PASSIVE HEAT TRANSPORT IN ADVANCED CANDU CONTAINMENT

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ABSTRACT

A passive CANDU containment design has been proposed to provide the necessary heat removal following a postulated accident to maintain containment integrity. To study its feasibility and to optimize the design, multi-dimensional containment modelling may be required. This paper presents a comparison of two CFD codes, GOTHIC and PHOENICS, for multi-dimensional containment analysis and gives pressure transient predictions from a lumped-parameter and a three-dimensional GOTHIC model for a modified CANDU-3 containment. GOTHIC proved suitable for multidimensional post-accident containment analysis, as shown by the good agreement with pressure transient predictions from PHOENICS. GOTHIC is, therefore, recommended for passive CANDU containment modelling.

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1. INTRODUCTION

A number of promising concepts have been identified for the passive heat removal following a postulated accident in an advanced CANDU [1]. As part of the overall passive safety concept, the containment system would provide the necessary cooling of the containment atmosphere, and thus limit containment pressure, without the use of active safety systems or operator intervention.

The passive containment design relies on steam condensation as the main mode of heat removal from containment. Therefore it must be shown that free convective steam condensation can provide sufficient heat removal to prevent over-pressurization of the containment shell. The free convective flows may necessitate multi-dimensional flow modelling to predict heat removal rates, gas and temperature distributions and containment pressure. A commercial CFD code, GOTHIC (owned by EPRI), was selected for this program, because it offers multi-dimensional flow modelling in addition to the traditional lumped-parameter containment modelling and is easy to implement for full scale containment modelling. It has a good validation base for lumped-parameter and pressure-driven flows, but has not been used extensively for multi-dimensional, buoyancy driven flows. Therefore, a general-purpose CFD code, PHOENICS (owned by CHAM), was used to compare with GOTHIC results.

This paper presents flow modelling results from GOTHIC and PHOENICS models for a CANDU-3 typical containment, incorporating certain passive containment features. The model geometry is a coarsely-meshed three-dimensional cartesian representation of a modified CANDU-3 typical containment, with enhancements for free-convective gas mixing. The objective of this comparison exercise was flow modelling under natural convective conditions. Although steam condensation is an important heat removal mechanism in containment, PHOENICS cannot readily model condensation on walls with noncondensable gases present. Therefore, steam condensation was not modelled for this comparison exercise. To facilitate direct comparison of results, the break was simulated by a constant-flow, constant-temperature nitrogen source and a constant temperature was applied to the outside walls. The comparison was based on the predicted pressure transient and local temperature and gas concentrations.

2. MODEL DESCRIPTION

Because of differences in the codes, the GOTHIC and PHOENICS discretizations of the CANDU-3 geometry are slightly different and are shown in Figures 1 and 2. GOTHIC can accommodate both subdivided and lumped parameter volumes, resulting in less nodes needed for an adequate representation of the containment than in PHOENICS, which has only one solution domain. Furthermore, GOTHIC uses a simple one- dimensional model for the solid walls, allowing fine subdivisions through the wall, whereas PHOENICS includes wall regions in the overall fluid solution domain, significantly increasing the number of nodes.

The GOTHIC model consists of two subdivided and three lumped volumes, as shown in Figure 1. The accessible area (volume 5) is subdivided into nine cells in both horizontal directions and six vertical levels, resulting in 486 nodes. While volume 5 extends over the entire containment, some of its nodes are blocked to model walls and space occupied by other volumes. The outlet vault and steam generator enclosure are modelled as one subdivided volume (volume 3) with two by three cells horizontally and five vertical levels. The shield tank area, inlet vault and fuel machine maintenance lock are modelled using lumped parameter volumes. Flow connections simulate openings between volumes and wall heat sinks are modelled using 1-D thermal conductors (not shown for clarity). The nitrogen inflow is prescribed through a fixed mass flow rate and temperature entering the outlet vault.

The PHOENICS model consists of a single subdivided volume with 16 by 13 horizontal nodes and six vertical levels as shown in Figure 2. The grid was defined in such a way that nodes are located in the same positions as in the GOTHIC model, allowing direct comparison of nodal values between the two models. Null cells are used to model walls while ceilings are modelled by blocked cell faces. Because openings between cells cannot be specified directly, cell or face porosities are used to prescribe a flow crossectional area, e.g. a door between two rooms. The nitrogen inflow enters the outlet vault with a fixed mass flux, velocity and temperature.

