

A SPATIAL CONVERGENCE STUDY FOR FLOWS AND HYDROGEN DISTRIBUTION IN THE CANDU 6 REACTOR VAULT FOLLOWING A LOSS OF COOLANT ACCIDENT USING THE GOTHIC CONTAINMENT ANALYSIS CODE

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ABSTRACT

During a LOCA (Loss of Coolant Accident) coincident with Loss of Emergency Core Cooling (LOECC) hydrogen can be generated in the fuel channels by the metal water reaction due to fuel channel heat up. The generated hydrogen subsequently flows out of the break and into containment. It is important to predict the ensuing hydrogen concentration in containment in order to identify potential flammable mixtures and to identify locations of possible mitigation devices.

As a starting point, a 3D model of the reactor vault is required to properly capture the thermal hydraulic behaviour in this area especially the predicted flows in the area where the break is postulated to occur. In this study only the accident vault was represented in 3D with the remainder of containment being treated as a lumped node connected to the accident vault. This work is the second of four integrated tasks leading to the development of a hybrid containment model for the CANDU 6 reactor. A spatial convergence study is performed to ensure the validity of the selected 3D grid. Flows and hydrogen concentrations at various locations were compared for the two grids and conclusions have been drawn regarding the adequacy of the grids employed.

INTRODUCTION

Breaks in the heat transport system can lead to conditions in the fuel channels which generate hydrogen due to the zircalloy/steam reaction. For most cases, hydrogen will be released via a header or feeder to one of the two fuelling machine vaults and subsequently transported to other areas in the reactor building. This hydrogen may accumulate locally in certain areas of containment. Therefore, it is important to determine the hydrogen distribution in the containment to verify if the above conditions exist.

One approach to obtain the hydrogen distribution is via computer simulations. Lumped parameter models may be adequate for well mixed accident conditions but predictions using this approach for low flow situations which are driven by natural convection may not be as adequate as those predictions based on three-dimensional models.

High temperature hydrogen discharge will be transported from the accident area (fuelling machine vault) mainly by buoyant forces (particularly when the LOCA has subsided). Convective flow of the hot hydrogen and steam-air mixture is local and high concentrations of hydrogen are expected in the vicinity of the break location above the release point if forced flows are not present. Therefore, 3-D models of the fuelling machine vault and the steam generator enclosure areas are needed to predict local hydrogen concentrations and a realistic flow field. The objective of this work is to determine the degree of nodalization required in the fuelling machine vault to be confident of the predicted flow and hydrogen distributions following a LOCA coincident with LOECC accident.

DESCRIPTION OF THE REACTOR FUELLING MACHINE VAULT

R-107 or R-108 (fuelling machine vaults) contain most of the primary heat transport circuit piping. These rooms are open on four faces: one side is directly open to the moderator room (R-111), another side is open to the fuelling machine maintenance room (R-103 or R-104) during fuelling, the top is open to the steam generator enclosure (R-508 or R-509) which is open to the reactor dome (R-501). The area between the steam generator enclosure and the perimeter wall is open to the moderator room and the reactor dome. There are four large local air coolers located below the steam generators blowing chilled air onto the face of the reactor and feeder cabinet (Figures 1, 2).

GOTHIC Computer Code

GOTHIC (Generation of Thermal Hydraulic Information in Containment) is a general purpose thermal hydraulics program specially written for design, licensing, safety and operating analysis of nuclear containments. Much of the code development, qualification and documentation has been completed under various EPRI contracts (Electric Power Research Institute, References 1, 2, 3). The code solves mass, momentum and energy balances for three separate phases: vapour, continuous liquid and dispersed liquid. The vapour phase can be a mixture of steam and non-condensable gases and a separate mass balance is maintained for each component of the vapour mixture. Phase balance equations are coupled by mechanistic models and correlations for interface mass, energy and momentum transfer that cover the entire flow regime from bubbly flow to film/drop flow as well as single phase flows. The interface models allow for the possibility of thermal non-equilibrium among the phases and unequal phase velocities. Containment compartments can be modelled using 1, 2 or 3 dimensional rectangular grids or as lumped volumes.

