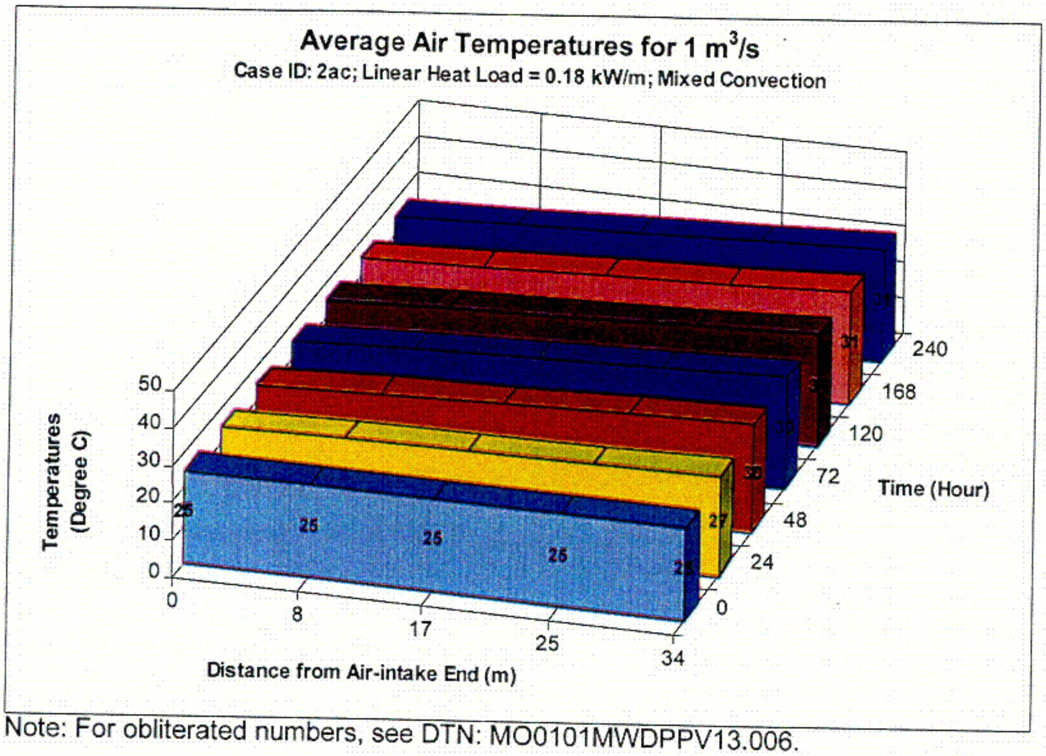
Figure 6-28. Predicted Average Temperatures in Segment No. 3 for Case 2ab

C16



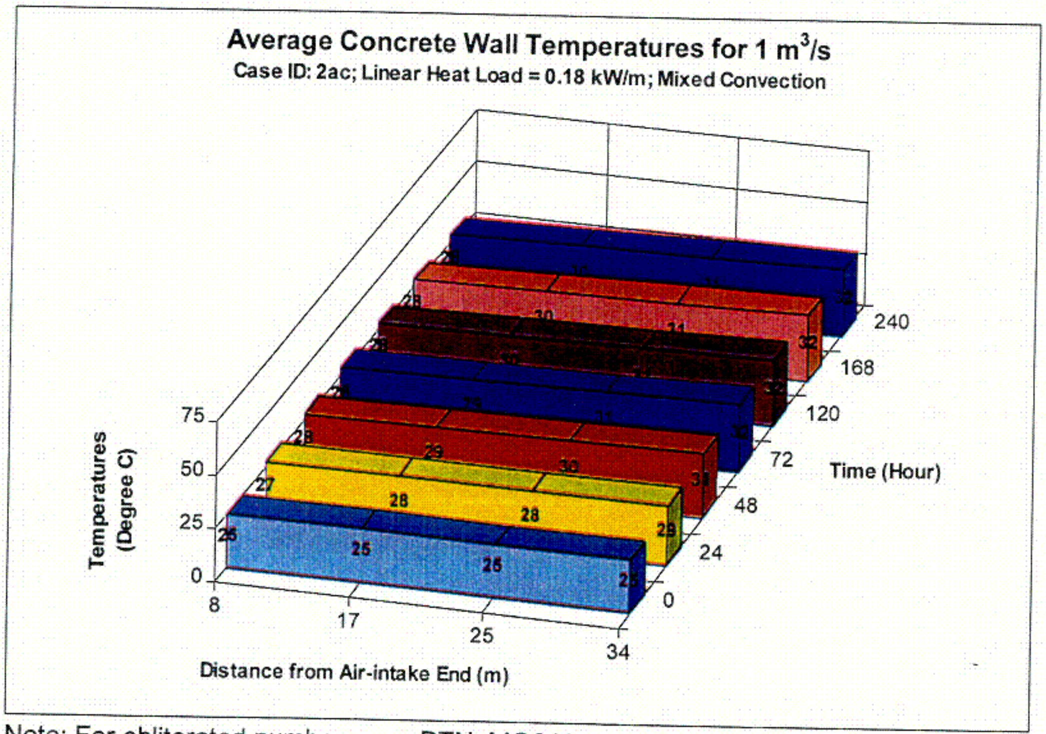
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-29. Predicted Average Temperatures in Segment No. 4 for Case 2ab



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

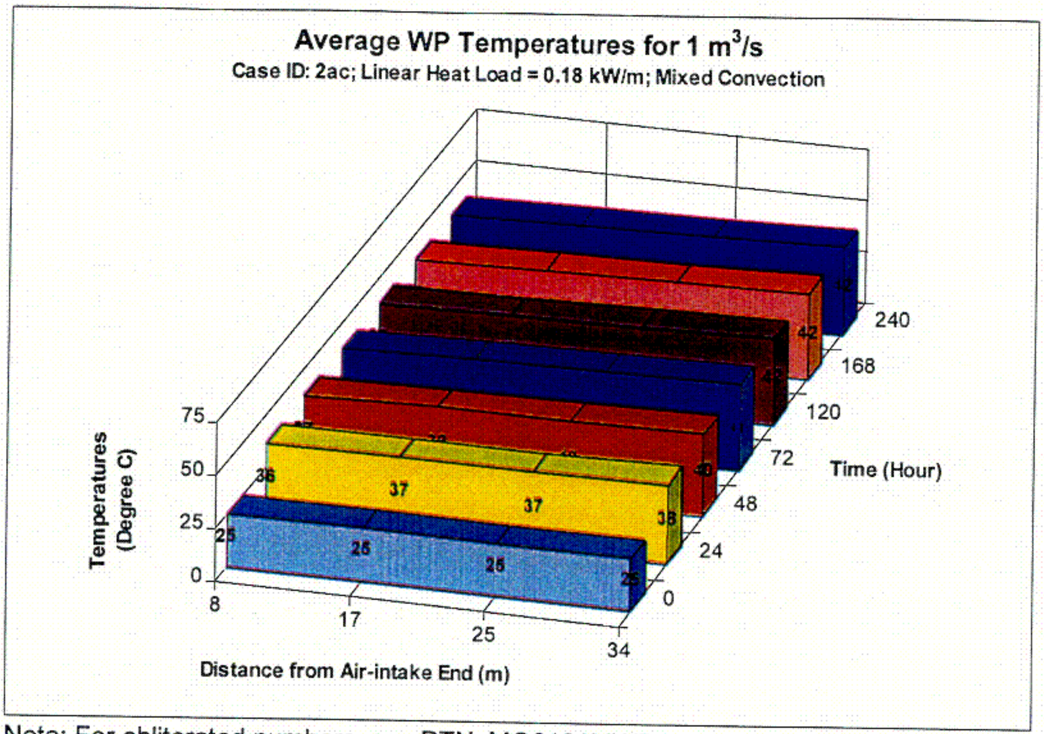
Figure 6-30. Predicted Air Temperatures for Case 2ac



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

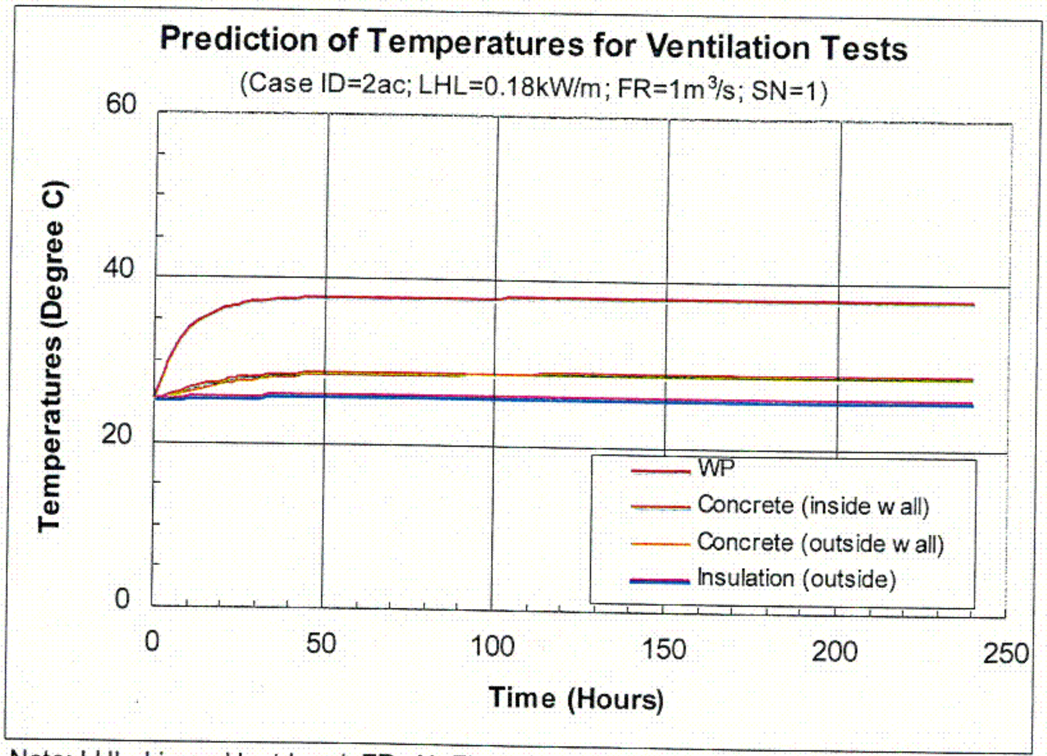
Figure 6-31. Predicted Concrete Inside Wall Temperatures for Case 2ac

C18



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

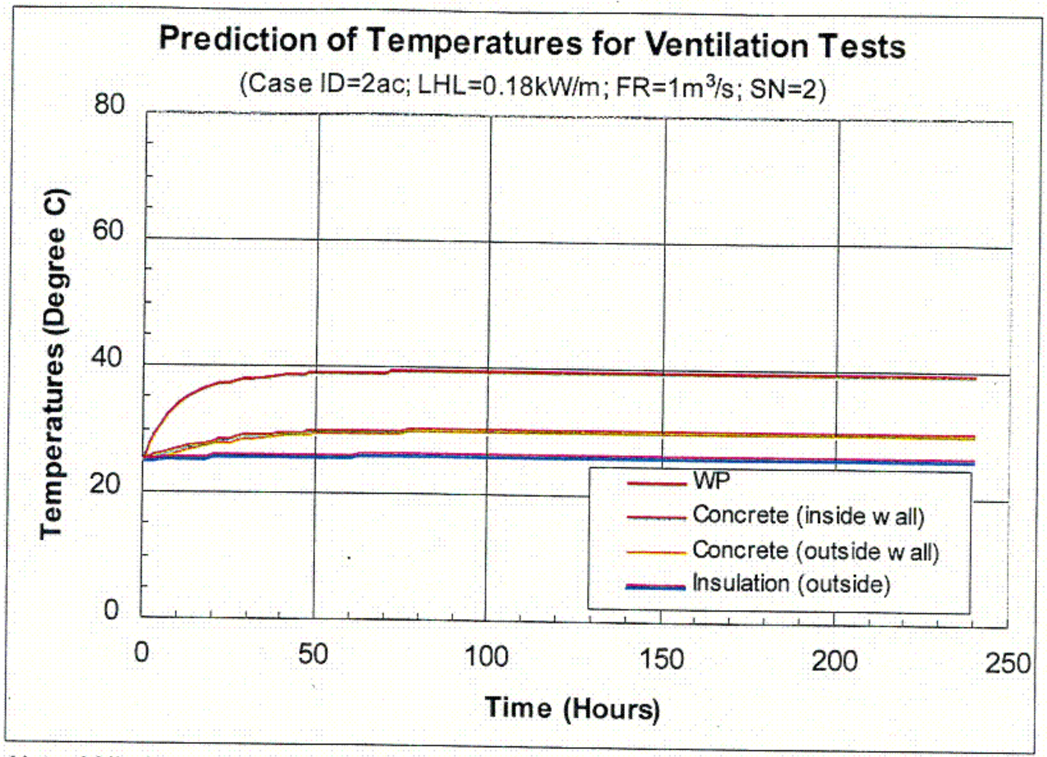
Figure 6-32. Predicted Waste Package Surface Temperatures for Case 2ac



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

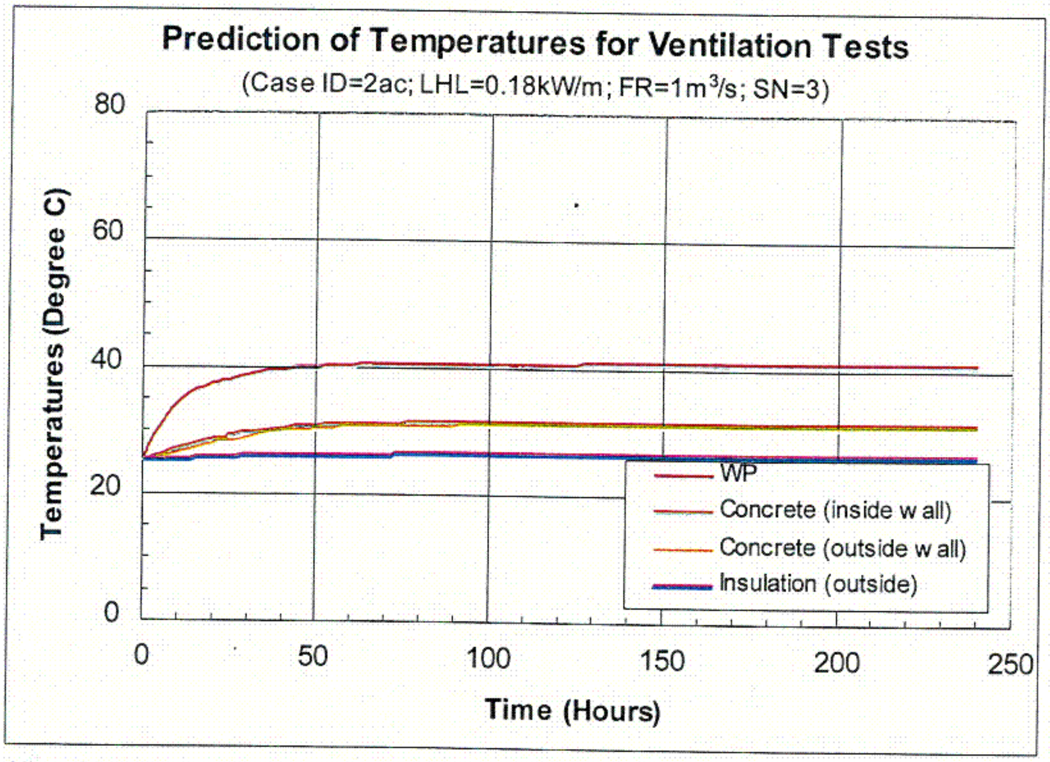
Figure 6-33. Predicted Average Temperatures in Segment No. 1 for Case 2ac

C19



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

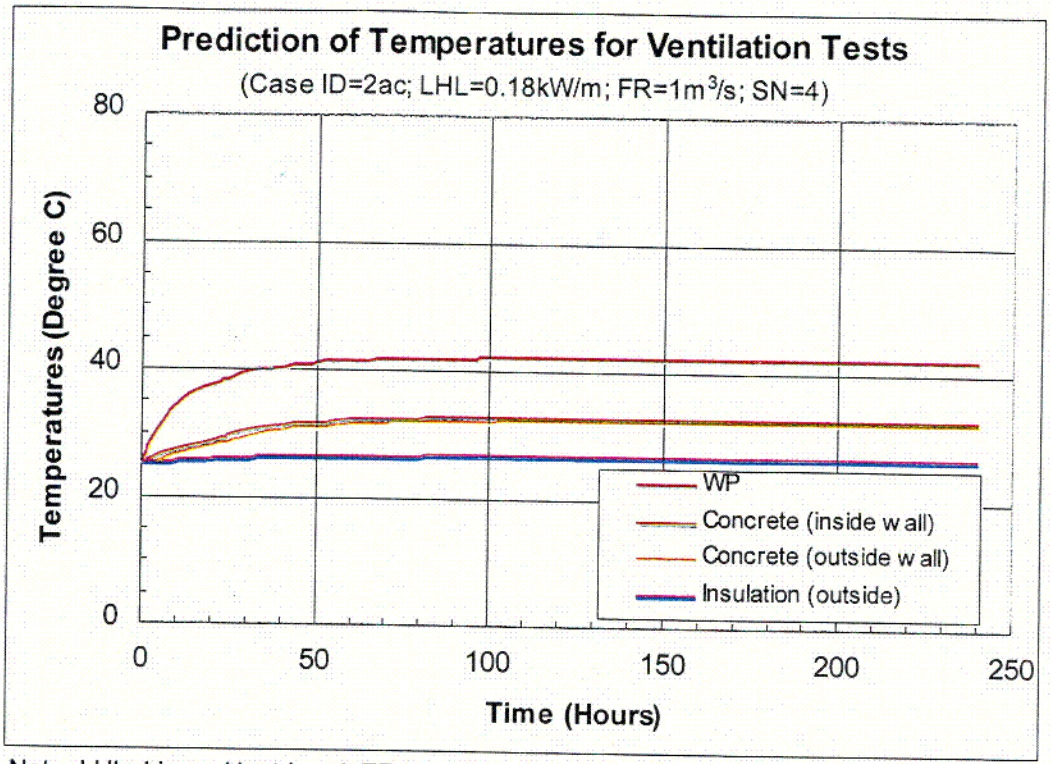
Figure 6-34. Predicted Average Temperatures in Segment No. 2 for Case 2ac



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

Figure 6-35. Predicted Average Temperatures in Segment No. 3 for Case 2ac

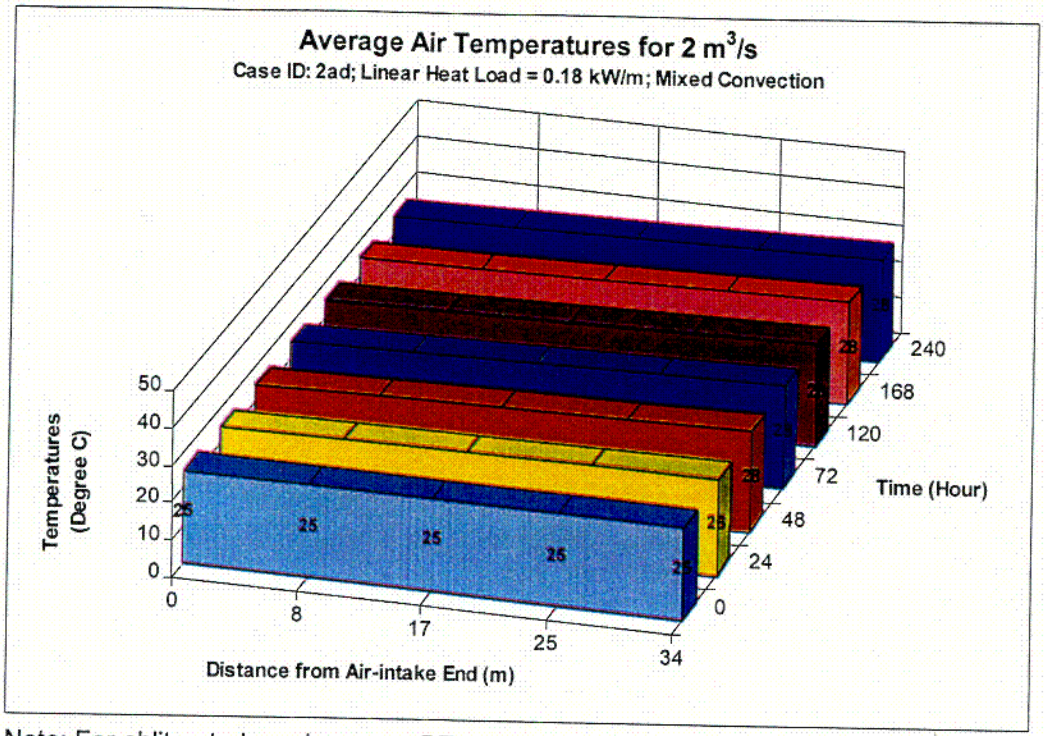
C20



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

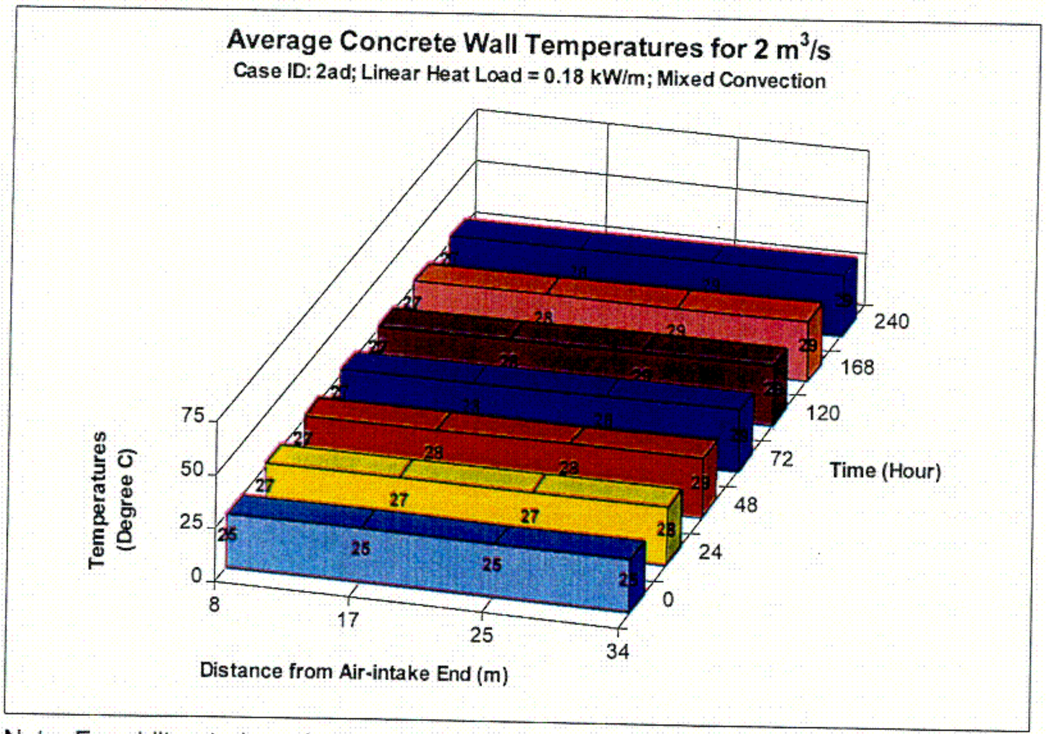
Figure 6-36. Predicted Average Temperatures in Segment No. 4 for Case 2ac