The comparison of the two models was performed under the following conditions, applied in both models: With the containment initially filled with air at STP, the inlet boundary condition used was a constant Nitrogen mass flow of 823 kg/s at 200 °C for 70 s. This mass flow is approximately equal to the time-averaged volumetric flow of vapour from a CANDU-3 break. A constant temperature of 30 °C was prescribed on the outside surface of the outer walls for the duration of the simulations with an initial temperature of 30 °C prescribed for the entire model. Properties of concrete were used for all wall regions in GOTHIC and heat transfer by turbulent convection was modelled using the built-in heat transfer package. Heat transfer to the walls was modelled in PHOENICS using a constant heat transfer coefficient.

Difficulties in model development with PHOENICS necessitated several simplifications, one of which was the use of nitrogen rather than steam. Fluid-to-wall heat transfer correlations for convection and condensation cannot be readily incorporated into the PHOENICS model, whereas they are available in GOTHIC. Although conjugate heat transfer (fluid convection and conduction in solids) is available in PHOENICS to model heat transfer between fluid and solid regions of the model, its activation resulted in erroneous pressure predictions and convergence problems. Furthermore, because the wall regions are part of the solution domain in PHOENICS, they cannot be modeled in detail, without prohibitive computation time penalties. In contrast GOTHIC treats solid walls separately from the fluid solution domain by modelling them as one-dimensional thermal conductors, connected to a cell. Therefore, the heat conduction in the walls can be modelled in more detail. In this program PHOENICS was used to verify that GOTHIC predicts reasonable fluid velocity, temperature and concentration fields in a three-dimensional containment model during and shortly after a mass-inflow transient, because PHOENICS has a much larger validation base for multidimensional fluid flow modelling than GOTHIC.

2.1 PHOENICS Model

PHOENICS solves the discretized equivalent of sets of differential equations which are, for single-phase flow, of the general form [2]:

$$\frac{\partial(\rho\varphi)}{\partial t} + \mathrm{div}\,(\rho v\varphi - \rho\Gamma_{\varphi}\mathrm{grad}\varphi) = S \qquad (1)$$

where t is time,
ρ is the density,
Φ is any conserved property, such as enthalpy,
V_{Φ} is the velocity vector;
Γ_{Φ} is the diffusion exchange coefficient of Φ, and
S is the source term for Φ.

The mass continuity equation is derived from (1) when Φ is set to unity.

The solution variables in the PHOENICS model were limited to the pressure, velocity, enthalpy and concentration in the fluid domain of the containment model. All terms of the governing transport equations were solved, except for the mass diffusion term. Mass diffusion is currently not included in GOTHIC, and therefore was also neglected in the PHOENICS model for this comparison. The whole-field solution method was used for all scalar variables, and underrelaxation was employed for all variables, to aid convergence. The ideal-gas approximation was used for property calculations for the compressible gas. The effect of gravity was simulated with a constant force field, resulting in a downward-directed momentum source proportional to the cell mass. Cell porosities were imposed to conserve the total free volume of the containment (39 100 m^3) and the free volumes of individual rooms. The flow was assumed to be laminar with wall friction on all solid surfaces (walls and ceilings). A PHOENICS simulation was performed at 1-s time steps for 500 s. Good convergence was obtained in the calculations.

2.2 GOTHIC Model

GOTHIC solves the same general equation as PHOENICS, equation (1), in cartesian coordinates for the mass balance of four phases (steam, liquid, drops and ice) and for each noncondensable gas component. Energy and momentum conservation equations are solved for three fluid phases, vapour (steam and gases), liquid and drops.

GOTHIC has many built-in features directly applicable to containment analysis, such as wall heat transfer correlations for convection and condensation [3], separate modelling of thermal conductors allowing surface area and thickness specification independent of the fluid modelling geometry, and empirical loss coefficients for flow connections. These features make GOTHIC more flexible than PHOENICS in modelling containments. For example, the heat transfer to internal structures or the flow through doorways can be defined without changing the solution domain geometry to include the physical dimensions of internal structures or doors. For this comparison, the internal structures were not modelled as heat sinks, but their contribution to cell volume decrease was included. Whereas cell and face porosities were employed in PHOENICS to accomplish this, in GOTHIC the volumes of the lumped parameter nodes and flow areas through doors were specified. In the subdivided volumes, the flow restriction effect of internal structures was accounted for by reducing cell-to-cell flow areas accordingly. In the GOTHIC model, heat transfer between the gas and the concrete walls was by natural convection. There is no user control over the solution procedure, variable relaxation and time step. GOTHIC automatically ensures convergence and adjusts the time step accordingly; typical maximum time step in this simulation was 0.1 second.