MODELLING DETAILS & ASSUMPTIONS

The 3-D volume represents one of the two fuelling machine vaults, the corresponding steam generator enclosure and the shutdown cooler/valve areas (Figure 2) based on the following reasons:

- In CANDU 6 the majority of the heat transport system pipe breaks are assumed to take place in the fuelling machine vault (R-107 or R-108) where most of the primary heat transport system piping is located (e.g., feeder cabinet area, space below the steam generator enclosures).
- The steam generator enclosure (R-508 or R-509) is included in the 3-D volume representation along with the fuelling machine vault concrete structure since the steam generator enclosure is directly connected to the fuelling machine vault and the steam generator enclosures produce the "chimney effect" which plays a major role in hydrogen transport.
- The geometric structure of R-108/R-509 or R-107/R-508 can be reasonably represented using rectangular coordinates (GOTHIC is restricted to rectangular coordinates). This ensures reasonably accurate geometric modelling of the concrete structure which may have some effect on the prediction of flow fields in this area during the LOCA period.
- The shutdown cooler and valve gallery area (R-108A) is considered to be part of the 3-D vault model since this area is wide open to the vault. Since the perimeter wall of the CANDU 6 reactor building is cylindrical, this area cannot be accurately modelled by GOTHIC rectangular coordinates. However, for vertical flow conditions (mainly driven by natural convection during the hydrogen release period) it will not have a major impact on the predicted flow field in the fuelling machine vault (R-108 or R-107) and in the steam generator enclosure (R-509 or R-508).

Dimensions of the fuelling machine vault (R-108) and the corresponding boiler enclosure (R-509) are taken from reactor building concrete arrangement drawings (Figure 3). The volume of the fuelling machine vault R-108, excluding its area below the steam generator enclosure, is estimated as:

$$V_1 = [50'-6"] [19'-0"] [(93'-0") - (45'-0")] \\ = (15.4 \text{ m})(5.8 \text{ m})(14.6 \text{ m}) = 1302 \text{ m}^3$$

- The volumes of the steam generator enclosure and the part of the fuelling machine vault below the steam generator enclosure (Figure 3) are estimated as:

$$V_2 = [50'-6"] [15'-4"] [(128'-0") - (45'-0")] \\ = (15.4 \text{ m})(4.6 \text{ m})(25.3 \text{ m}) = 1792 \text{ m}^3$$

- It is estimated that two boilers (Figure 2) occupy a net volume of 135 m^3 . The four LAC's in the fuelling machine (Figure 2) are also estimated to have a net volume of 60 m^3 and the concrete separator between the two steam generators has a volume of 14 m^3 .

- The volume occupied by the shutdown cooler volume being modelled is estimated as 857 m^3 .

- Based on the above estimated values, the net free volume is:

$$V = (1302 \text{ m}^3 + 1792 \text{ m}^3 + 857 \text{ m}^3) - (135 \text{ m}^3 + 60 \text{ m}^3 + 14 \text{ m}^3) = 3742 \text{ m}^3$$

The remaining free volume inside containment is modelled as a lumped volume with total containment walls surface area estimated from Reference 4. The meshing for the coarse grid model (base model) is $8 \times 9 \times 21$ (1512 cells, Figure 3). However, not all 1512 cells are used for the free volume. Null cells are employed to block off the areas which are not part of the reactor vault. The total number of null cells is 479 which consists of:

$3 \times 9 \times 11 = 297$ cells (heat transport system pump area, Figure 4)

$2 \times (1 \times 2 \times 11) = 44$ cells (two steam generators, Figure 5)

$3 \times 1 \times 3 = 9$ cells (cooler block, Figure 5)

$3 \times 1 \times 1 = 3$ cells (concrete separator between the two boilers, Figure 5)

$7 \times 2 \times 9 = 126$ cells (area above the shutdown cooler and valve gallery area, Figure 6)

This results in an effective meshing of 1033 cells to model a free volume of 3742 m^3 (i.e., 3.6 m^3 average cell size). Figure 7 shows the schematic modelling diagram of the reactor vault area using the GOTHIC code. This degree of resolution is expected to be adequate to represent the fuelling machine vault and its surrounding for the following reasons:

- The geometry of the fuelling machine vault and the steam generator inclosure is simple and can be adequately represented by rectangular coordinates. Detailed modelling of corners (complex geometry which requires a high resolution 3-D mesh) is not required for low velocity flow in the vertical direction (local buoyancy driven flows).