C21



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

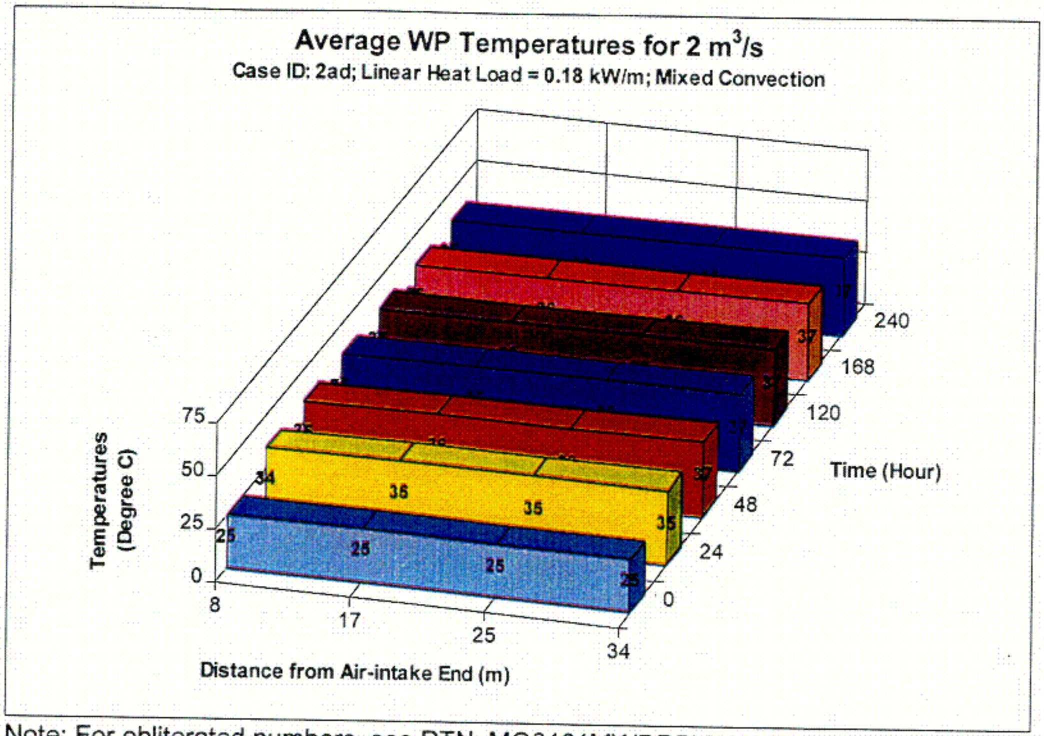
Figure 6-37. Predicted Air Temperatures for Case 2ad



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

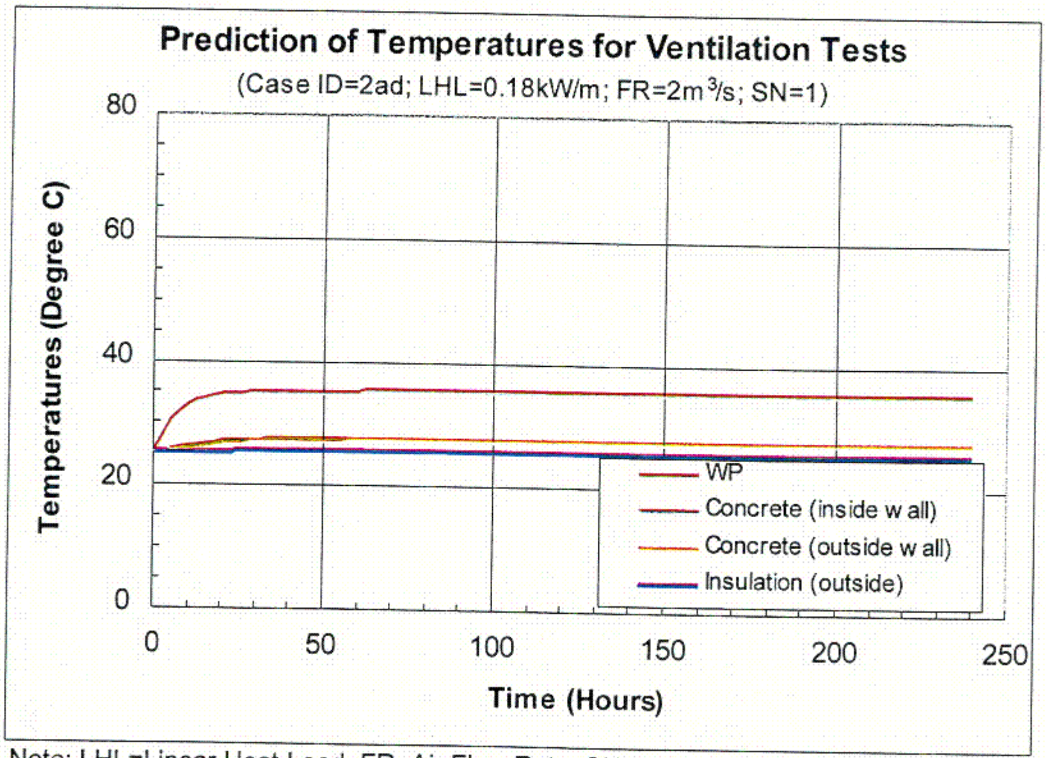
Figure 6-38. Predicted Concrete Inside Wall Temperatures for Case 2ad

C22



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

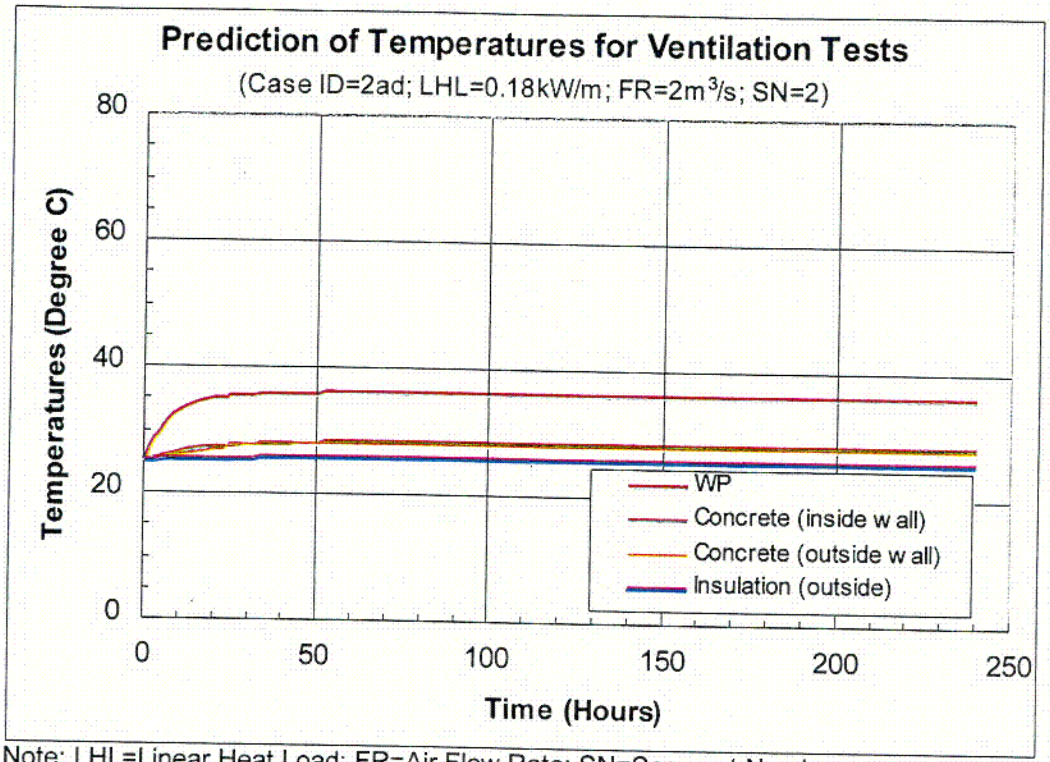
Figure 6-39. Predicted Waste Package Surface Temperatures for Case 2ad



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

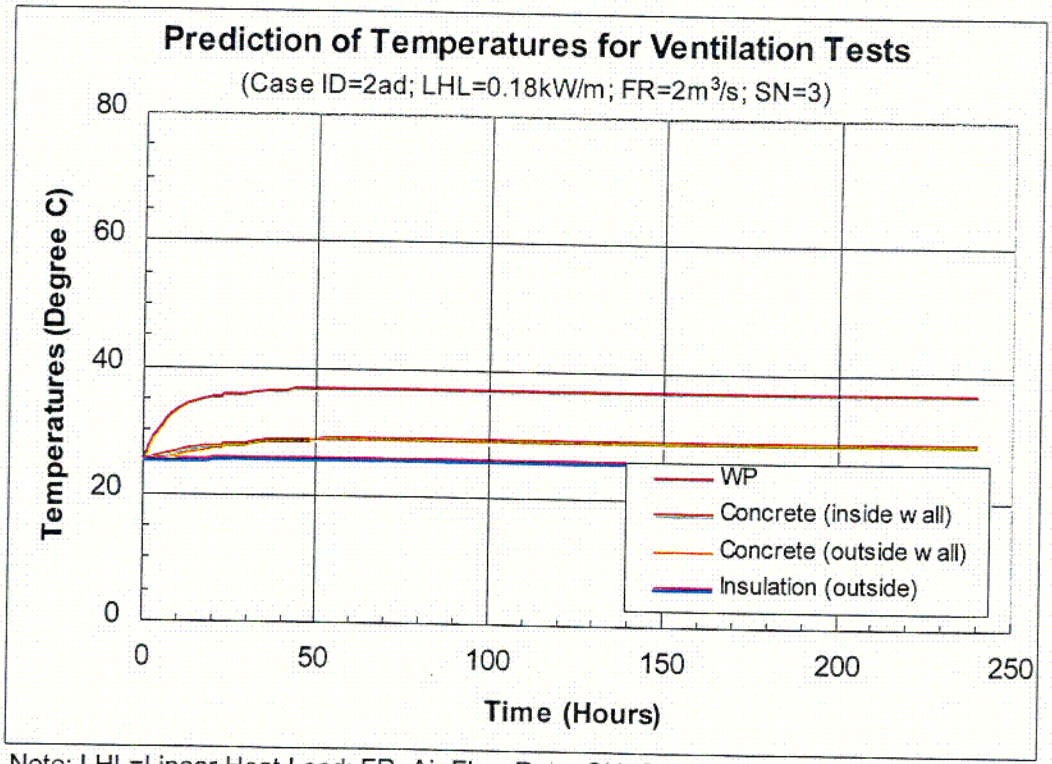
Figure 6-40. Predicted Average Temperatures in Segment No. 1 for Case 2ad

C23



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

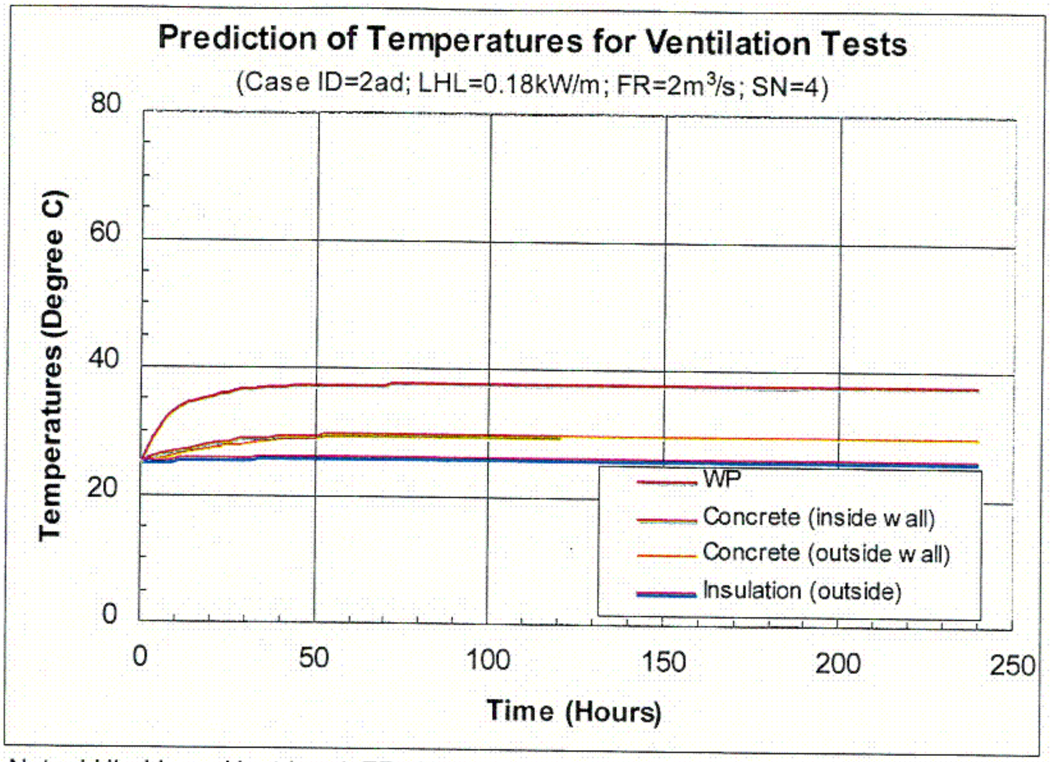
Figure 6-41. Predicted Average Temperatures in Segment No. 2 for Case 2ad



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

Figure 6-42. Predicted Average Temperatures in Segment No. 3 for Case 2ad

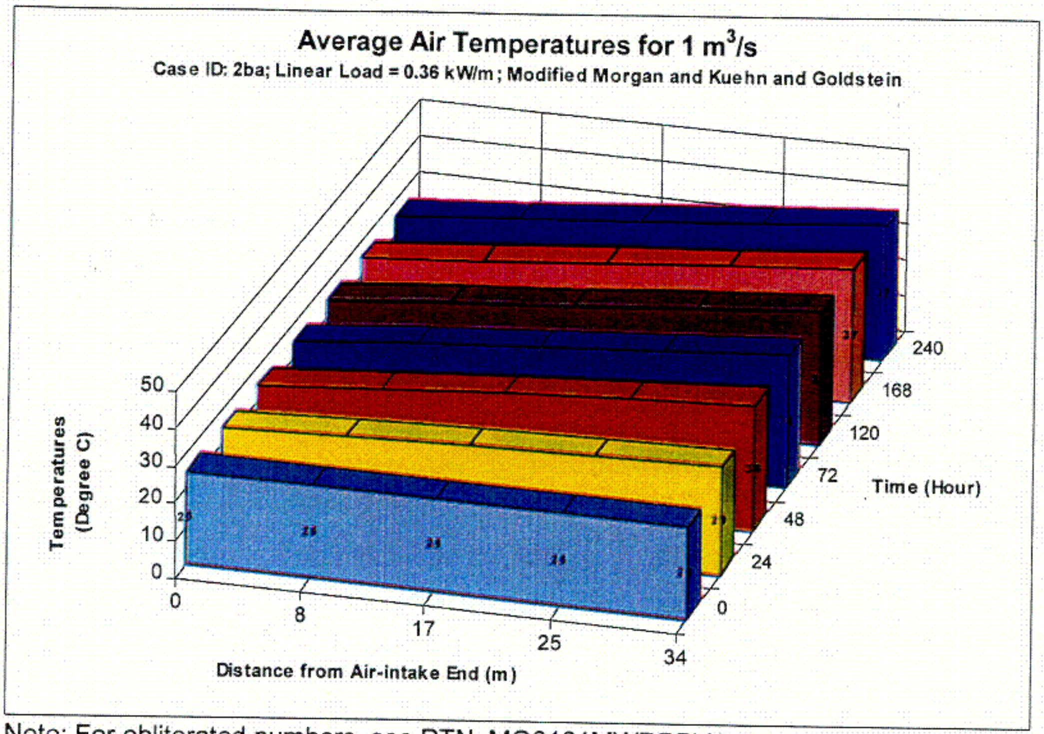
C24



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

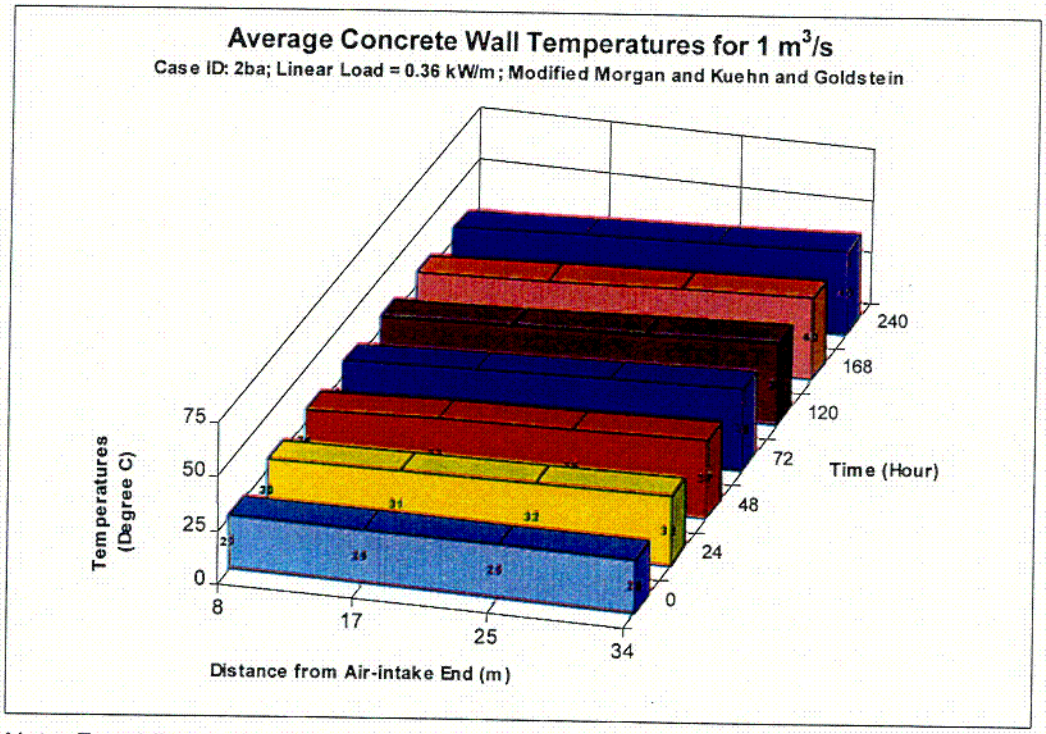
Figure 6-43. Predicted Average Temperatures in Segment No. 4 for Case 2ad

C25



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

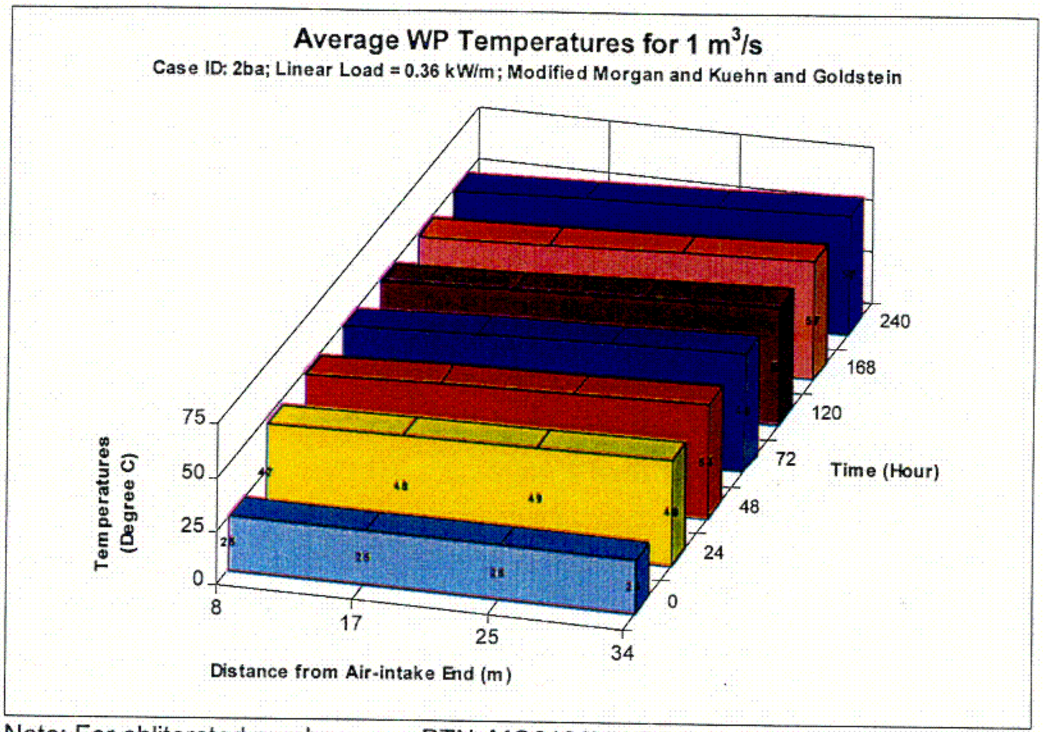
Figure 6-44. Predicted Air Temperatures for Case 2ba



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

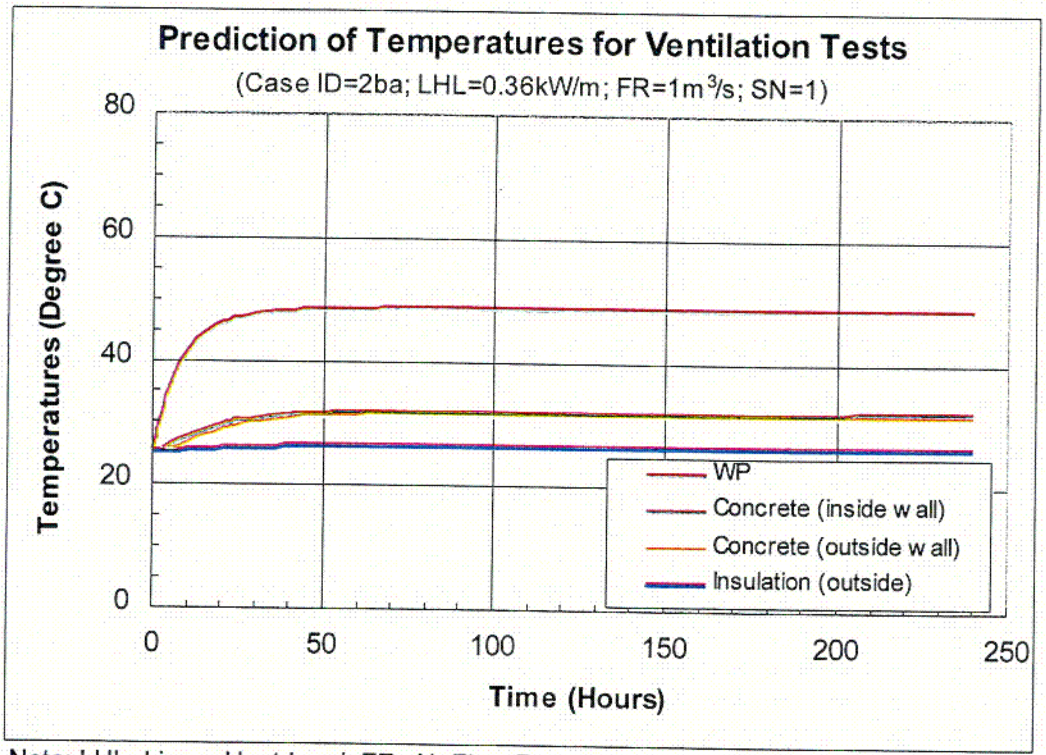
Figure 6-45. Predicted Concrete Inside Wall Temperatures for Case 2ba