3. MODELLING RESULTS FROM GOTHIC/PHOENICS COMPARISON

The results from the GOTHIC and PHOENICS simulations are compared on the basis of predicted overall containment pressure, and the predicted velocity, temperature and concentration fields at various times. Figure 3 shows the absolute pressure transients predicted by PHOENICS and GOTHIC. In GOTHIC the built-in heat transfer package calculates the heat transfer to the walls using the maximum heat transfer coefficient from turbulent forced and turbulent free convection. Turbulent forced convection is calculated using the Dittus-Boelter correlation [4] and turbulent natural convection is given by McAdams [5]. Two PHOENICS simulations were performed, one without any heat transfer to the walls (h=0) and one with a constant heat transfer coefficient of 50 $W/(m^2 \cdot K)$ (h=50), a heat transfer coefficient approximately equal to the one resulting from the GOTHIC heat transfer package. Predicted peak pressure is marginally higher with the GOTHIC model and a similar pressure decrease is predicted by both models which account for heat transfer to the containment walls. Since pressure is a measure of the overall energy content of the containment, good agreement between GOTHIC and PHOENICS for overall containment pressure, as shown here, is necessary before any further comparisons.

Figure 4 shows the gas concentration (of the incoming nitrogen) from the three models at three elevations in the containment. GOTHIC predicts a well mixed atmosphere shortly after the end of the break, while both PHOENICS models show more stratified conditions. Without wall heat transfer the atmosphere remains stratified (solid curves) with high nitrogen concentrations near the top of the containment. However, with heat transfer to the containment walls (dotted curves) convective currents are induced, promoting gas mixing resulting in a well mixed atmosphere at the end of the transient simulation. This demonstrates the effect of heat transfer on gas mixing. The final nitrogen concentration under well-mixed conditions are similar with GOTHIC and PHOENICS, as would be expected from an overall mass balance.

The temperature predictions are significantly different in GOTHIC and PHOENICS, as shown in Figure 5. GOTHIC predicts a peak temperature of 210 °C, while PHOENICS shows over 250 °C near the top of the containment. The temperature distributions are also much more stratified in the PHOENICS models. A comparison of velocity fields showed that, in general, GOTHIC predicts higher velocities, and thus more convective mixing, throughout the simulation.

4. CONCLUSION

GOTHIC proved to be much more suitable for post accident containment analysis than PHOENICS; it has a better user interface resulting in shorter model setup time. Important physical phenomena, such as steam condensation with noncondensable gases, can be easily incorporated into this containment model to make it more realistic. GOTHIC has a good validation base for containment analysis (lumped parameter) and many built-in models (gas properties, heat transfer correlations, hydrogen burning (planned)). However, the generation of the grid for a subdivided volume is time consuming and changes cannot be implemented easily.

This study showed that PHOENICS is not well suited for post-accident containment analysis. Although it has capabilities for modelling two-phase flow, multiple gases and conjugate (fluid to solid) heat transfer, it cannot model condensation heat transfer to walls in the presence of noncondensable gases. It has, however, some advantages over GOTHIC, namely direct control over solution process, time-step, relaxation, etc., easier setup and change of modeling geometry (grid refinement), better vector and contour plots (postprocessor), and turbulence (k-epsilon) and combustion capabilities.

Validation of GOTHIC for three-dimensional containment modeling has been performed against a similar PHOENICS model. From the good agreement of the results (except for the stratification in PHOENICS vs. good mixing in GOTHIC) with a simplified PHOENICS 3-D model it can be concluded that GOTHIC is suitable for multidimensional modeling of passive CANDU containments. However, the reason for GOTHIC to predict a much more homogeneous atmosphere than PHOENICS needs further investigation.