- Not all major equipment in the fuelling machine vault is modelled. Only the volume occupied by the 4 LAC's and the two steam generators are accounted for. Also, the volume occupied by the 4 LAC's is modelled as a continuous block (areas between coolers are neglected to simplify the modelling mesh). Thus, only a simplified representation of this area based on the concrete geometry is required.

- During the blowdown phase (provided that the steam discharge rate is sufficiently high), forced convection flows due to the discharge will form a well defined flow field which will not require a high resolution mesh to predict the overall picture of the flow field.

- During the hydrogen discharge phase, the high temperature and therefore low density (low momentum) H_2 /air/steam discharge is expected to rise locally. The flow field, at locations far away from the vicinity of the hydrogen release, will not be affected by this low momentum discharge. Therefore, for local buoyancy driven flow situations, only the vertical direction requires a finer grid and only the location (volume) around the assumed pipe break requires a detailed 3-D grid.

It is important to identify if the grid is too coarse to obtain a reasonably converged solution of the predicted key parameters (i.e., temperature, hydrogen and steam concentrations). To address this issue a grid dependency study (spatial convergence study) is required. This was done by increasing the number of cells in the base model by a factor of 2 and comparing the results to those of the reference case (Figure 8). In order to create the refined model, the following modifications are made in the 3-D volume:

- Maximum vertical noding decreased from 2 m to 1 m.
- Minimum vertical noding decreased from 1 m to 0.5 m.
- Maximum horizontal noding decreased from 3 m to 2 m.

The above modifications are applied to the following areas in the reactor vault, resulting in an increase of number of active cells from 1033 to 2356 and a reduction in average cell volume from 3.5 m^3 to 1.7 m^3 :

a) The volume of the fuelling machine vault R-108, excluding its area below the steam generator enclosure is subdivided into $5 \times 10 \times 31$ cells (an increase from $3 \times 9 \times 21$ in the coarse grid model). Cells in all channels from elevation 18 and upward are null cells. At elevation below 82' (for Point Lepreau and 60'-6" for Gentilly-2, area below the headers/feeder joints) the vertical noding distance decreases from 2 m to 1 m to obtain a finer vertical resolution in this area. Above this elevation where the discharge is assumed to occur, the vertical noding distance is decreased from 1 m to 0.5 m to obtain a higher resolution and accuracy of the prediction in the vertical direction at the break discharge elevation and the elevations above the break (important for a buoyant hydrogen/air mixture at high temperature). This effectively reduces the volume of the cells surrounding the steam/hydrogen release location by a factor of 12.

b) The volume comprising the steam generator enclosure (R-509) and the part of the fuelling machine vault below the steam generator enclosure is subdivided into $3 \times 10 \times 31$ cells (an increase from $3 \times 9 \times 21$ cells). Most of the refinement is in the vertical noding: 1 m spacing for area below elevation 82'-0" for point Lepreau (elevation 60'-6" for Gentilly-2). Above this elevation and up to the boiler plenum elevation a 0.5 m spacing is used.

c) The area below the solid platform supporting the ECCS heat exchanger R-108A is subdivided into $2 \times 10 \times 31$ cells (an increase from $2 \times 9 \times 21$ in the coarse grid model). Most of the refinement is in the vertical noding as described in R-108 and R-509 areas. Below the solid platform a vertical spacing of 1m is used. At the solid platform level and up to the boiler plenum, a 0.5 m spacing is employed and a 1m spacing is used for the areas above this level.

RESULTS & DISCUSSIONS

A 0.5 % Reactor Inlet Header Break (Figures 7a, 7b) was chosen for this analysis. The small break was chosen since it is expected to provide a less well mixed environment in the break area due to a lower discharge rate compared to that of a larger break (e.g., 80 percent break). Hydrogen is assumed to be released after the blowdown phase (Figures 7b, 7c). Both hydrogen and LOCA discharges were modelled with discharges pointed to the calandria face to provide a less well mixed environment in the break area.