C26



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

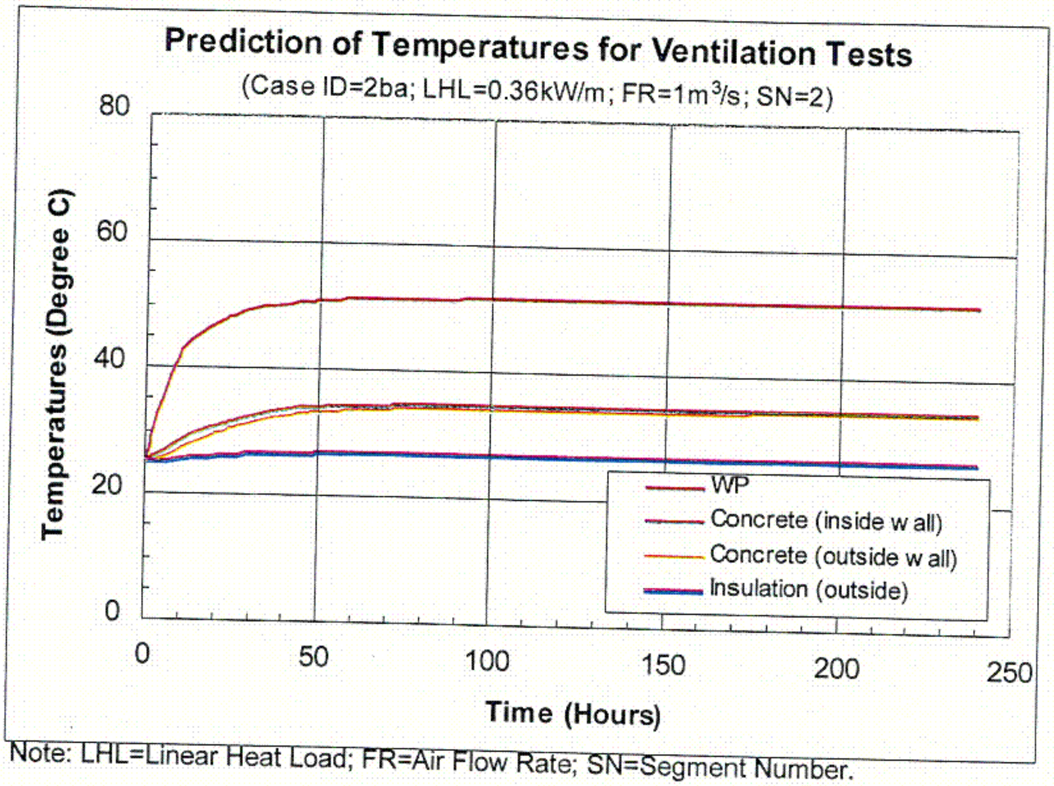
Figure 6-46. Predicted Waste Package Surface Temperatures for Case 2ba



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

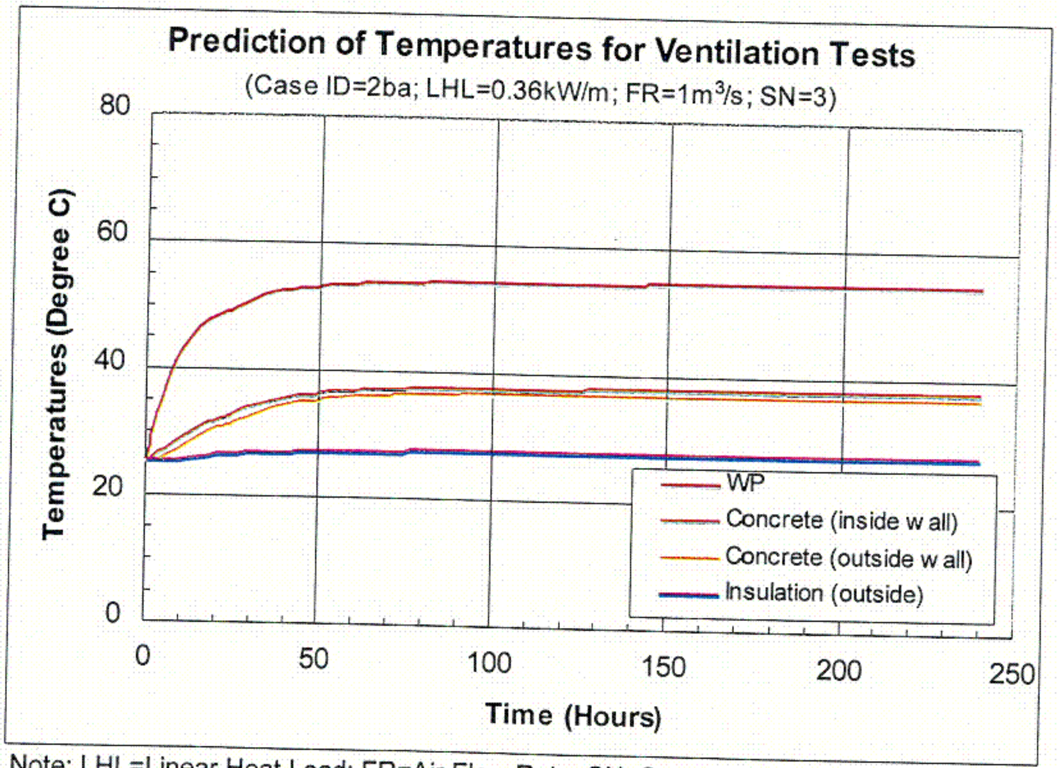
Figure 6-47. Predicted Average Temperatures in Segment No. 1 for Case 2ba

C27



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

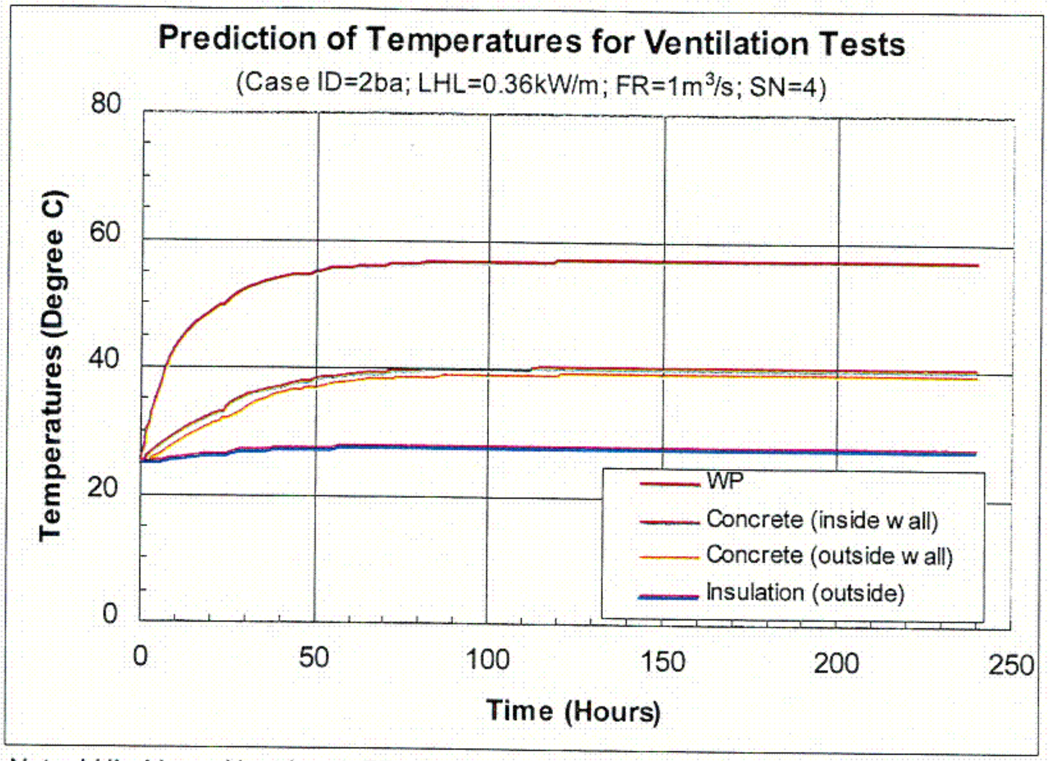
Figure 6-48. Predicted Average Temperatures in Segment No. 2 for Case 2ba



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

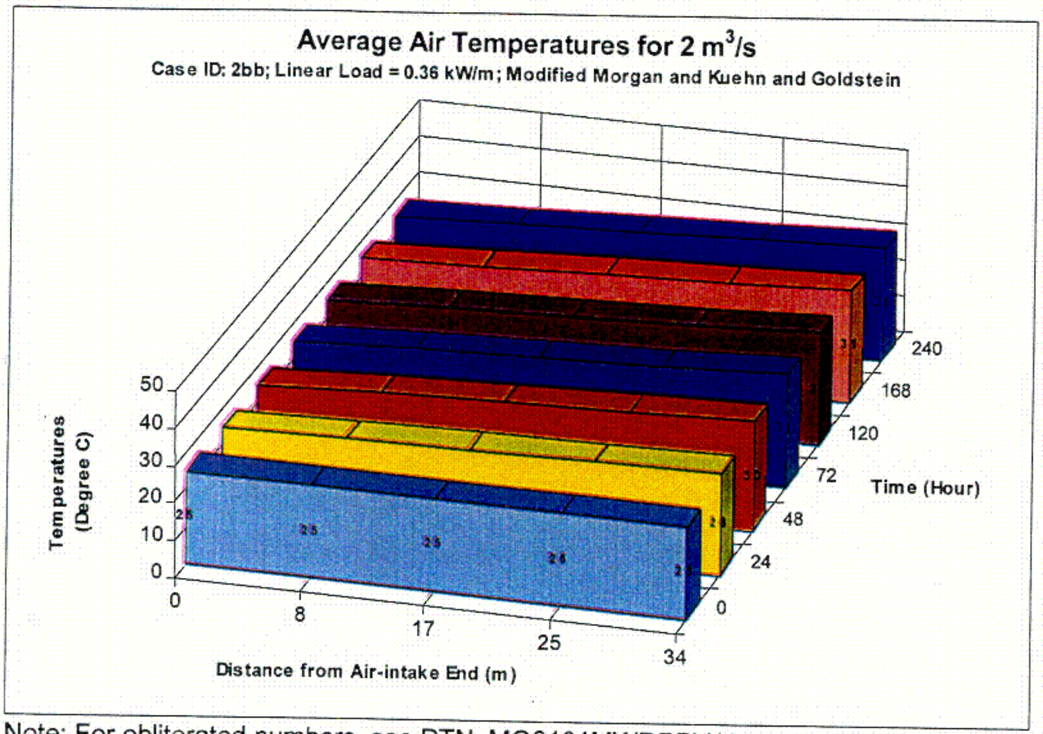
Figure 6-49. Predicted Average Temperatures in Segment No. 3 for Case 2ba

C28



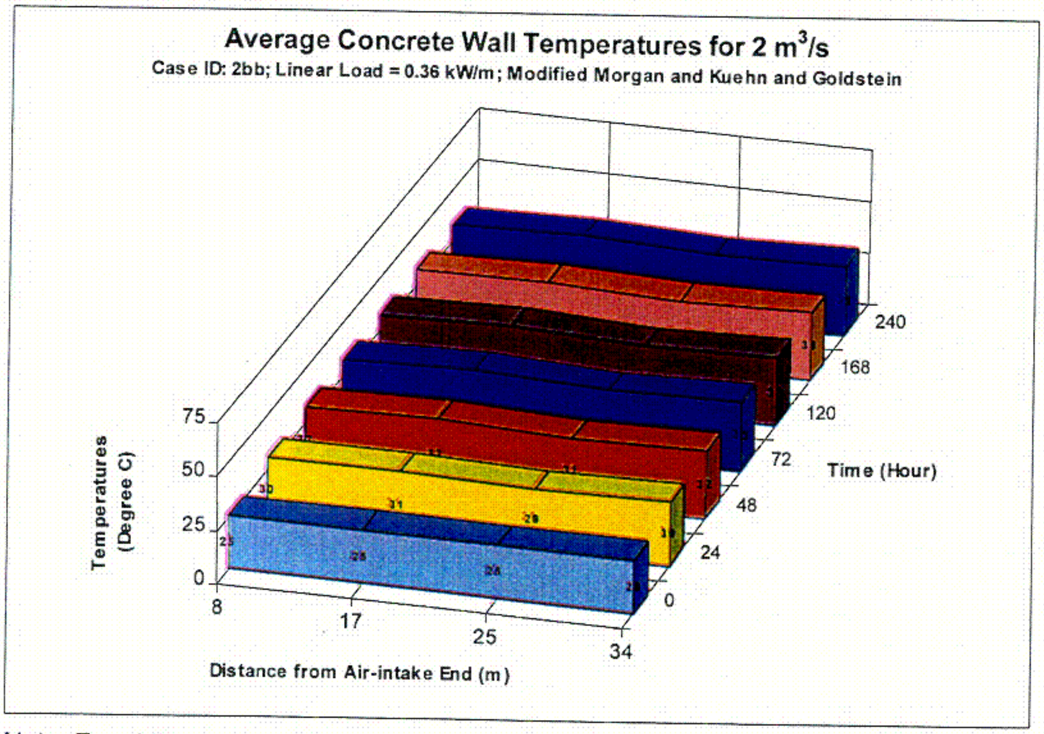
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-50. Predicted Average Temperatures in Segment No. 4 for Case 2ba



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

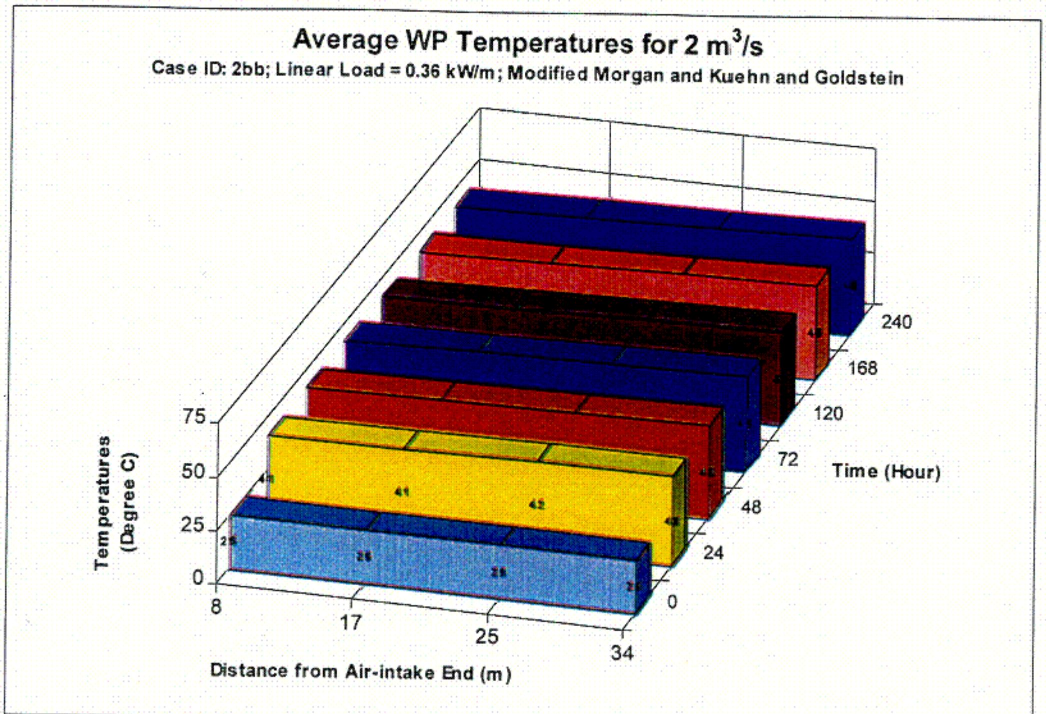
Figure 6-51. Predicted Air Temperatures for Case 2bb



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

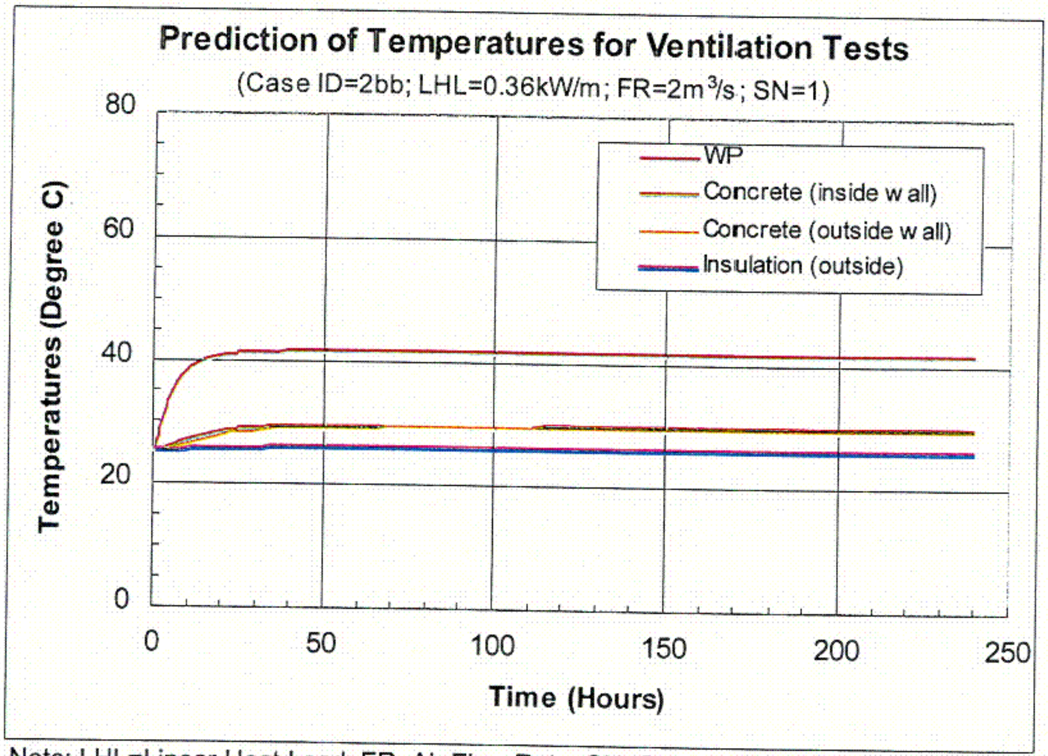
Figure 6-52. Predicted Concrete Inside Wall Temperatures for Case 2bb

C30



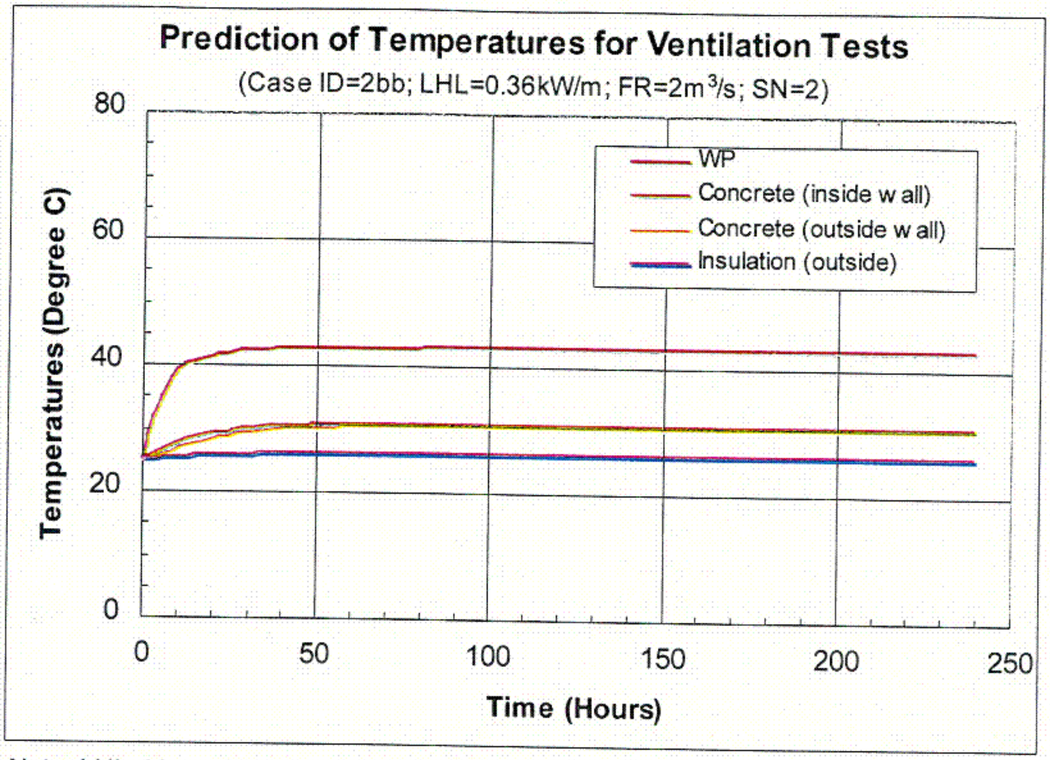
Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