Because of the long run-times involved in any detailed three-dimensional containment modelling, it is suggested that parametric studies on heat transfer enhancements are done using lumped parameter or one-dimensional models. Once the parameters have been established, a three-dimensional GOTHIC model should be used to provide an estimate on temperature, velocity and concentration fields. This would be necessary to assess possible stratifications and hydrogen pockets inside the containment.

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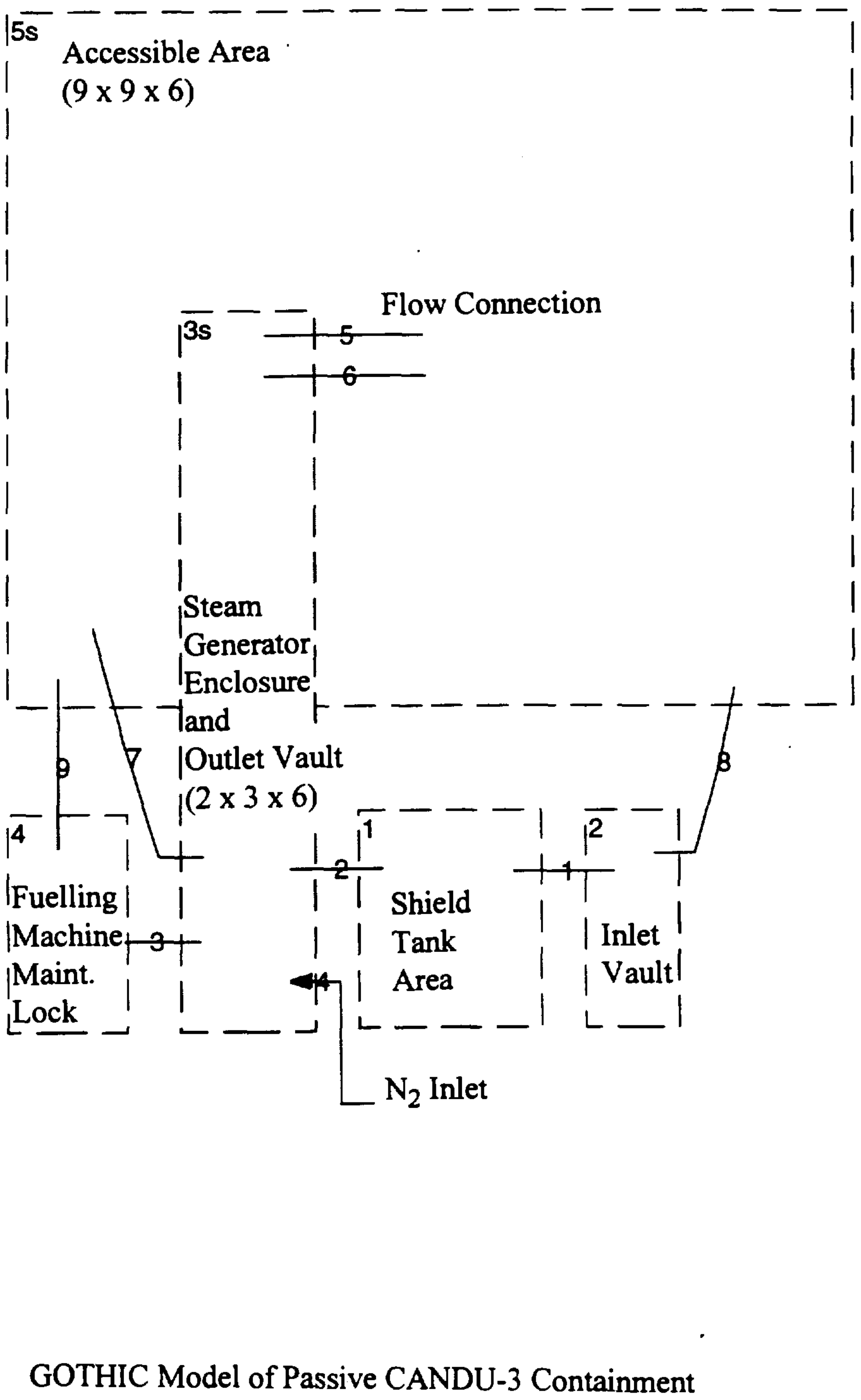