Figures 8a,b,c,d show the predicted hydrogen concentration in the areas near the break location (channel 33 level 9 in Figure 8c). The predicted hydrogen concentration reaches a maximum of approx. 12 percent at approx. 2000 seconds following the accident. Elsewhere, the predicted hydrogen concentration is fairly uniform (about 3 to 4 percent depending on locations, also see Figure 9a,b,c,d. After approx. 3000 seconds the hydrogen concentration is well mixed in the reactor vault (except near the release location).

Figures 10a,b,c (top) show the predicted velocity in the fuelling machine vault during the LOCA phase (30 seconds following the accident). These are the projected velocities on the vertical planes 33-34, 17-24 and 5-69 for all elevations inside the fuelling machine vault. Figures 10d,e,f (bottom) show the same predicted velocity during the hydrogen release phase (1800 seconds following the accident).

The predicted velocity fields indicate a well defined flow loop circulating between the fuelling machine vault (R-108) and the dome above (R-501) via the steam generator enclosure (R-509) and the openings below (valve gallery and moderator areas (Figures 2, 1). Figures 11a, 11b show the difference in predicted temperature in various areas inside the accident vault at different elevations. Figure 11a shows a significant difference in predicted temperature inside the steam generator enclosure and the temperature in the valve area. This difference provides the driving force for the flow loop mentioned above.

Spatial convergence is assessed by comparing the hydrogen concentration at several locations predicted by the two nodalizations (see Figures 5a and 5b) : the 1033 cell model (coarse grid model, Figure 5a) and the 2356 cell model (fine grid model, Figure 5b). Figures 12a,b,c,d to Figures 14a,b,c,d show the results of such comparisons:

Coarse grid model (1033 cells)	Fine grid model (2356 cells)
Channel 45 Level 16 (Figure 12a, top)	Channel 67 Level 26 (Figure 12b, bottom)
Channel 42 Level 3 (Figure 12c, top)	Channel 64 Level 5,6 (Figure 12d, bottom)
Channel 31 Level 4 (Figure 13a, top)	Channel 39 Level 7,8 (Figure 13b, bottom)
Channel 66 Level 6 (Figure 13c, top)	Channel 94 Level 11,12 (Figure 13d, bottom)
Channel 2 Level 7 (Figure 14a, top)	Channel 4 Level 13,14 (Figure 14b, bottom)
Channel 29 Level 14 (Figure 14c, top)	Channel 37 Level 24 (Figure 14d, bottom)

The results show comparable predictions between the two nodalizations. In most areas the predicted hydrogen concentrations are very similar, except areas near the wall corner where the present grids employed are not fine enough to resolve details (Figures 14a,b).

CONCLUSIONS

A spatial convergence study was performed (by increasing the number of cells in the coarse grid model by a factor of 2) to ensure the validity of the coarse grid employed in the analysis. Predicted hydrogen concentrations at various locations in the reactor fuelling machine vault were compared for the two grids.

The predicted hydrogen concentrations obtained by the two nodalizations were consistent. This indicates that the solution obtained by the coarse grid model can be employed to predict the thermal hydraulic behaviour in the CANDU 600 fuelling machine vault. Although global convergence is ideal it may not be achieved due to code limitations and computing time (as demonstrated in this study). A reasonable compromise based on local convergence criteria is the only solution for this costly exercise.

REFERENCES

1. Thomas L. George et al., "GOTHIC Containment Analysis package, Technical Manual Version 5.0: RP-4444-1", Electric Power Research Institute, Inc., December 1995.
2. Thomas L. George et al., "GOTHIC Containment Analysis package, User Manual Version 5.0: RP-4444-1", Electric Power Research Institute, Inc., December 1995.
3. Lawrence E. Wiles et al., "GOTHIC Containment Analysis package, Qualification Report Version 5.0 RP3048-1", Electric Power Research Institute, Inc., December 1995.