Figure 6-53. Predicted Waste Package Surface Temperatures for Case 2bb



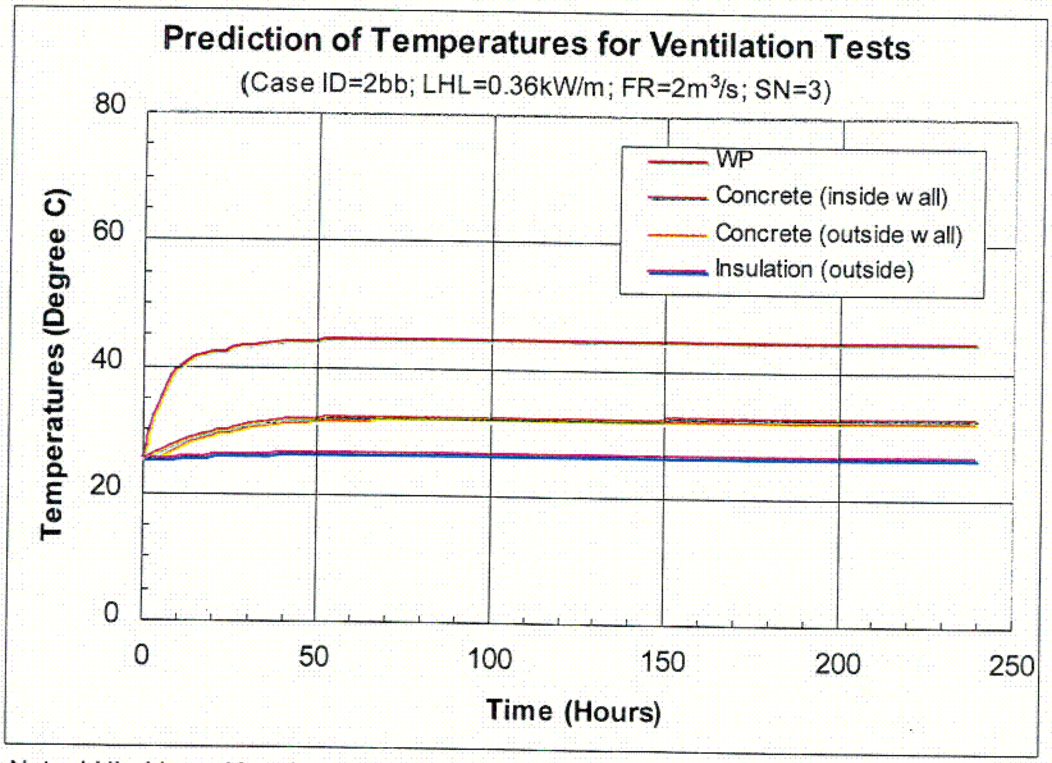
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-54. Predicted Average Temperatures in Segment No. 1 for Case 2bb



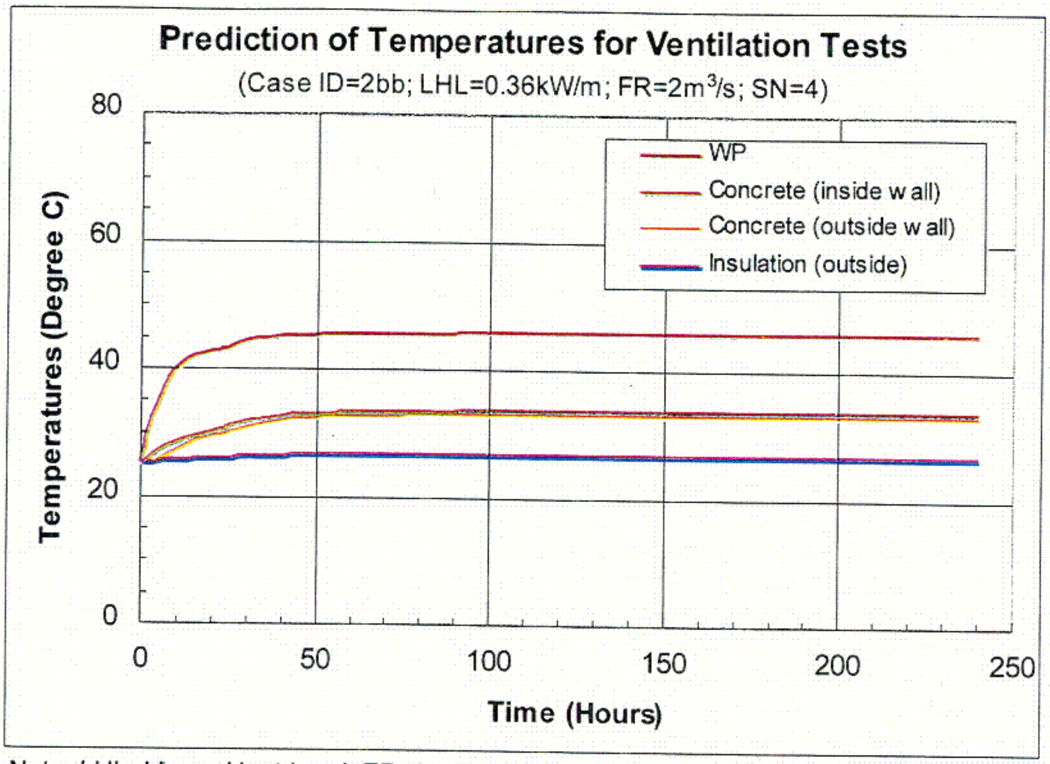
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-55. Predicted Average Temperatures in Segment No. 2 for Case 2bb



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

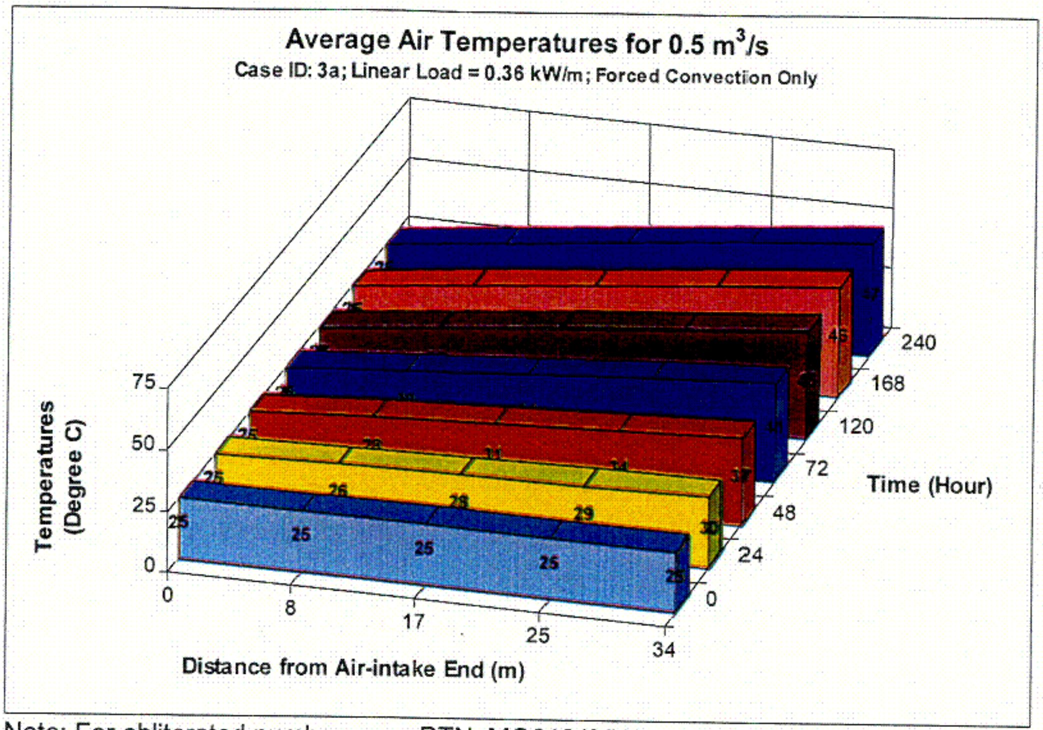
Figure 6-56. Predicted Average Temperatures in Segment No. 3 for Case 2bb



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

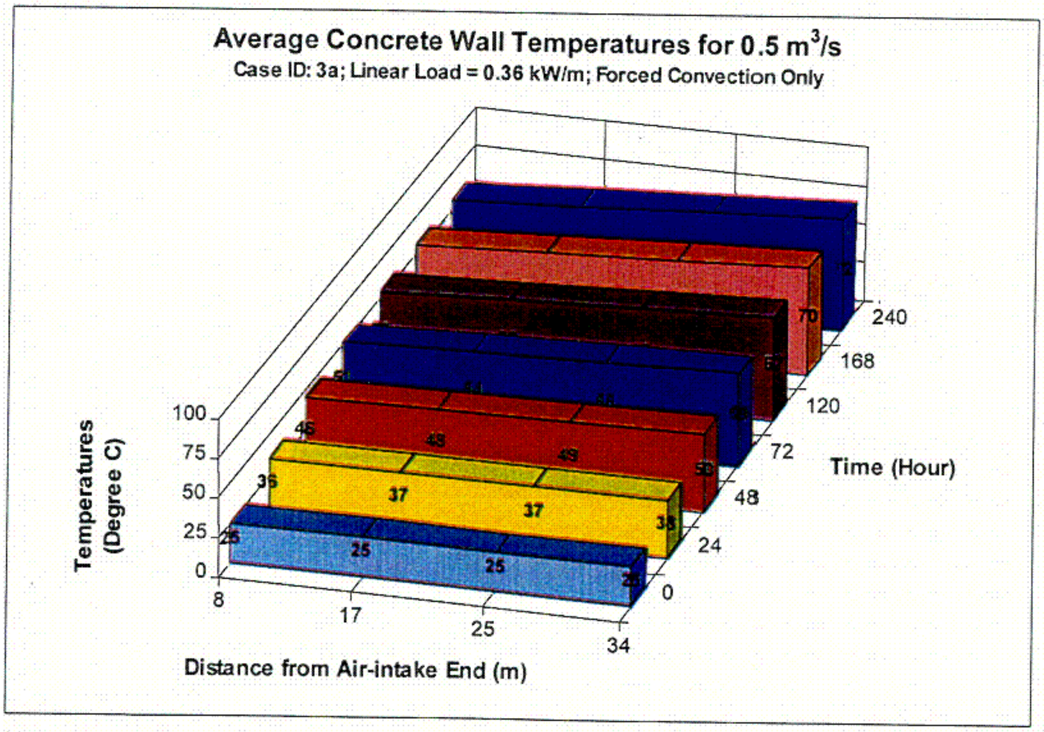
Figure 6-57. Predicted Average Temperatures in Segment No. 4 for Case 2bb

C33



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

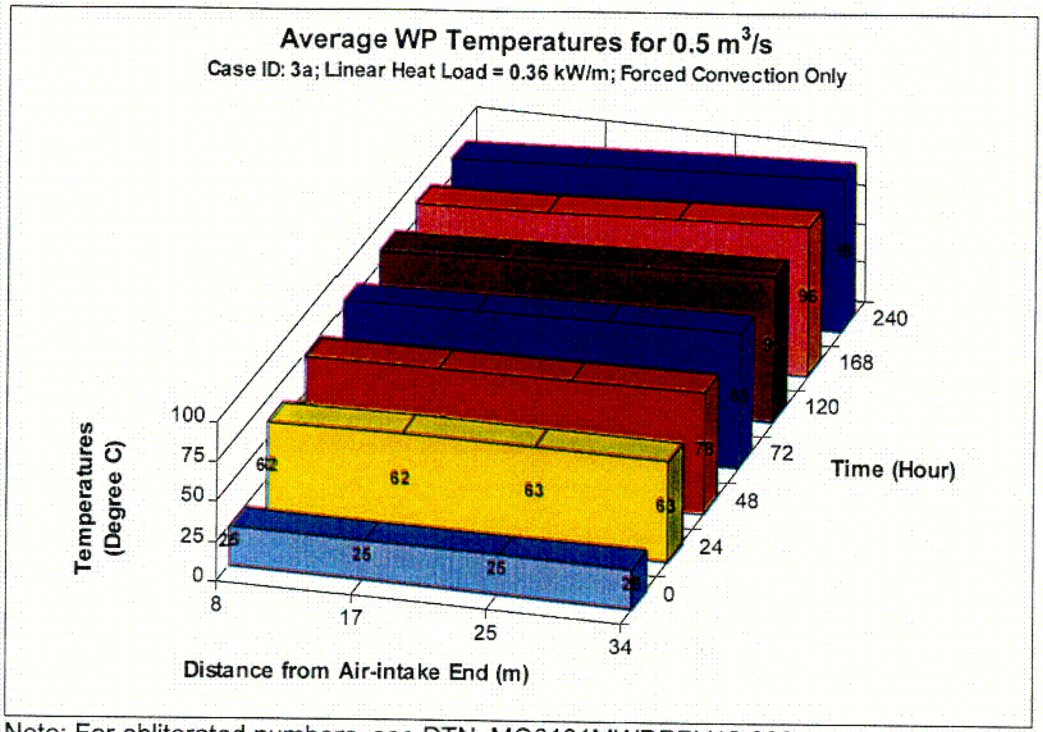
Figure 6-58. Predicted Air Temperatures for Case 3a



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

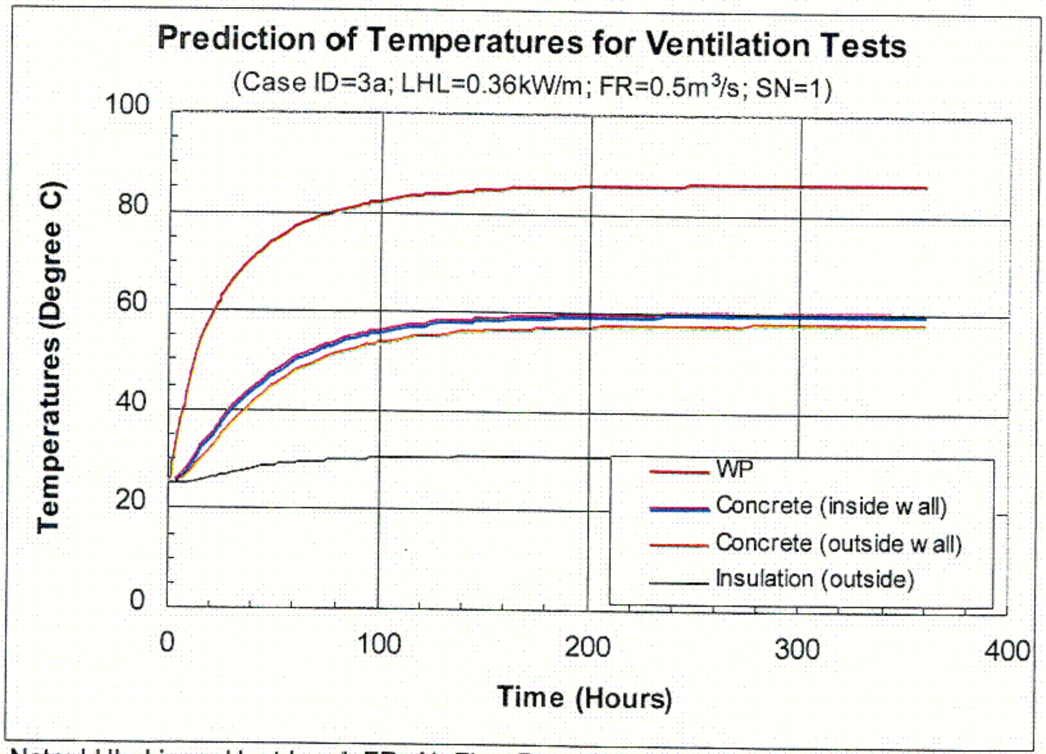
Figure 6-59. Predicted Concrete Inside Wall Temperatures for Case 3a

C34



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

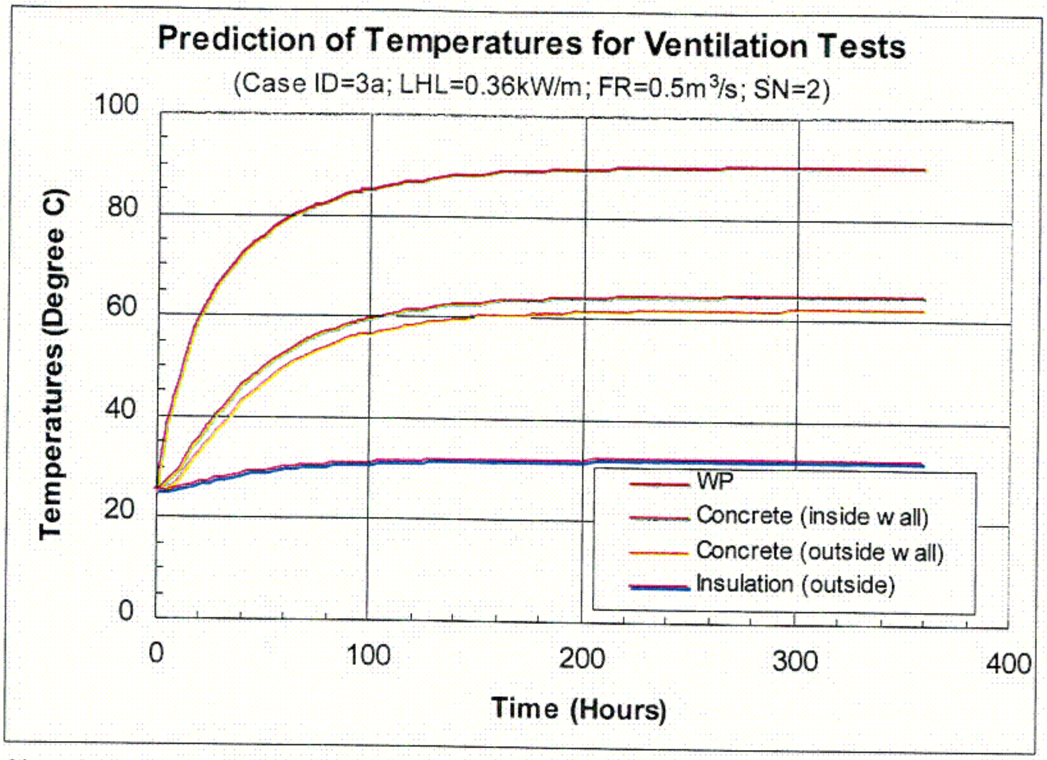
Figure 6-60. Predicted Waste Package Surface Temperatures for Case 3a



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

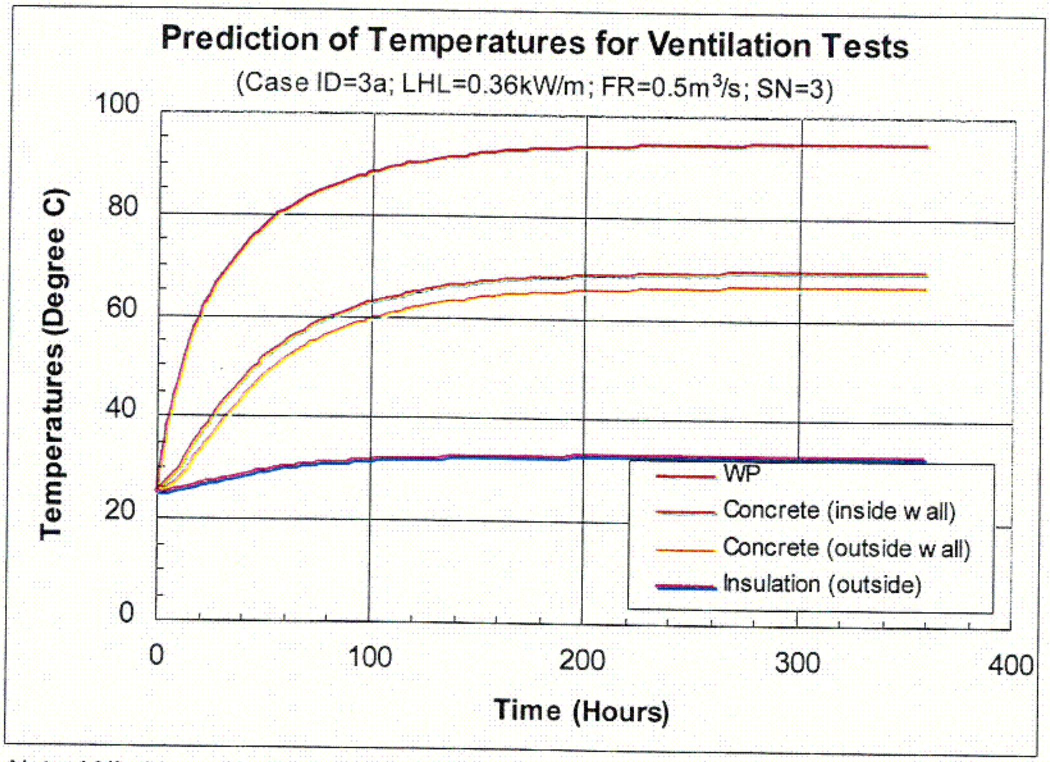
Figure 6-61. Predicted Average Temperatures in Segment No. 1 for Case 3a

C35



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

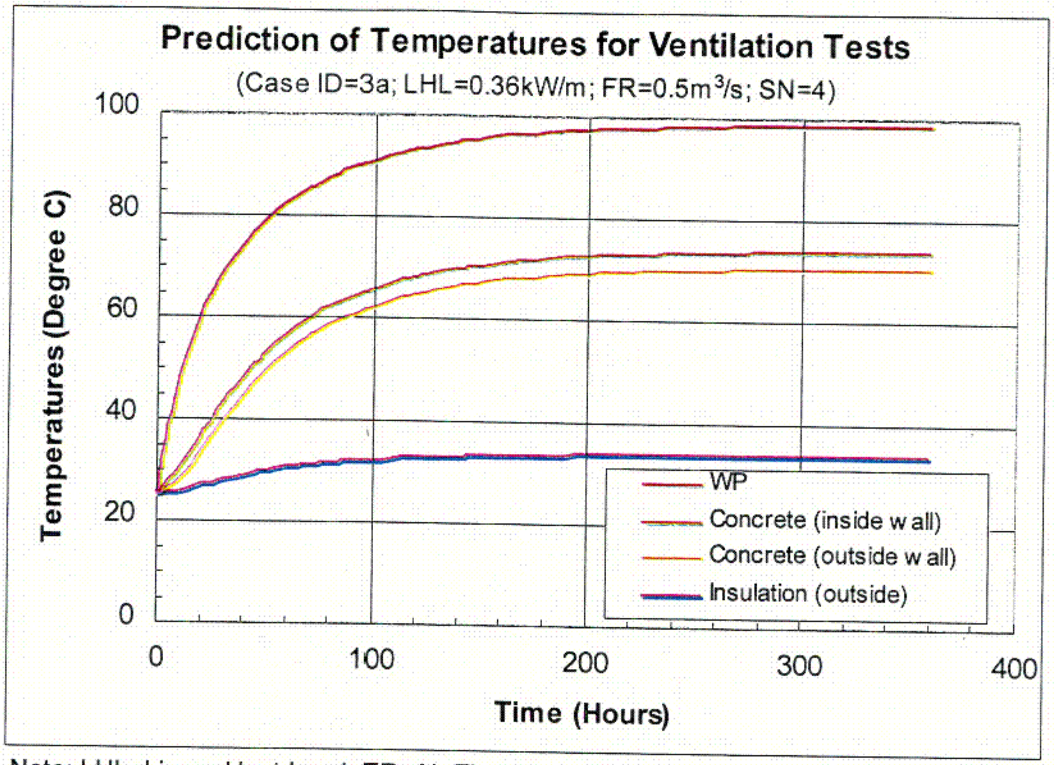
Figure 6-62. Predicted Average Temperatures in Segment No. 2 for Case 3a