Figure 1: GOTHIC Model of Passive CANDU-3 Containment

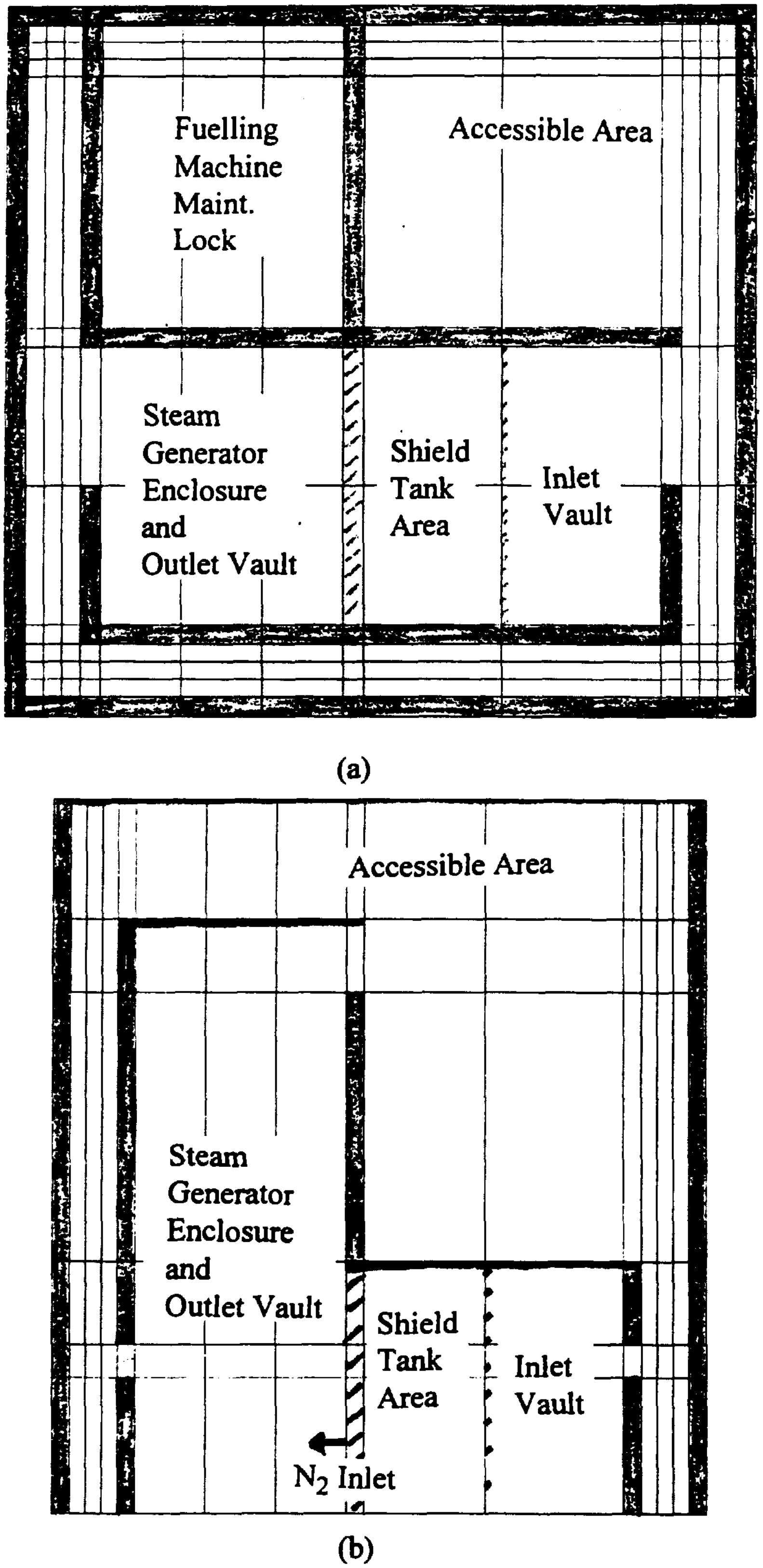

Figure 2: PHOENICS Model of CANDU-3 Containment, (a) plan view, (b) elevation