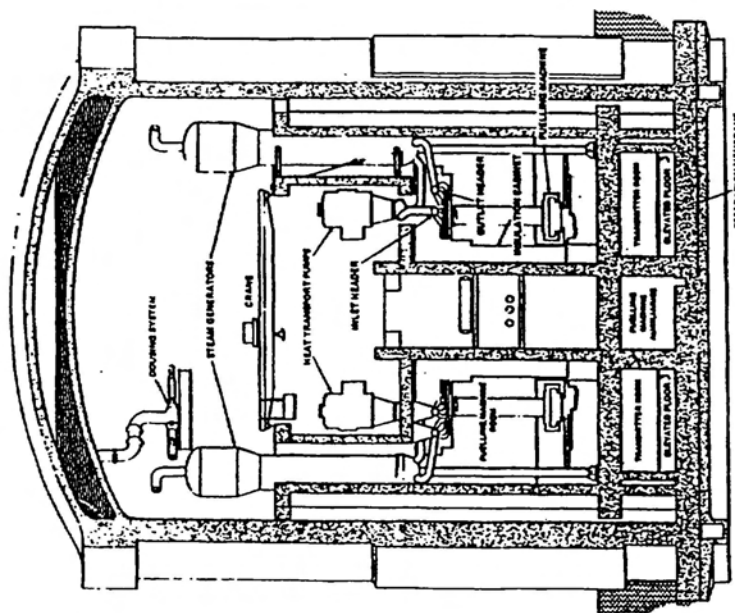
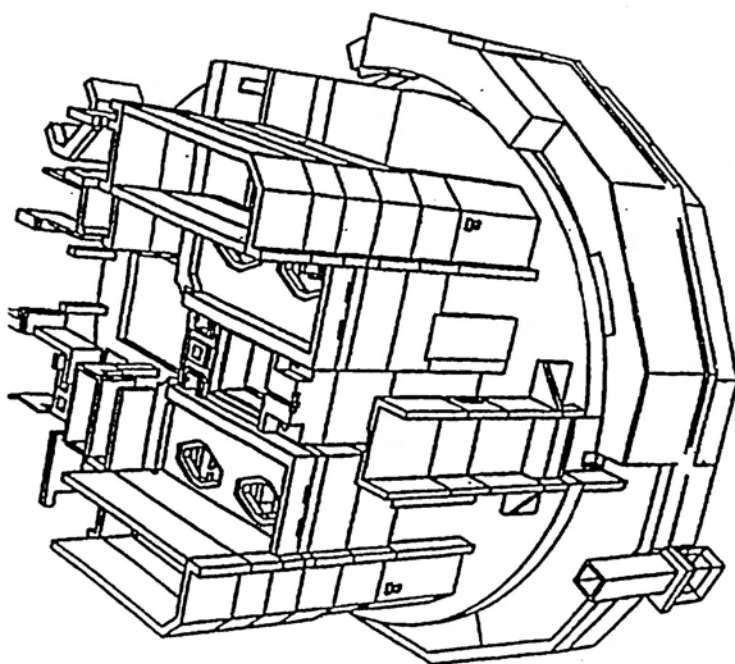