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

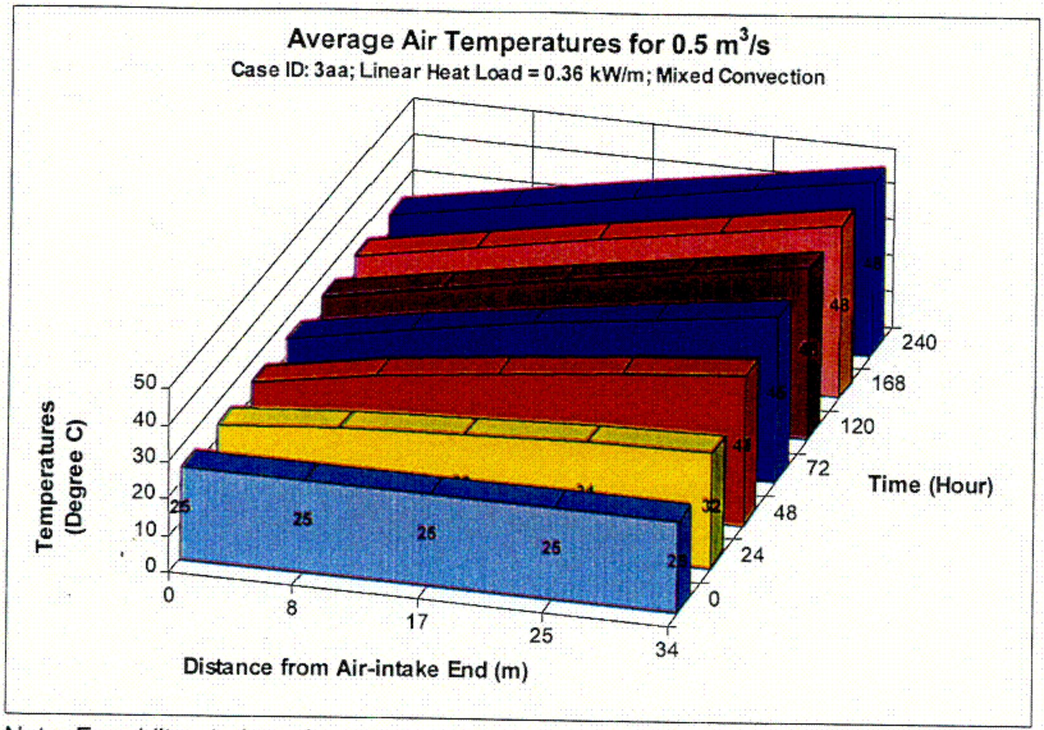
Figure 6-63. Predicted Average Temperatures in Segment No. 3 for Case 3a

C36



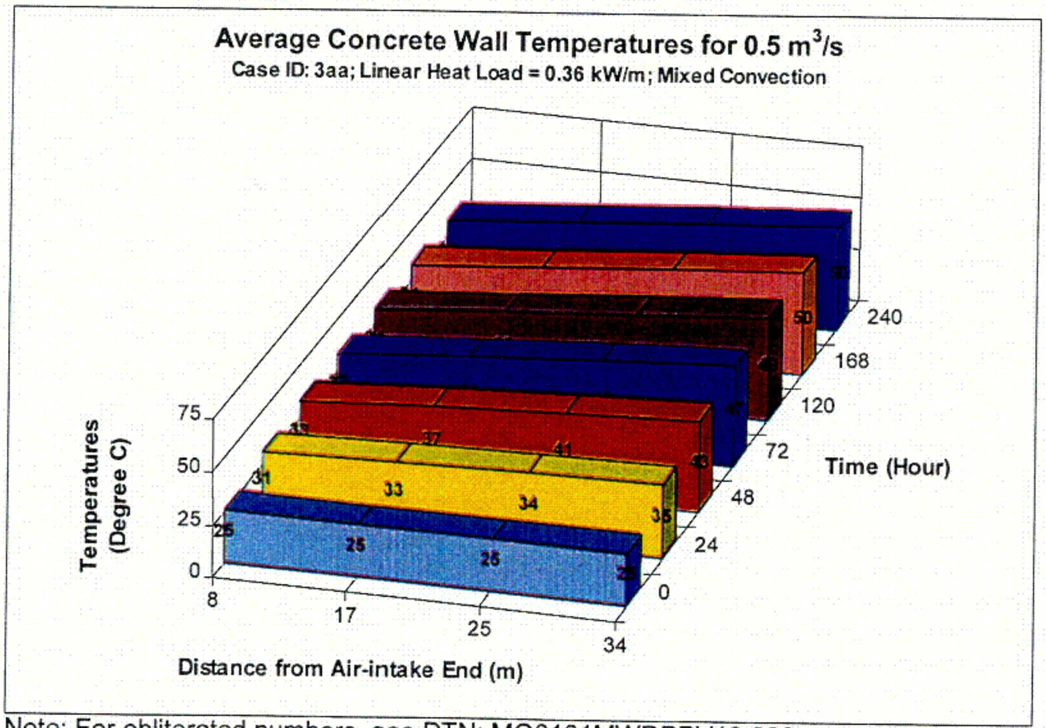
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-64. Predicted Average Temperatures in Segment No. 4 for Case 3a



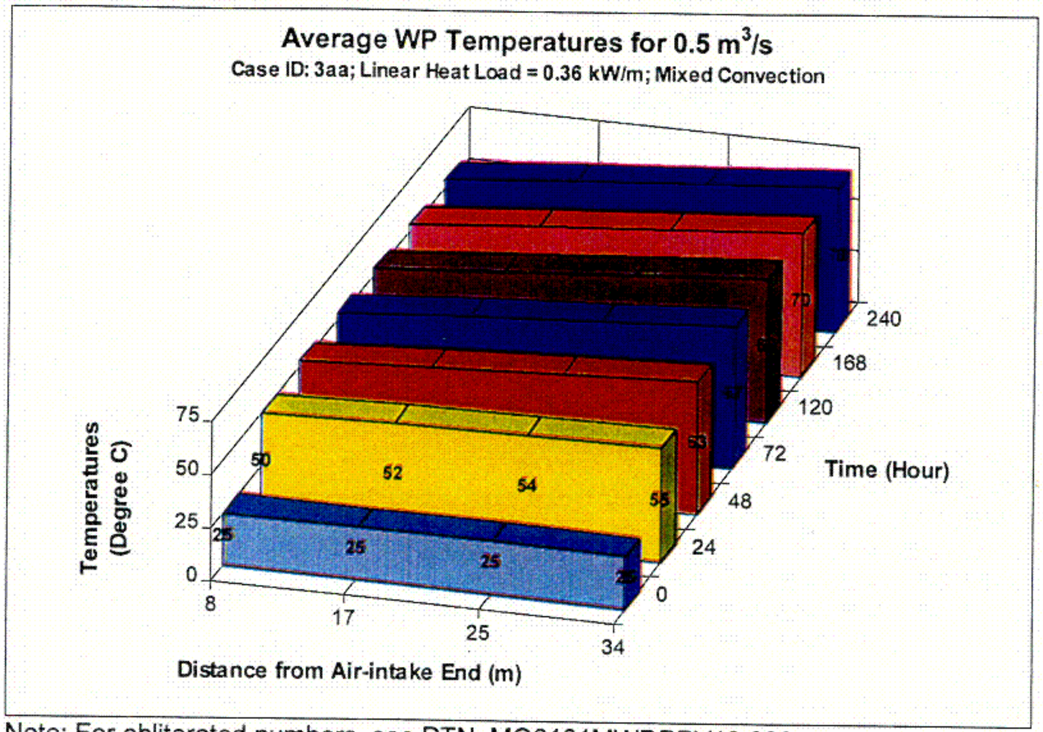
Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

Figure 6-65. Predicted Air Temperatures for Case 3aa



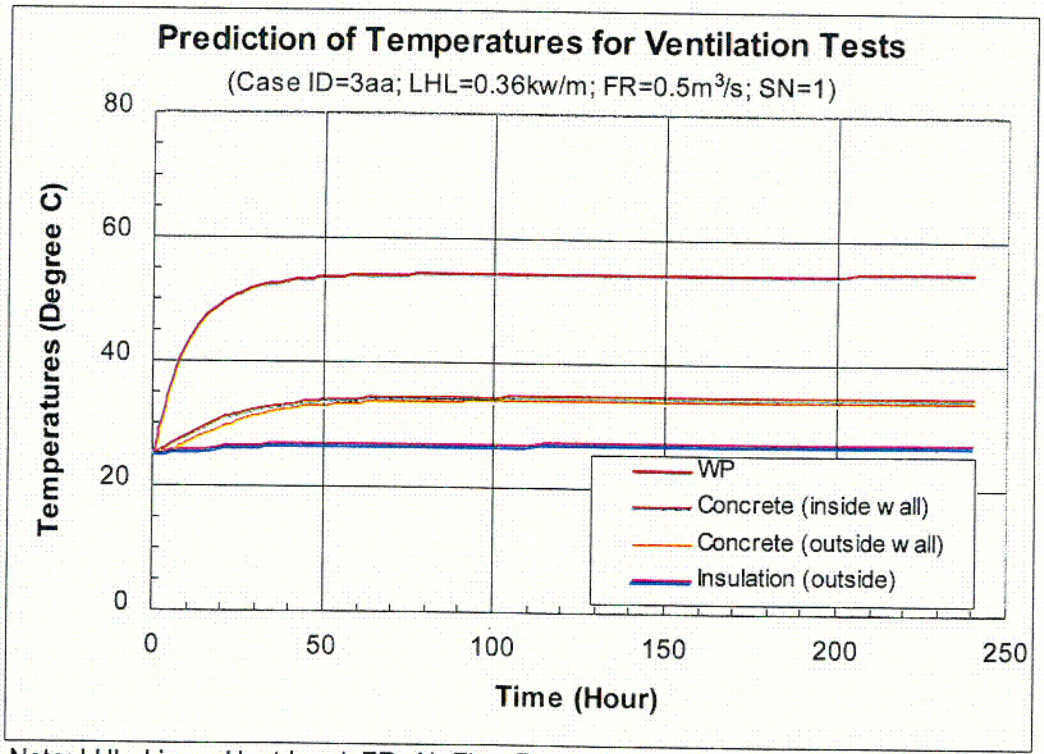
Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

Figure 6-66. Predicted Concrete Inside Wall Temperatures for Case 3aa



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

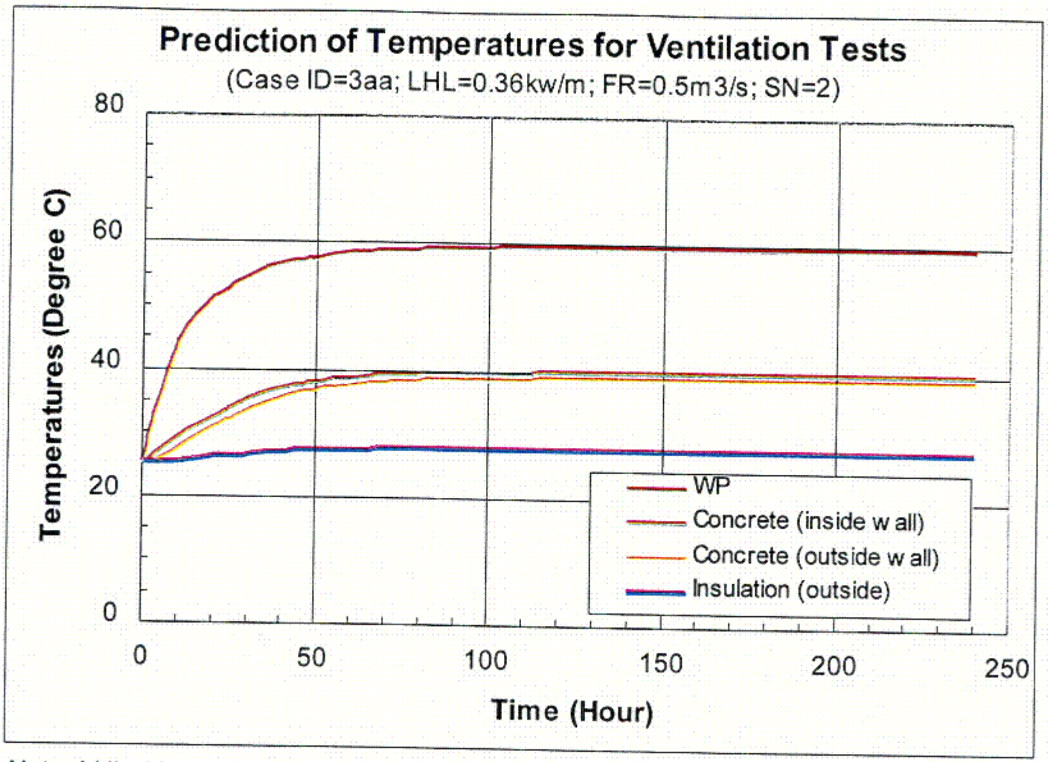
Figure 6-67. Predicted Waste Package Surface Temperatures for Case 3aa



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

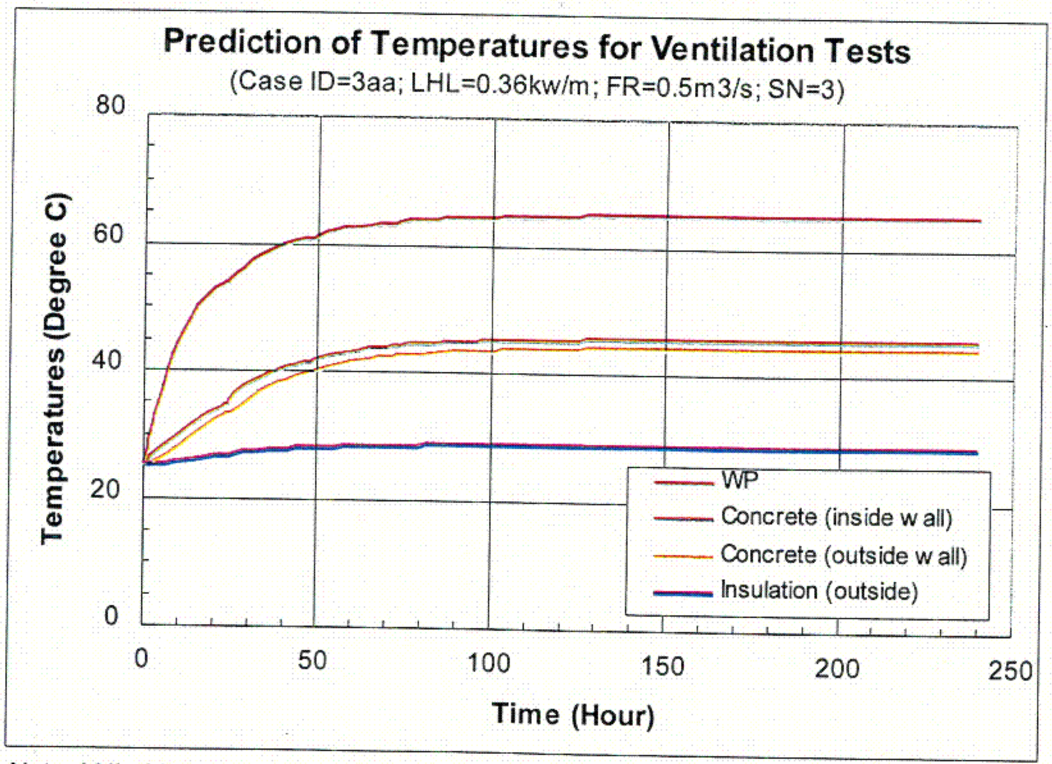
Figure 6-68. Predicted Average Temperatures in Segment No. 1 for Case 3aa

C39



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

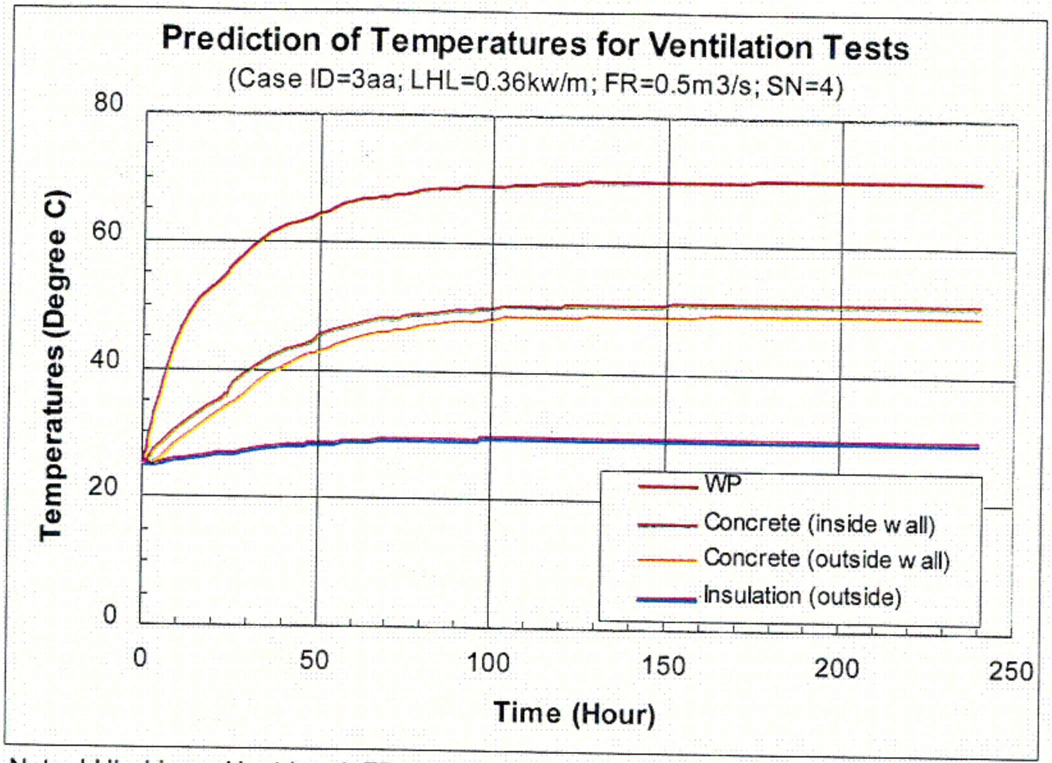
Figure 6-69. Predicted Average Temperatures in Segment No. 2 for Case 3aa



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

Figure 6-70. Predicted Average Temperatures in Segment No. 3 for Case 3aa

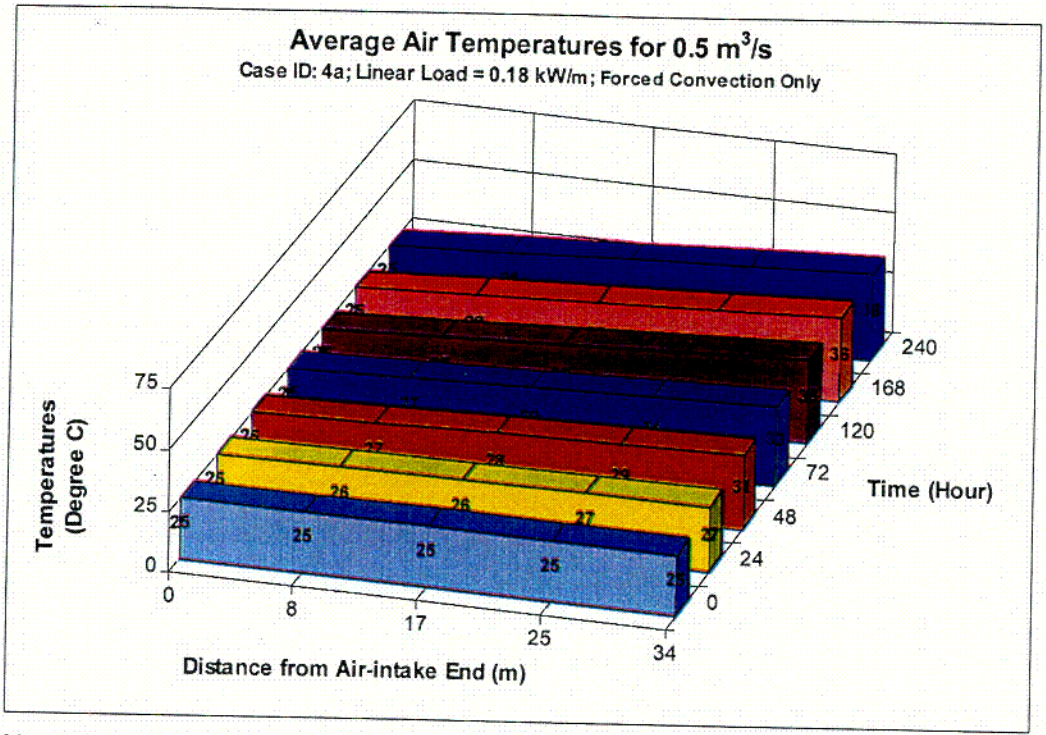
C40



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

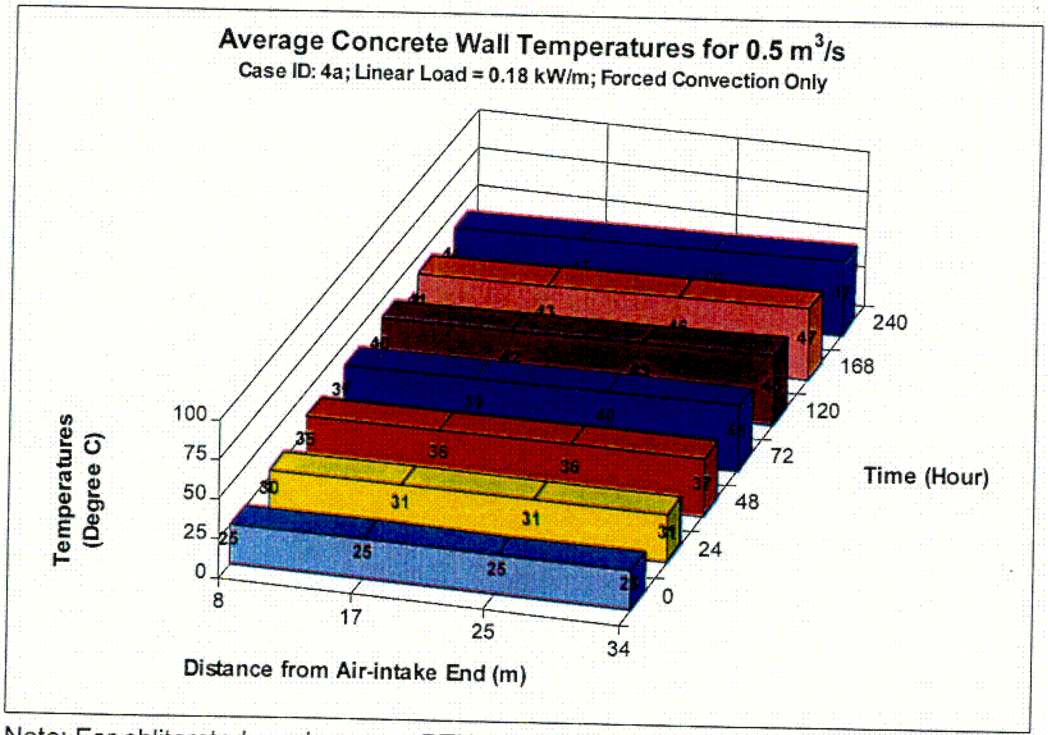
Figure 6-71. Predicted Average Temperatures in Segment No. 4 for Case 3aa