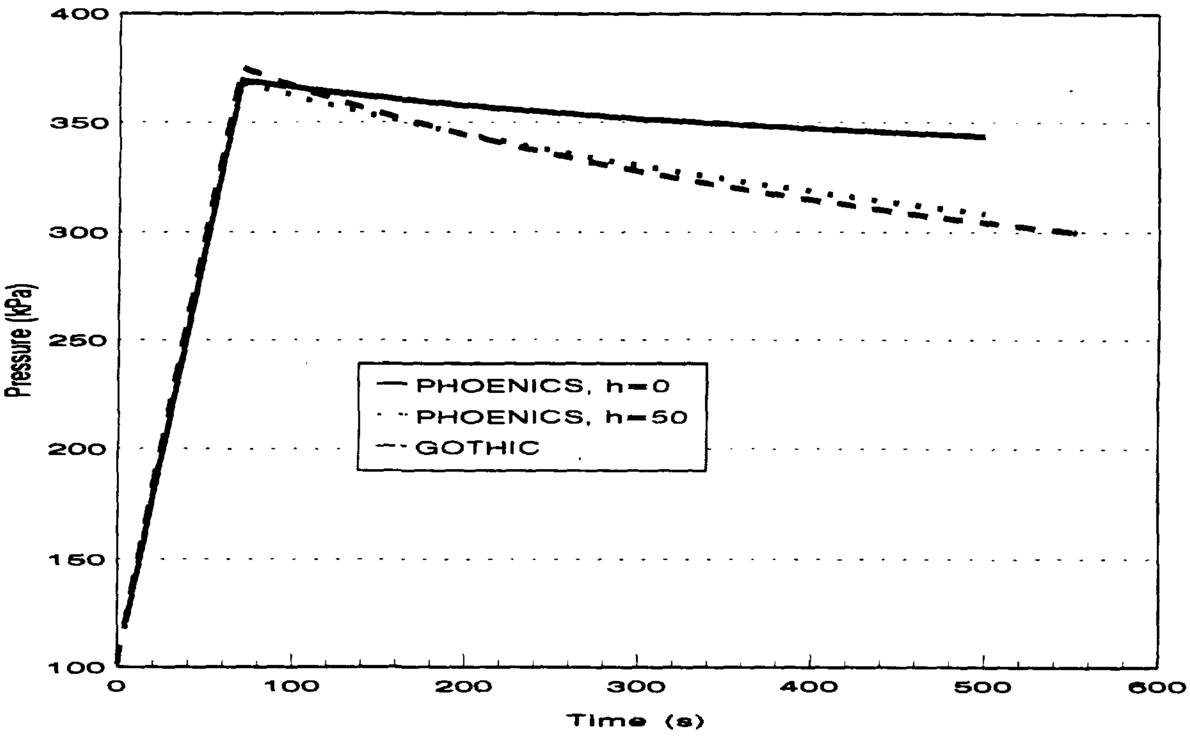

Figure 3: Predicted Pressure Transient Resulting from a Nitrogen Inlet

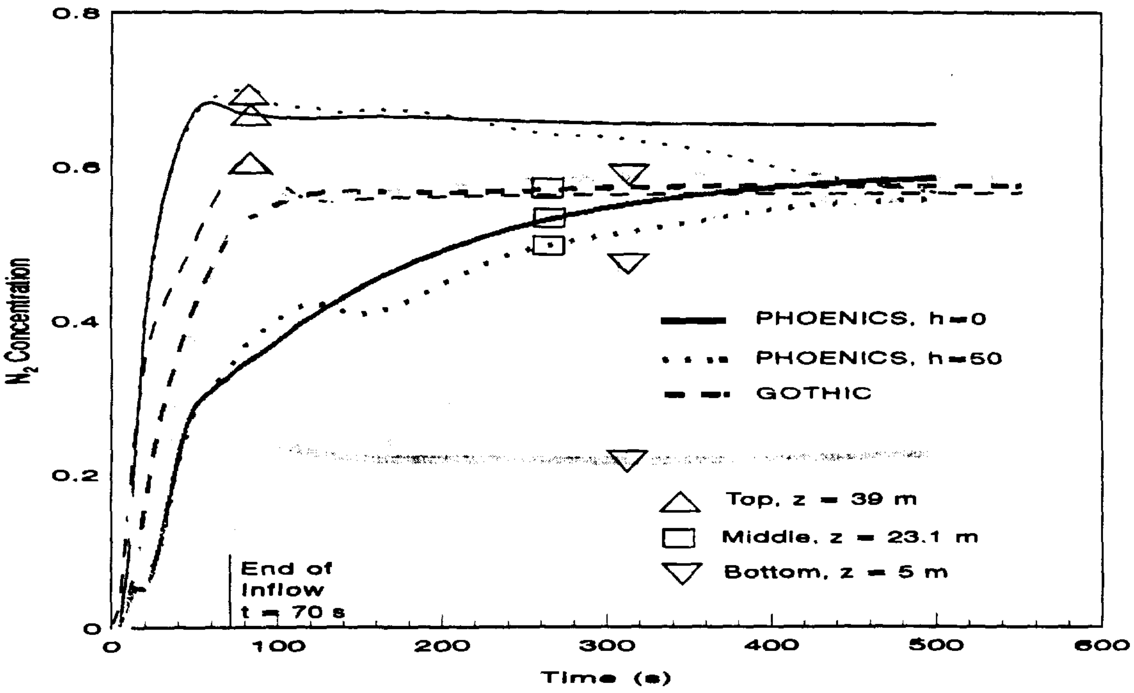