Figure 1 CANDU 6 Reactor Building

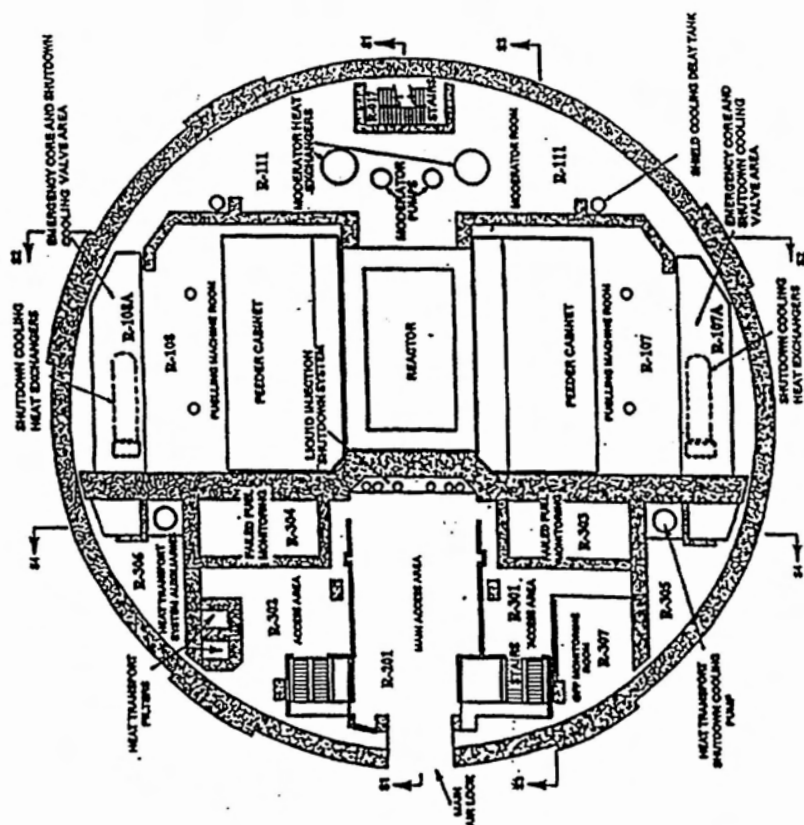


Figure 2 CANDU 6 Reactor Building Concrete Arrangements

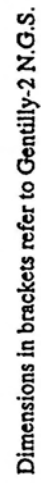
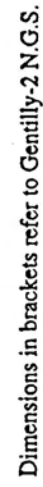


Figure 3 CANDU 6 Fuelling Machine Vault and Steam Generator Enclosure Dimensions

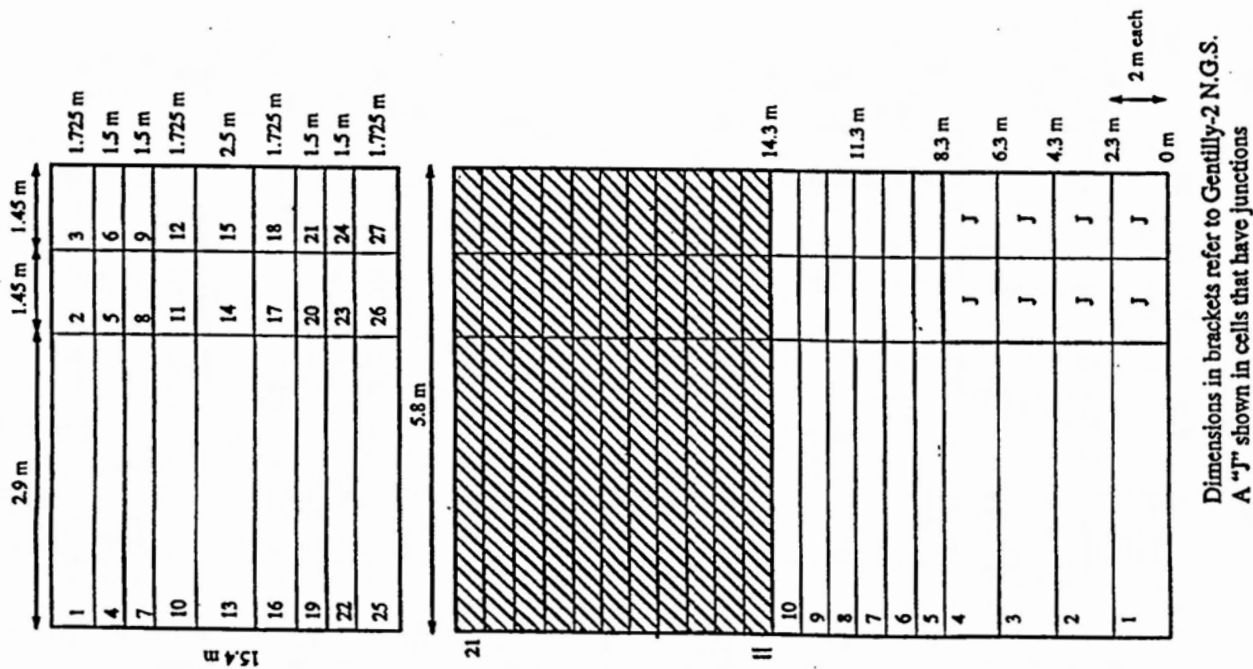


Figure 4 3-D Model of the Fuelling Machine Vault (R-108)