C41



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

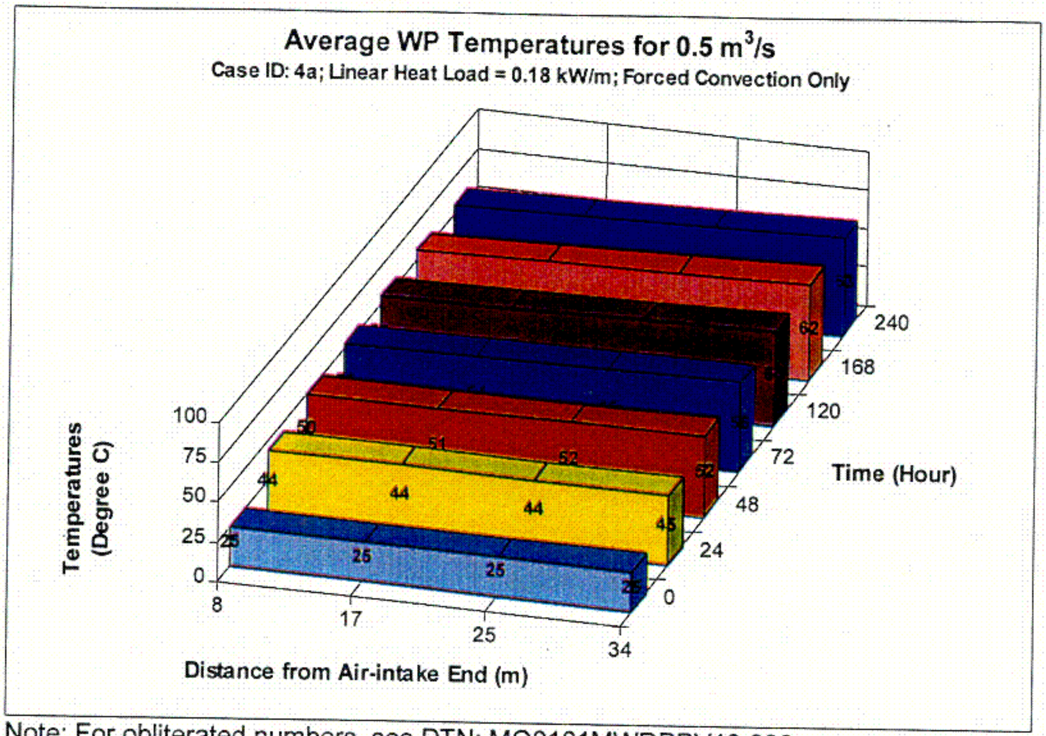
Figure 6-72. Predicted Air Temperatures for Case 4a



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

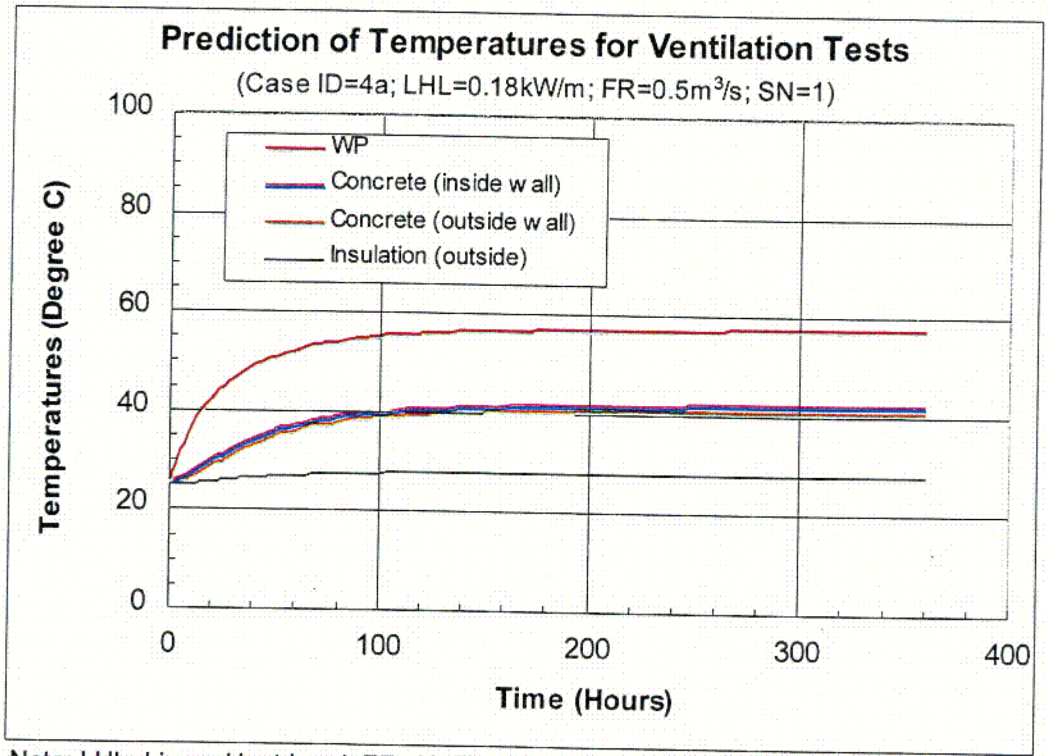
Figure 6-73. Predicted Concrete Inside Wall Temperatures for Case 4a

C42



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

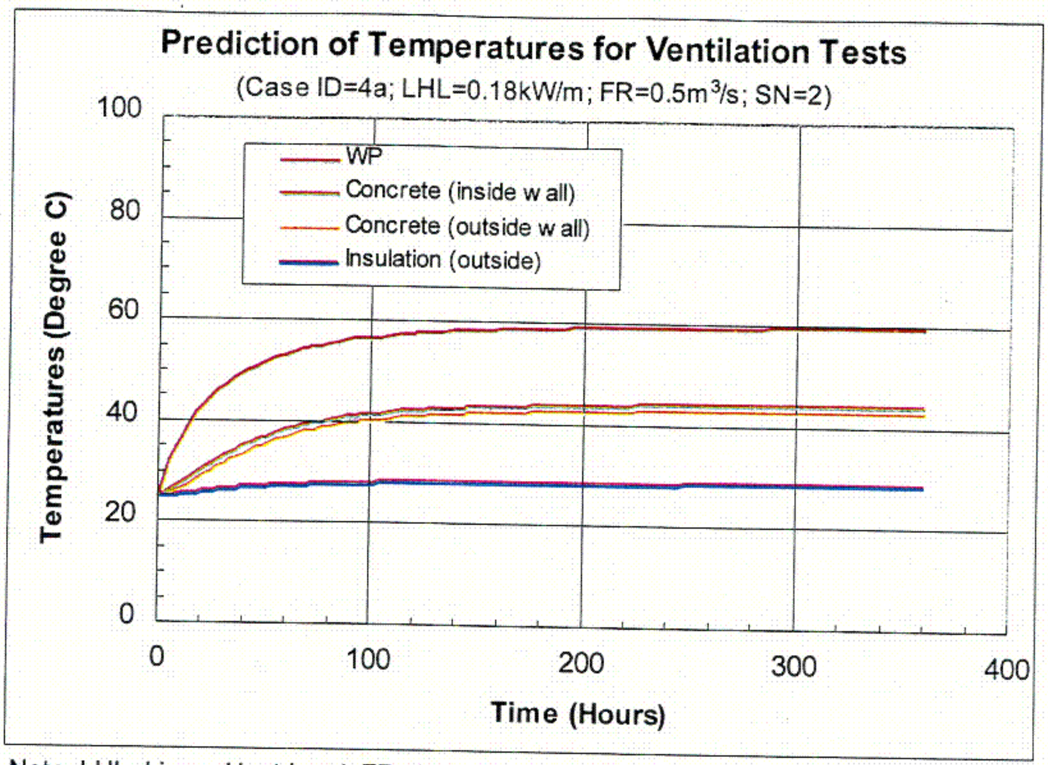
Figure 6-74. Predicted Waste Package Surface Temperatures for Case 4a



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

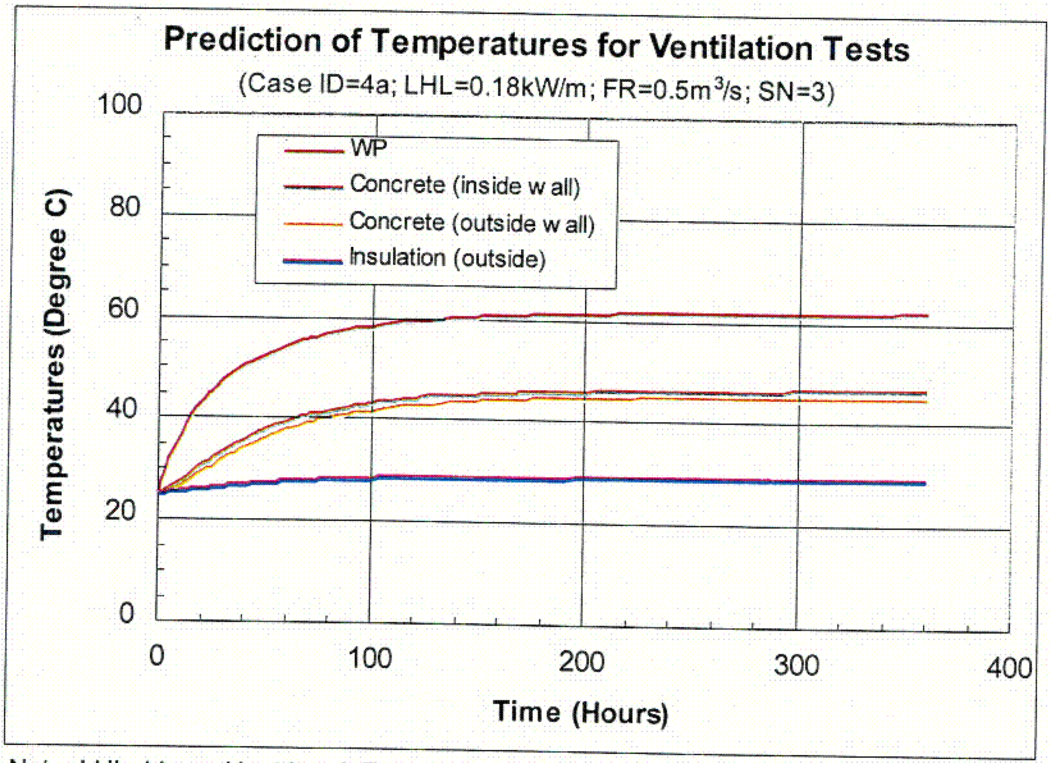
Figure 6-75. Predicted Average Temperatures in Segment No. 1 for Case 4a

C43



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

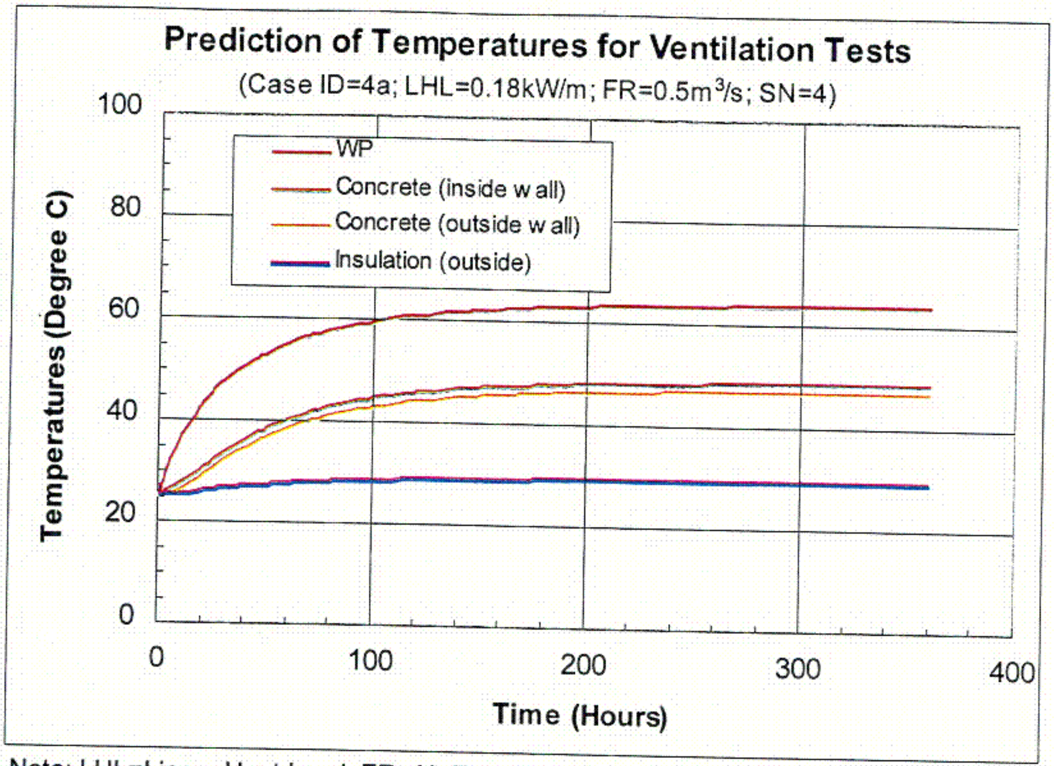
Figure 6-76. Predicted Average Temperatures in Segment No. 2 for Case 4a



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

Figure 6-77. Predicted Average Temperatures in Segment No. 3 for Case 4a

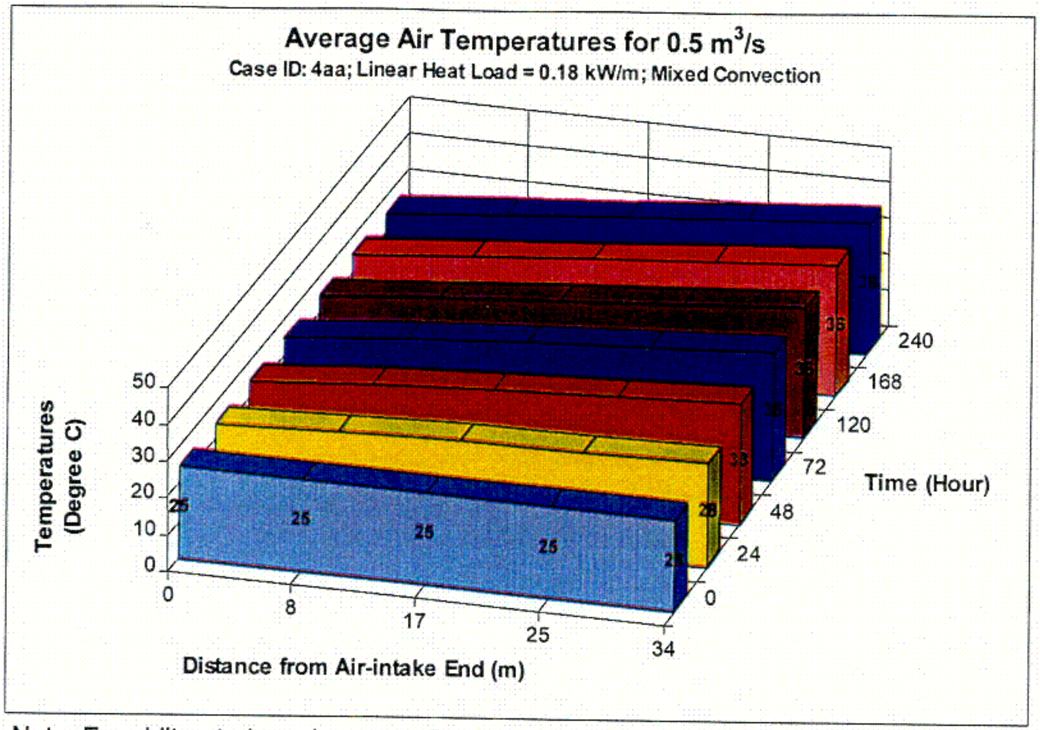
C44



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

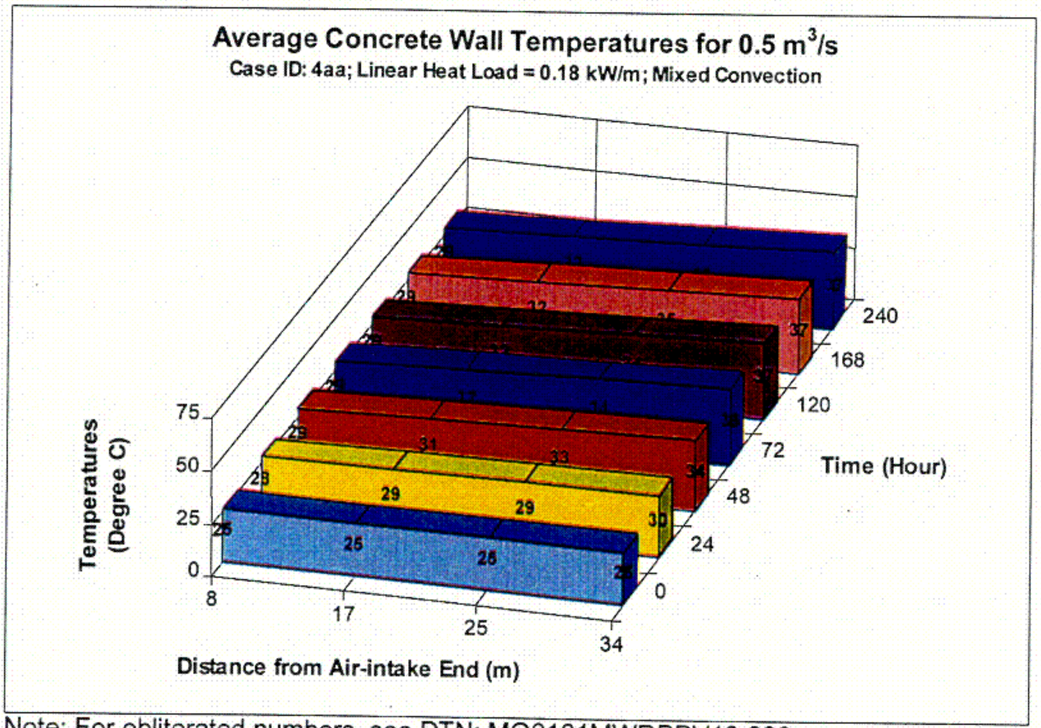
Figure 6-78. Predicted Average Temperatures in Segment No. 4 for Case 4a

C45



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

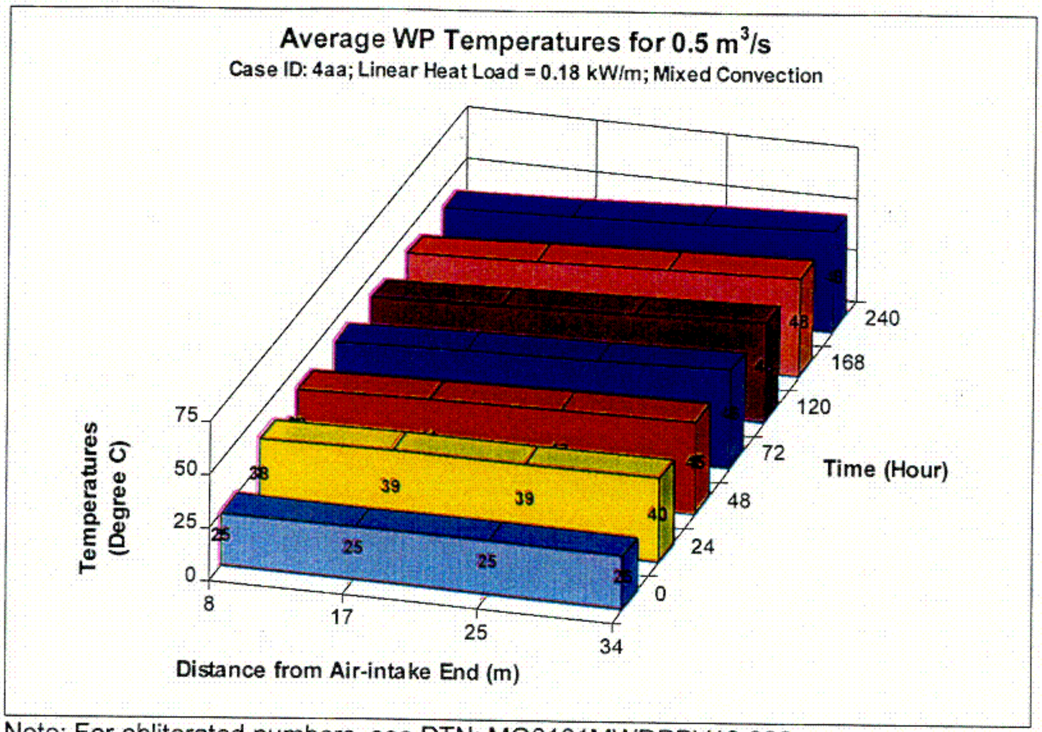
Figure 6-79. Predicted Air Temperatures for Case 4aa



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

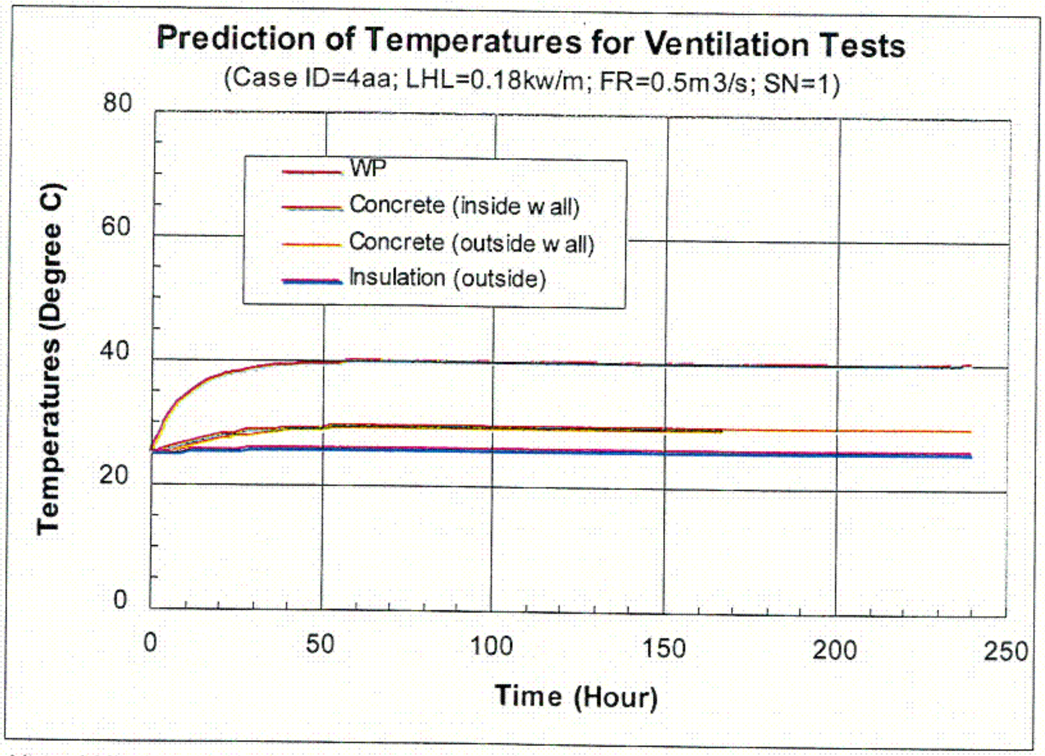
Figure 6-80. Predicted Concrete Inside Wall Temperatures for Case 4aa