Figure 4: Predicted N_2 Concentration at Three Different Elevations

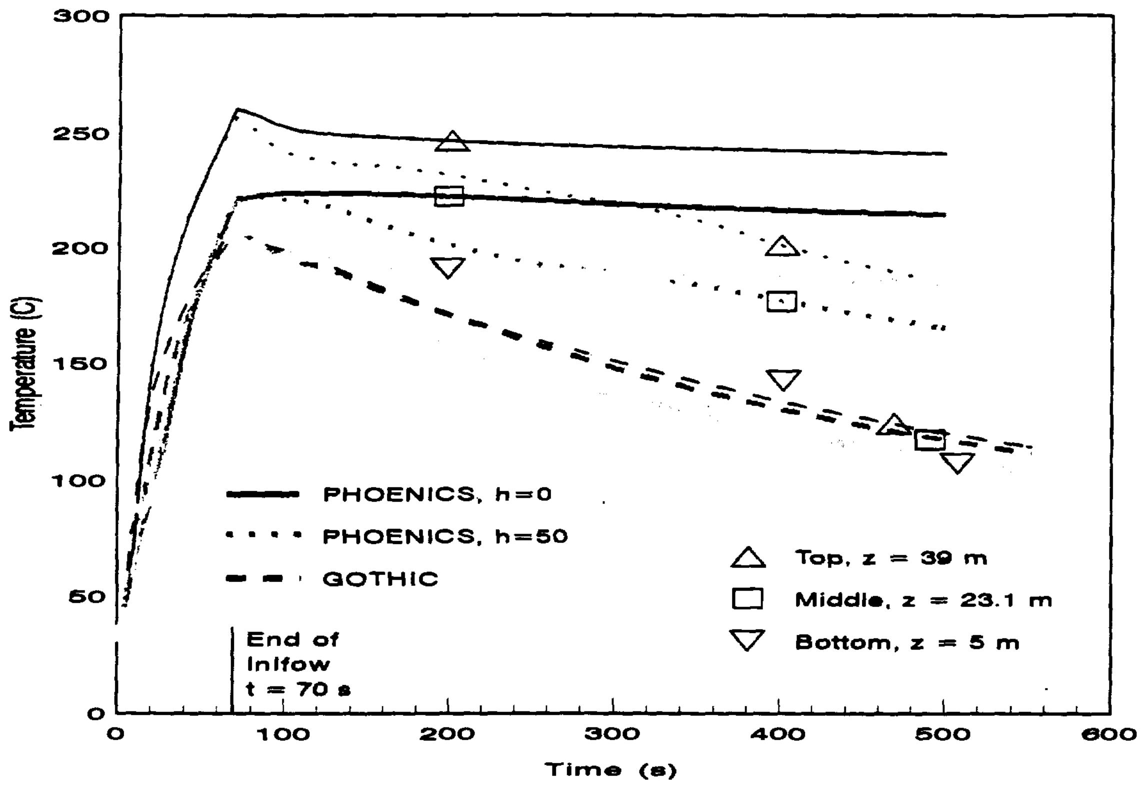

Figure 5: Predicted Temperatures at Three Different Elevations