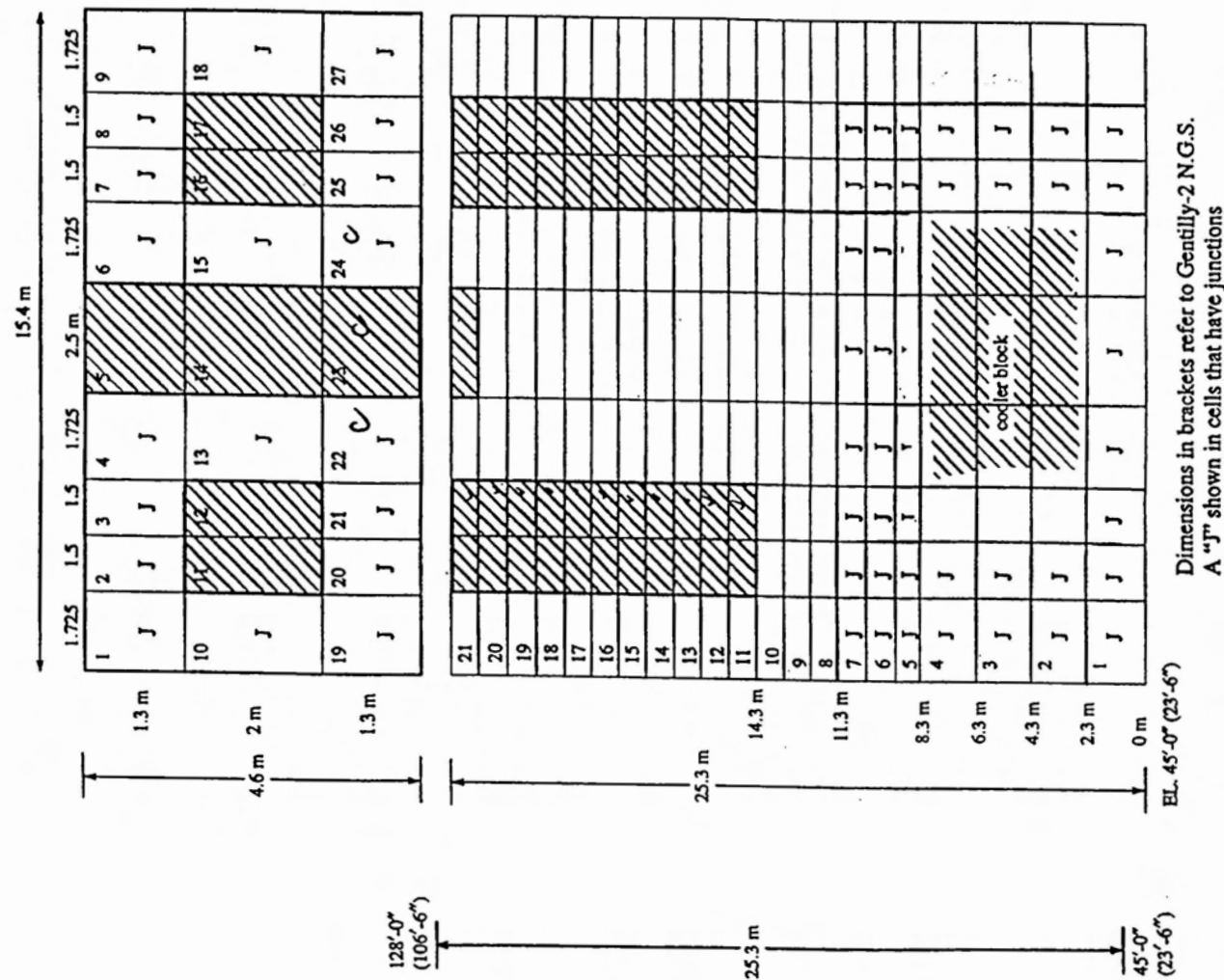


Figure 5 3-D Model of the Steam Generator Enclosure (R-509)