C46



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

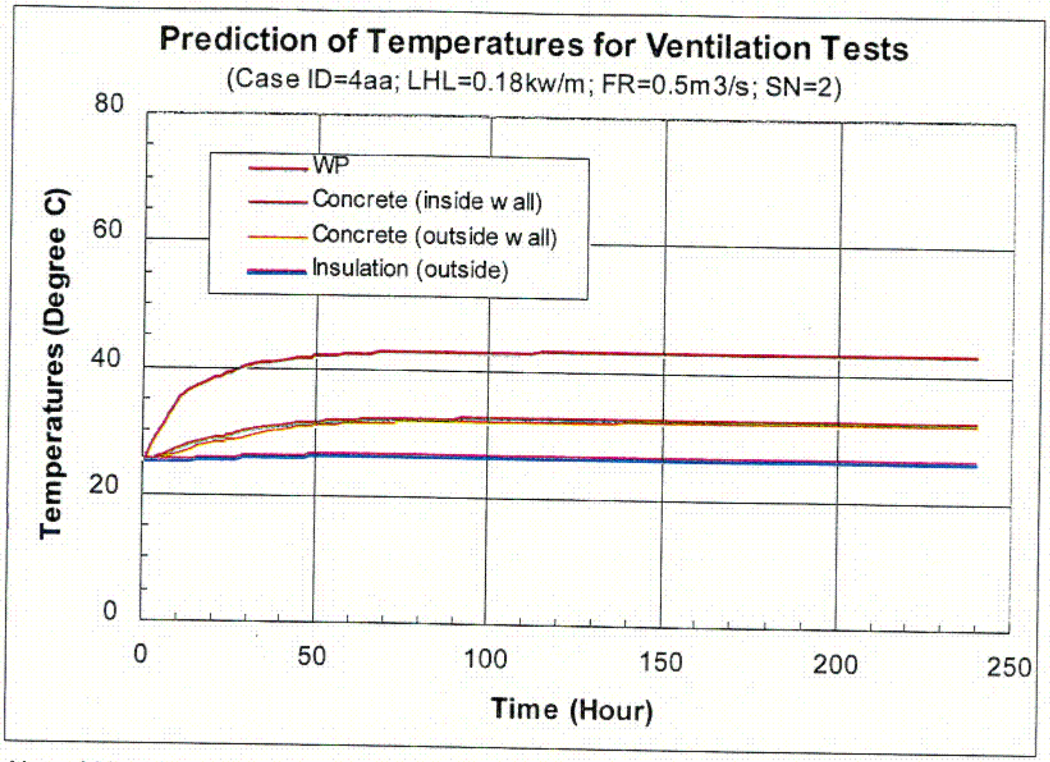
Figure 6-81. Predicted Waste Package Surface Temperatures for Case 4aa



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

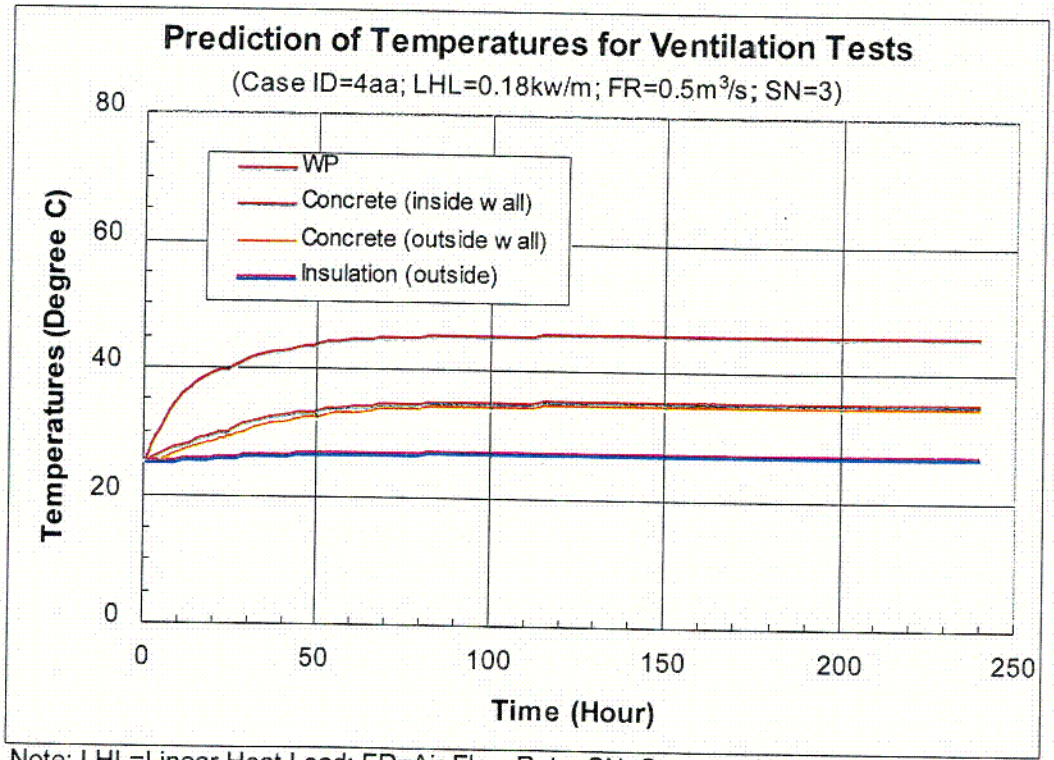
Figure 6-82. Predicted Average Temperatures in Segment No. 1 for Case 4aa

C47



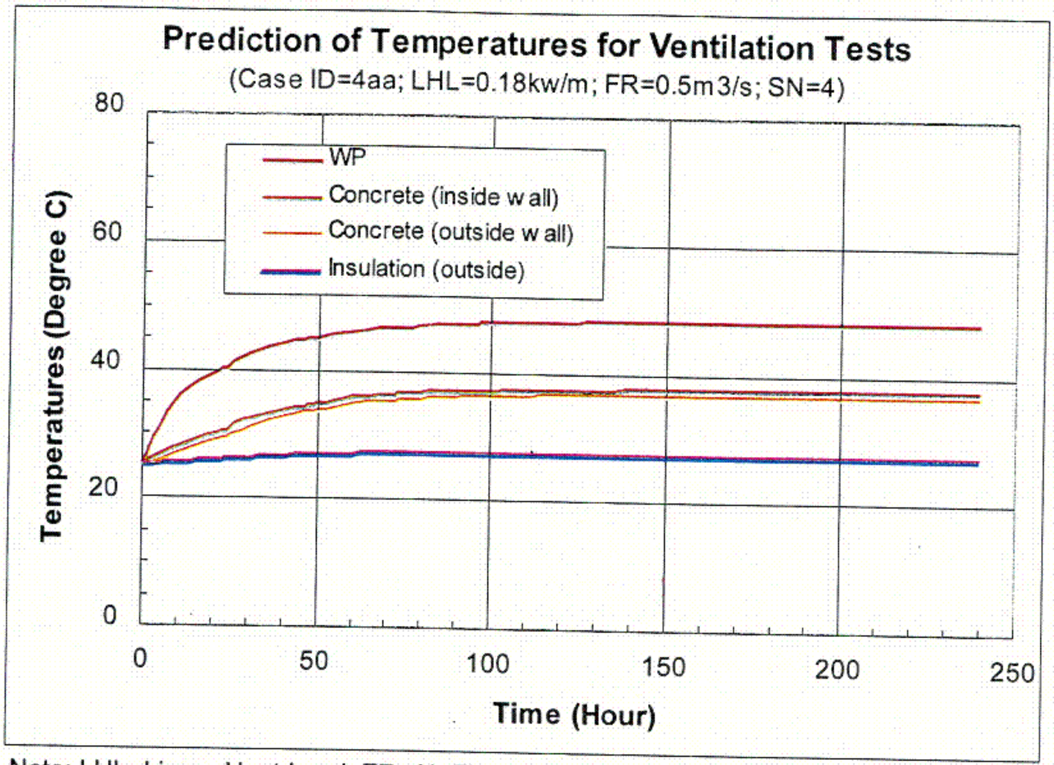
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-83. Predicted Average Temperatures in Segment No. 2 for Case 4aa



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

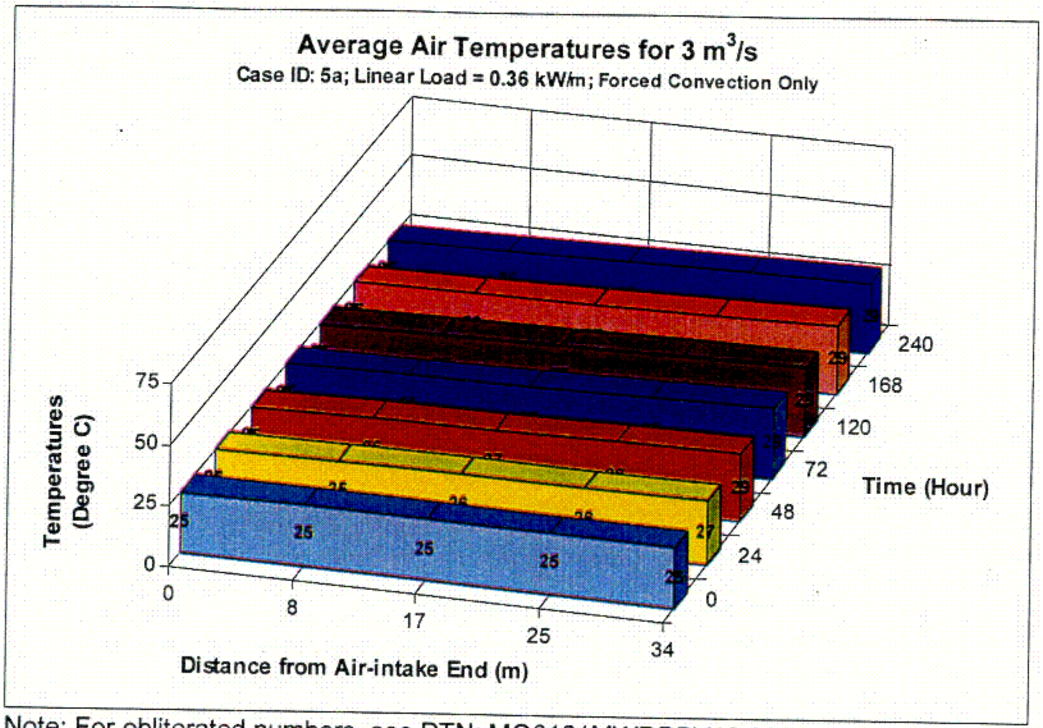
Figure 6-84. Predicted Average Temperatures in Segment No. 3 for Case 4aa



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

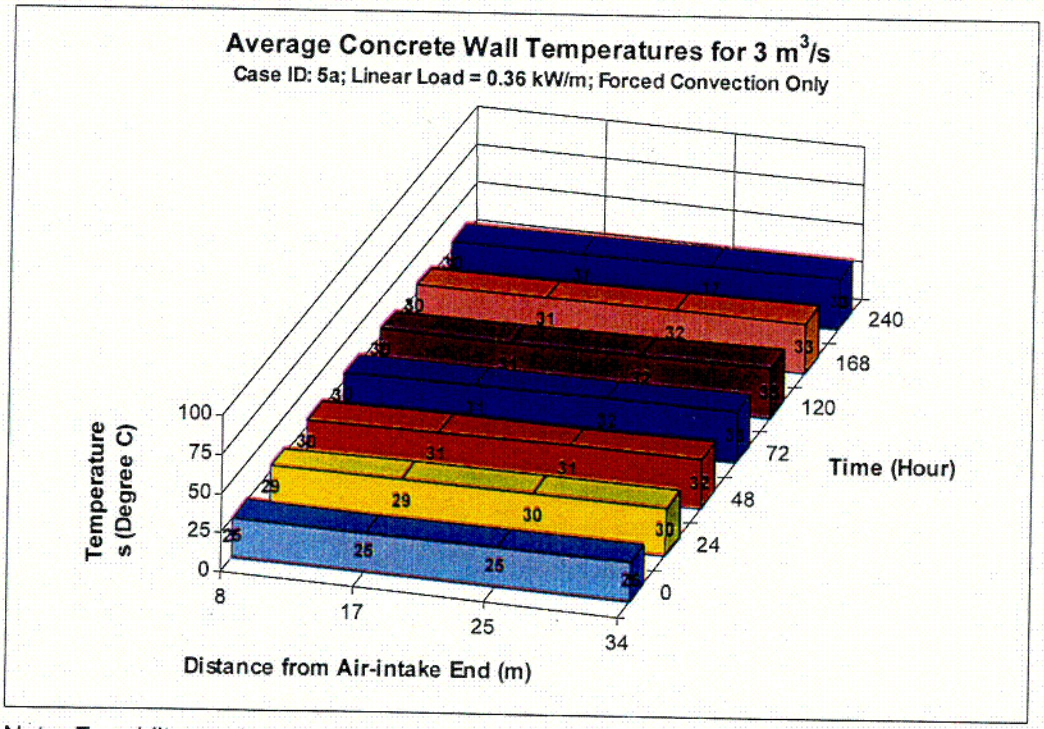
Figure 6-85. Predicted Average Temperatures in Segment No. 4 for Case 4aa

C49



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

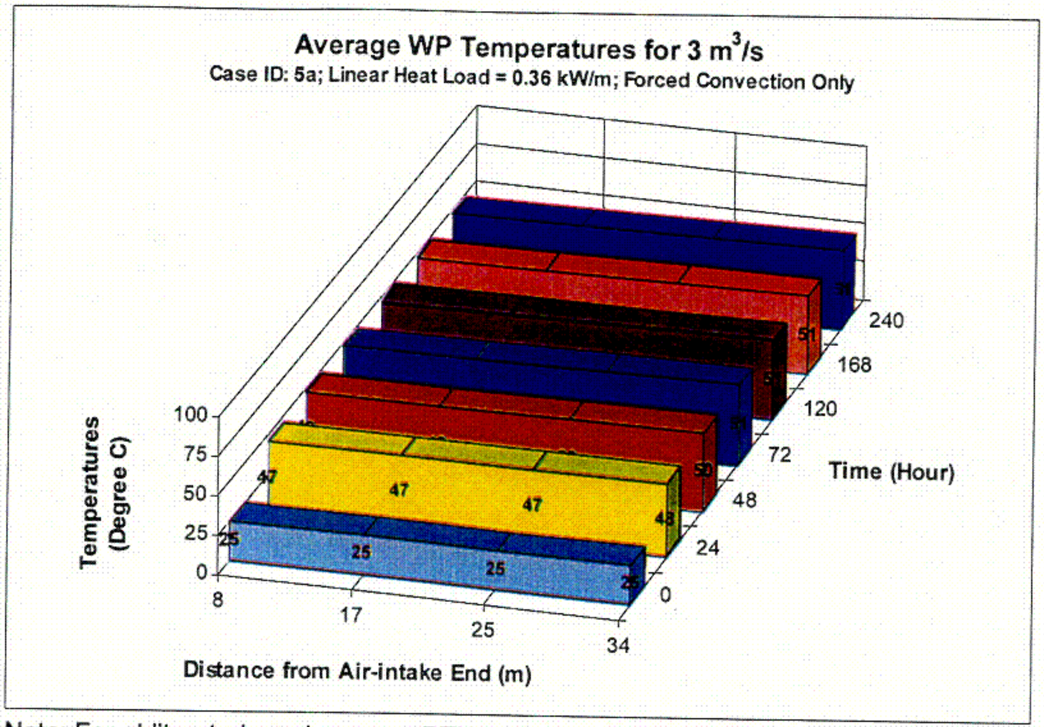
Figure 6-86. Predicted Air Temperatures for Case 5a



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

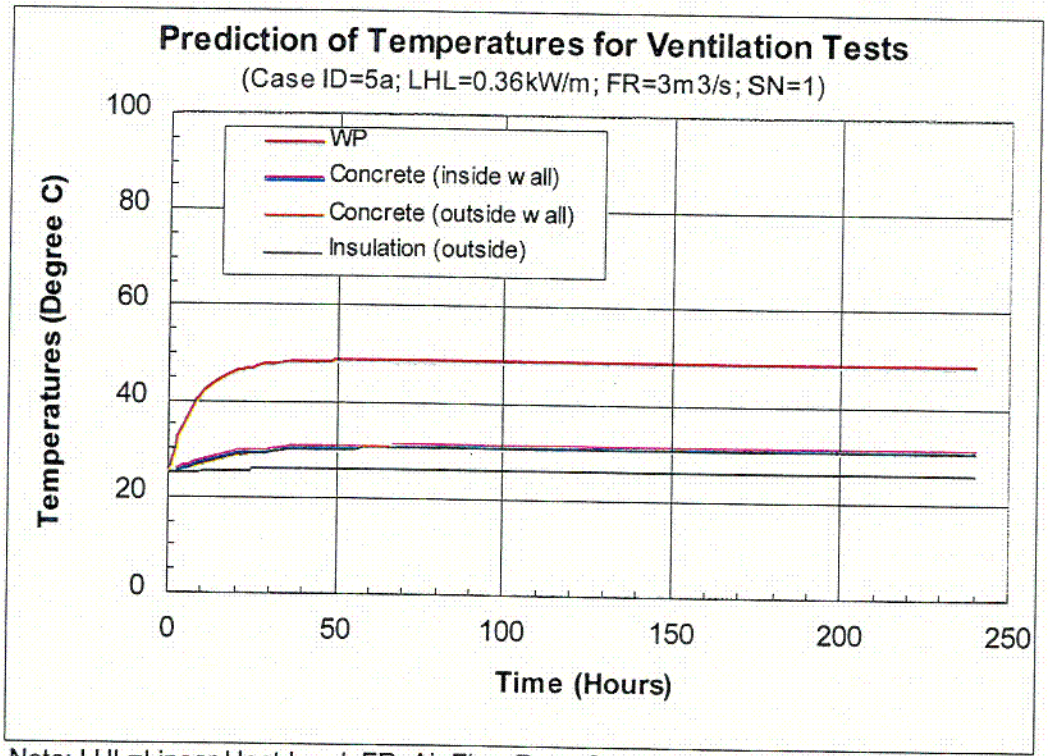
Figure 6-87. Predicted Concrete Inside Wall Temperatures for Case 5a

C50



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

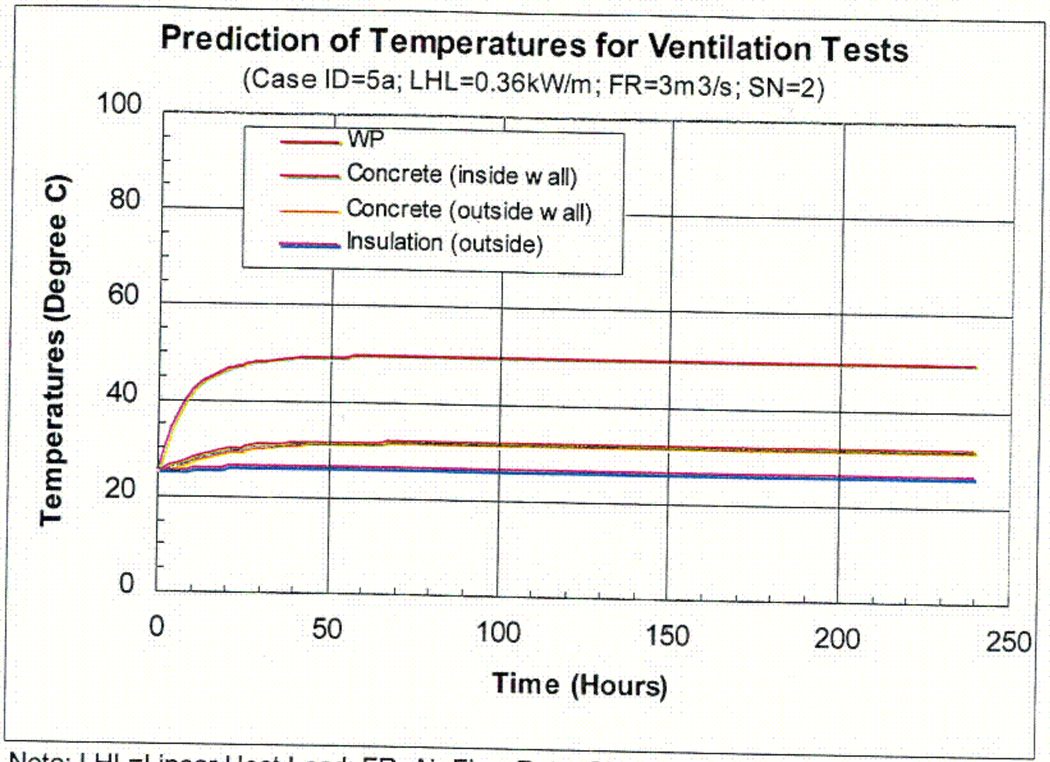
Figure 6-88. Predicted Waste Package Surface Temperatures for Case 5a



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

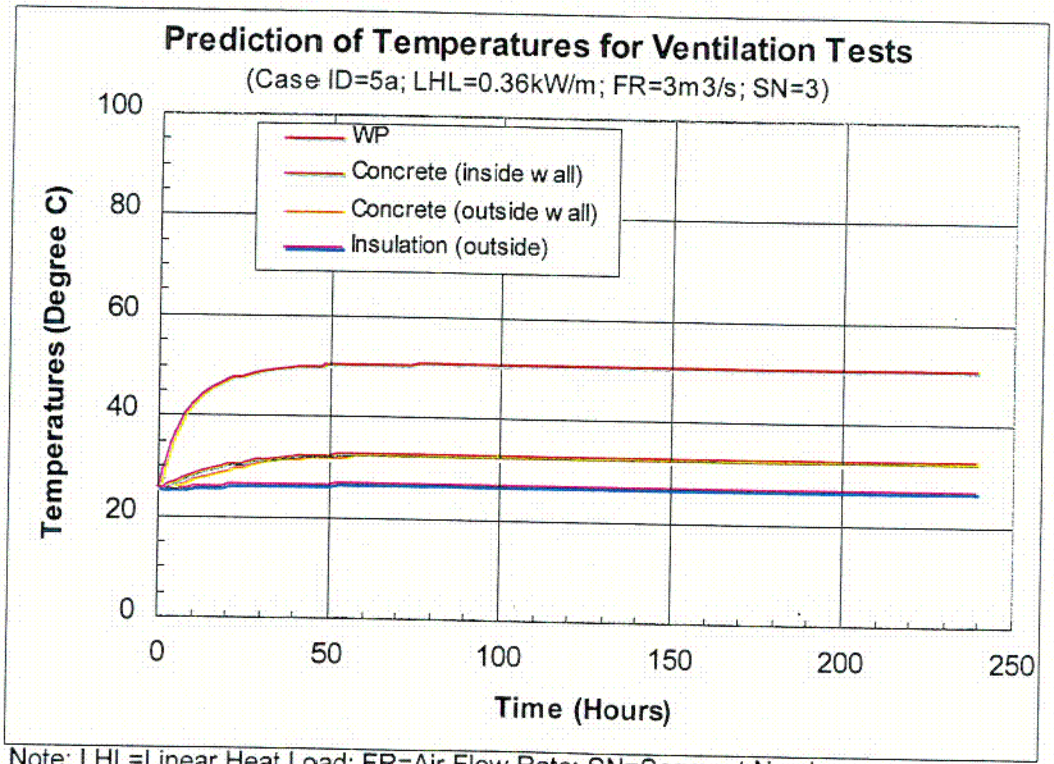
Figure 6-89. Predicted Average Temperatures in Segment No. 1 for Case 5a

C51



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

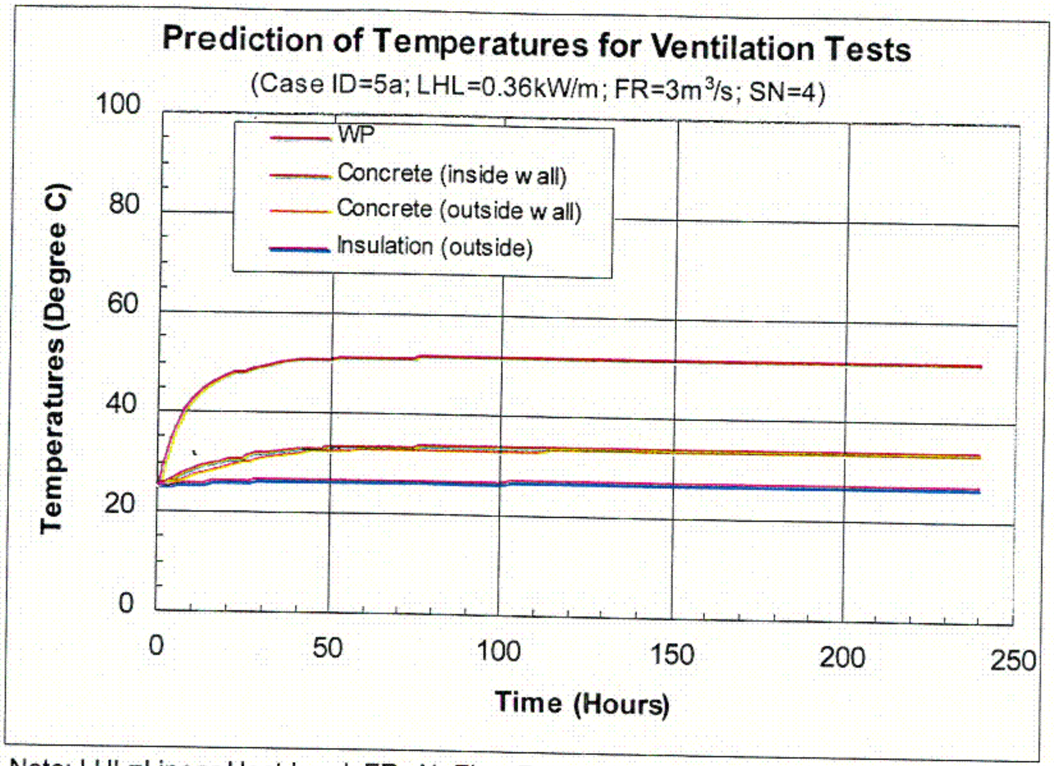
Figure 6-90. Predicted Average Temperatures in Segment No. 2 for Case 5a



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

Figure 6-91. Predicted Average Temperatures in Segment No. 3 for Case 5a

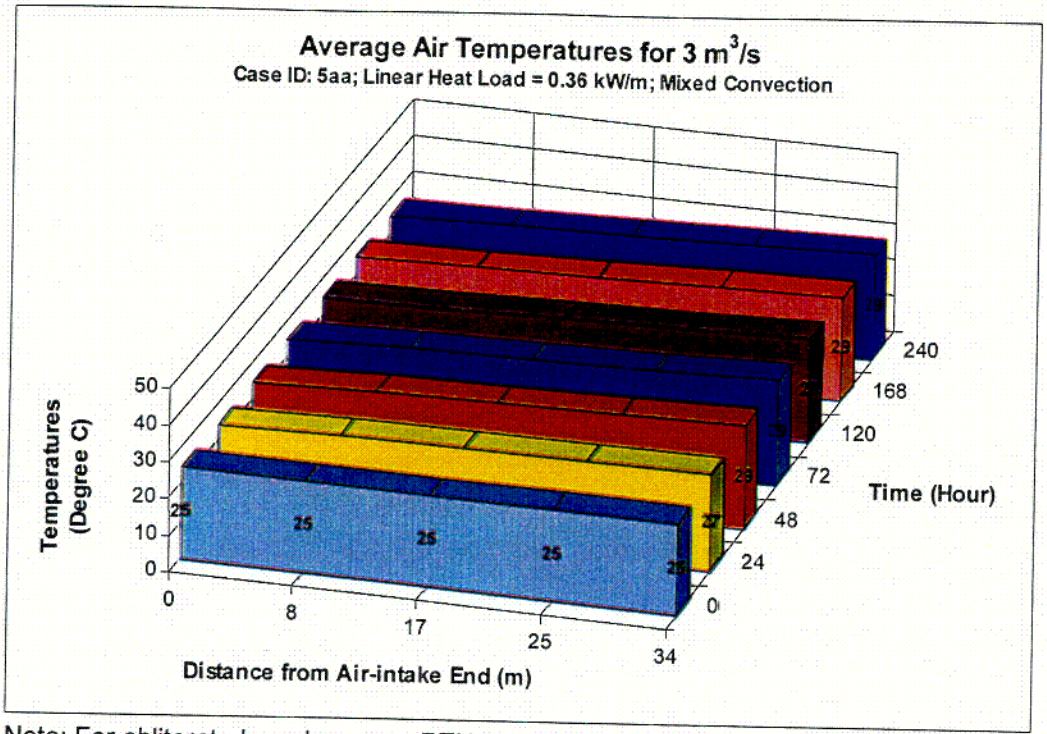
C52



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

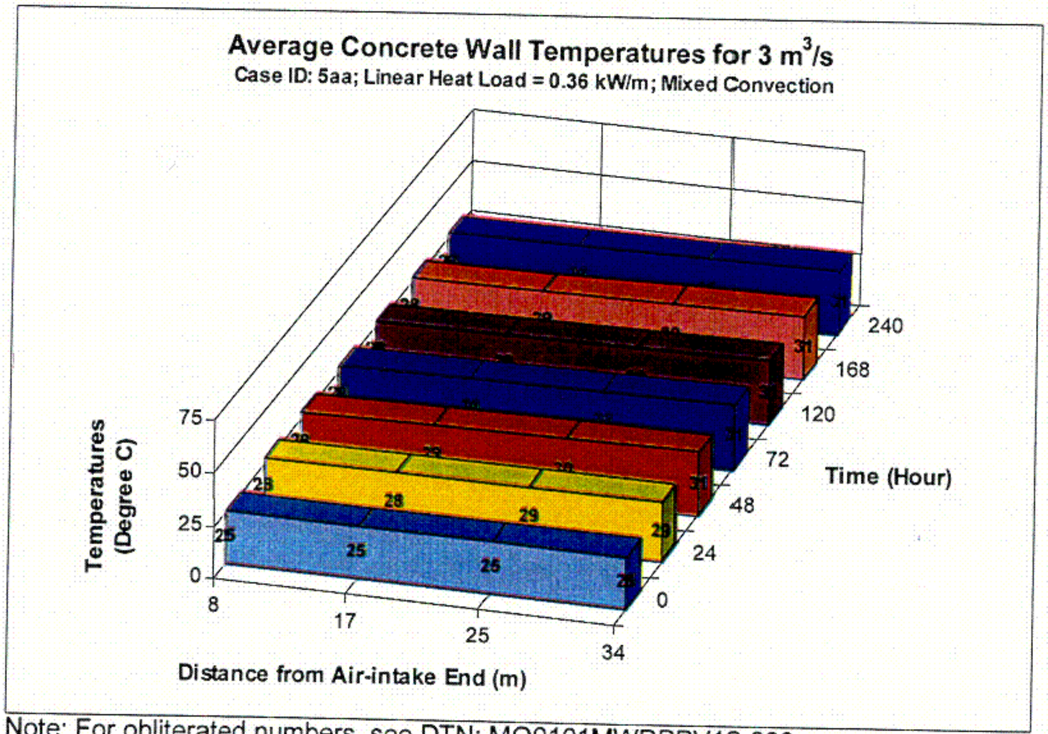
Figure 6-92. Predicted Average Temperatures in Segment No. 4 for Case 5a

C53



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

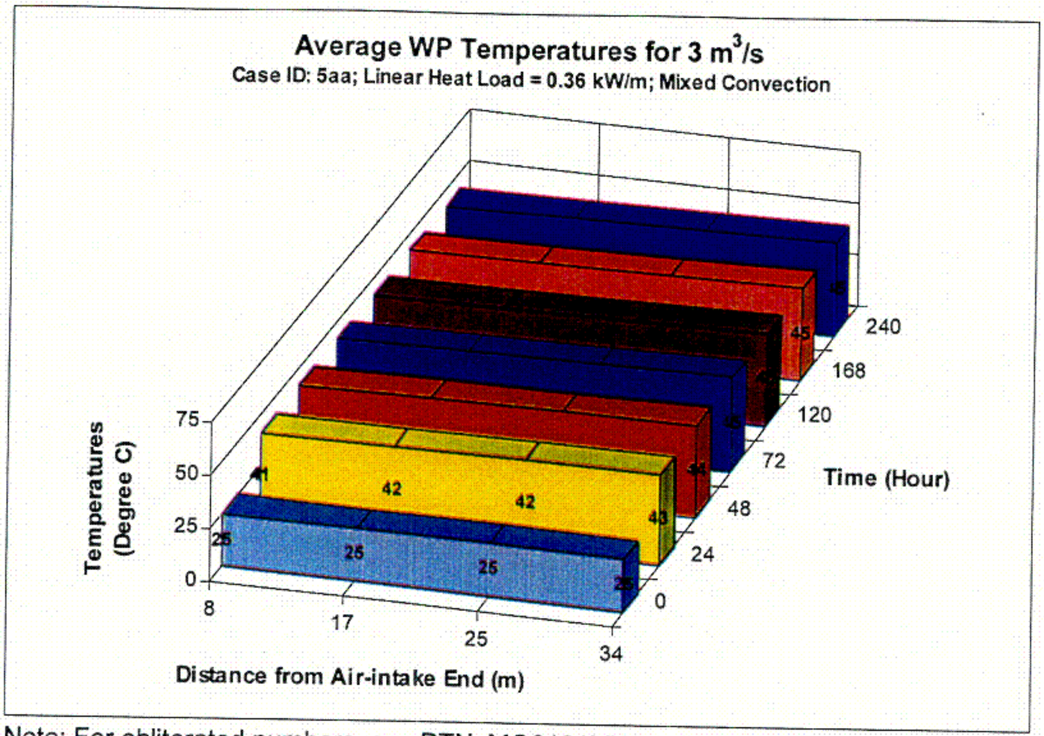
Figure 6-93. Predicted Air Temperatures for Case 5aa



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

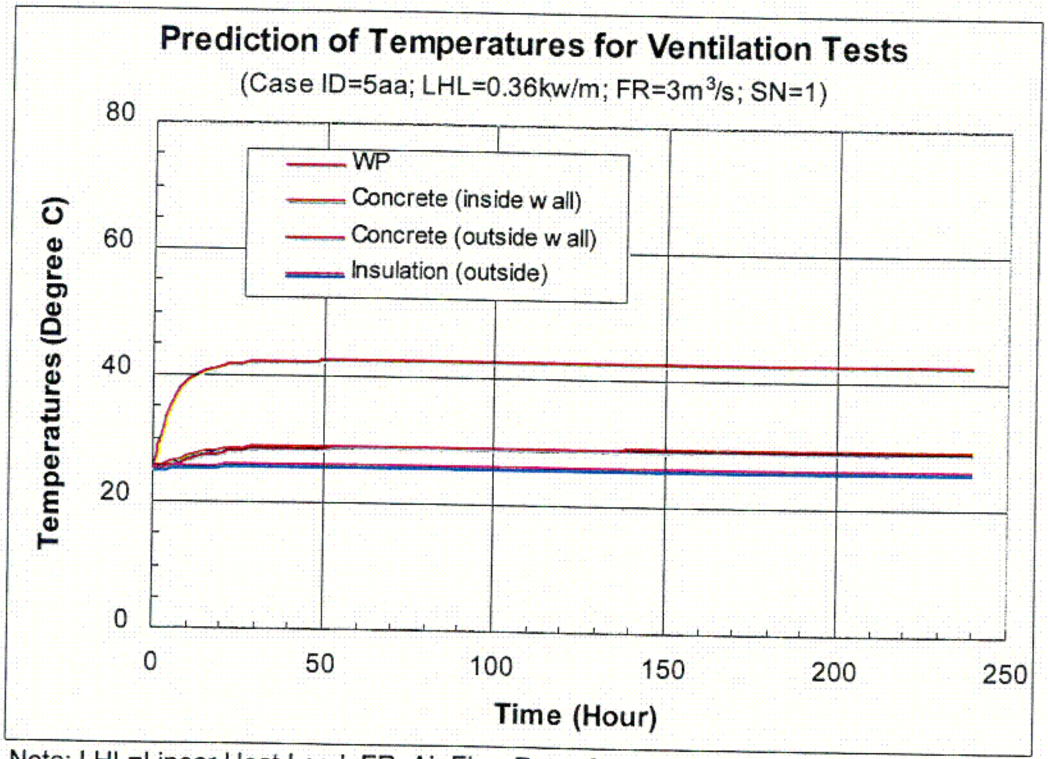
Figure 6-94. Predicted Concrete Inside Wall Temperatures for Case 5aa

C54



Note: For obliterated numbers, see DTN: MO0101MWDPPV13.006.

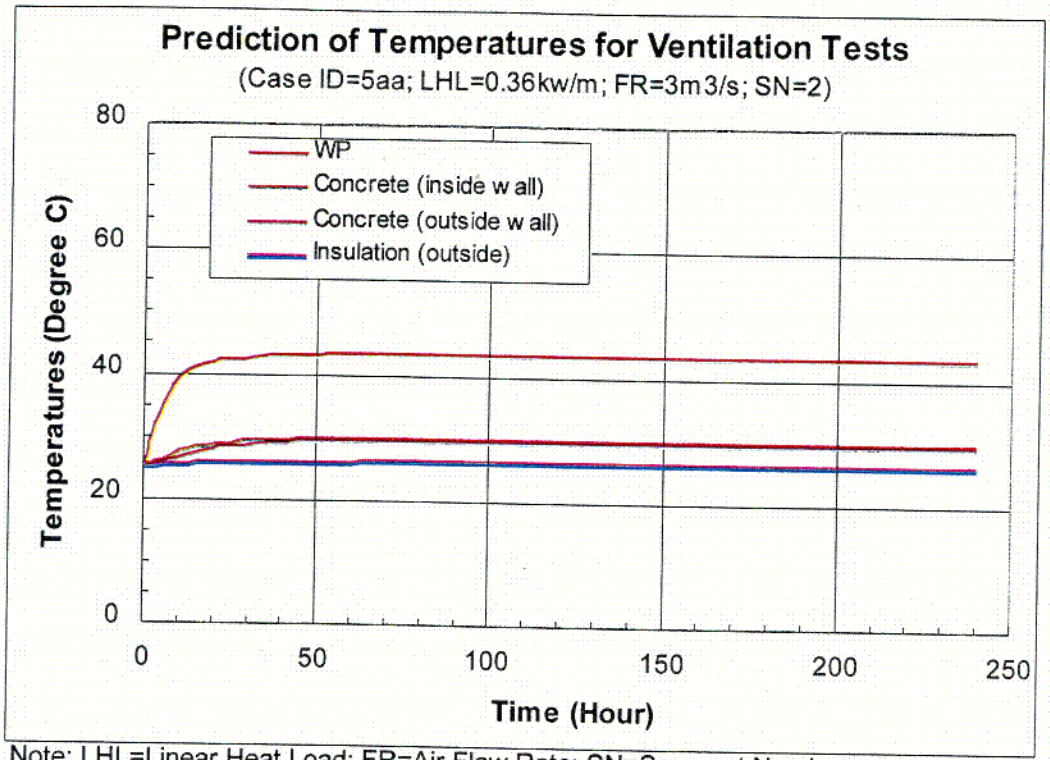
Figure 6-95. Predicted Waste Package Surface Temperatures for Case 5aa



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

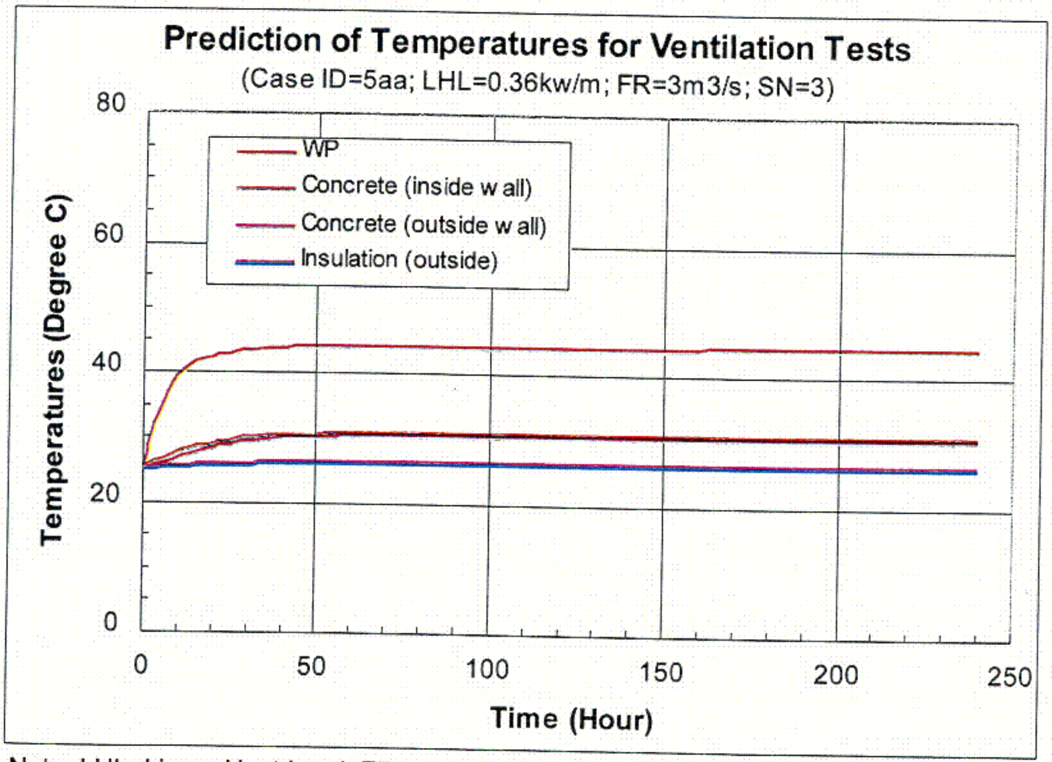
Figure 6-96. Predicted Average Temperatures in Segment No. 1 for Case 5aa

C55



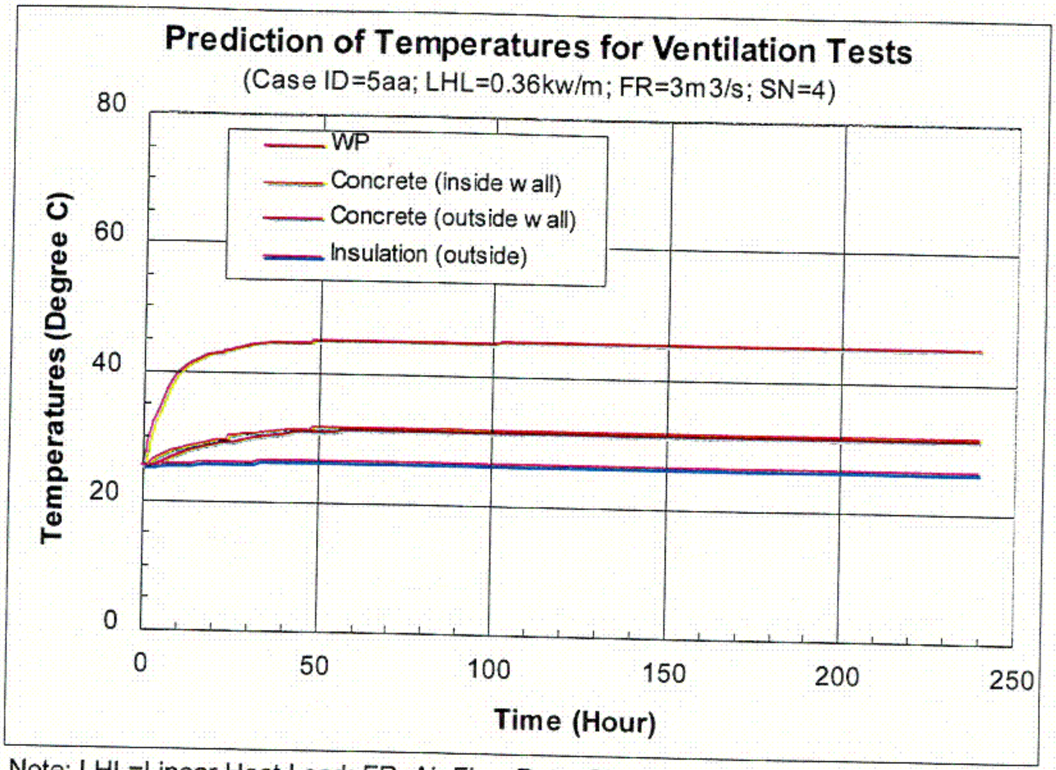
Note: LHL=Linear Heat Load; FR=Air Flow Rate; SN=Segment Number.

Figure 6-97. Predicted Average Temperatures in Segment No. 2 for Case 5aa



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

Figure 6-98. Predicted Average Temperatures in Segment No. 3 for Case 5aa



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

Figure 6-99. Predicted Average Temperatures in Segment No. 4 for Case 5aa

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7.3 SOURCE DATA

None.

7.4 OUTPUT DATA

MO0101MWDPPV13.006. Input and Output Files for Pretest Predictions for Ventilation Tests. Submittal date: 01/02/2001.