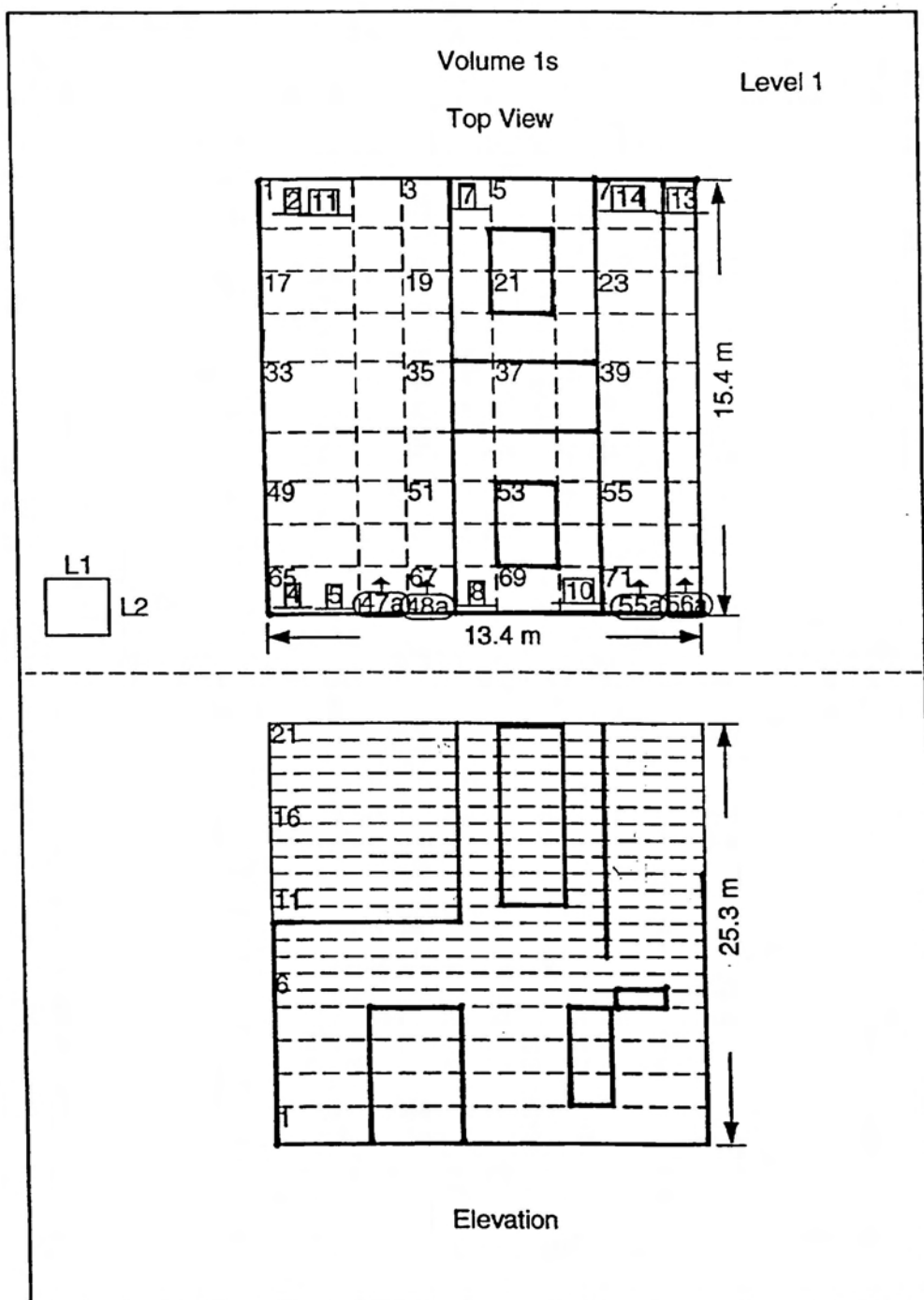


Figure 7 GOTHIC Nodal Diagram of R-108 and R-509 (1033 cell Model)

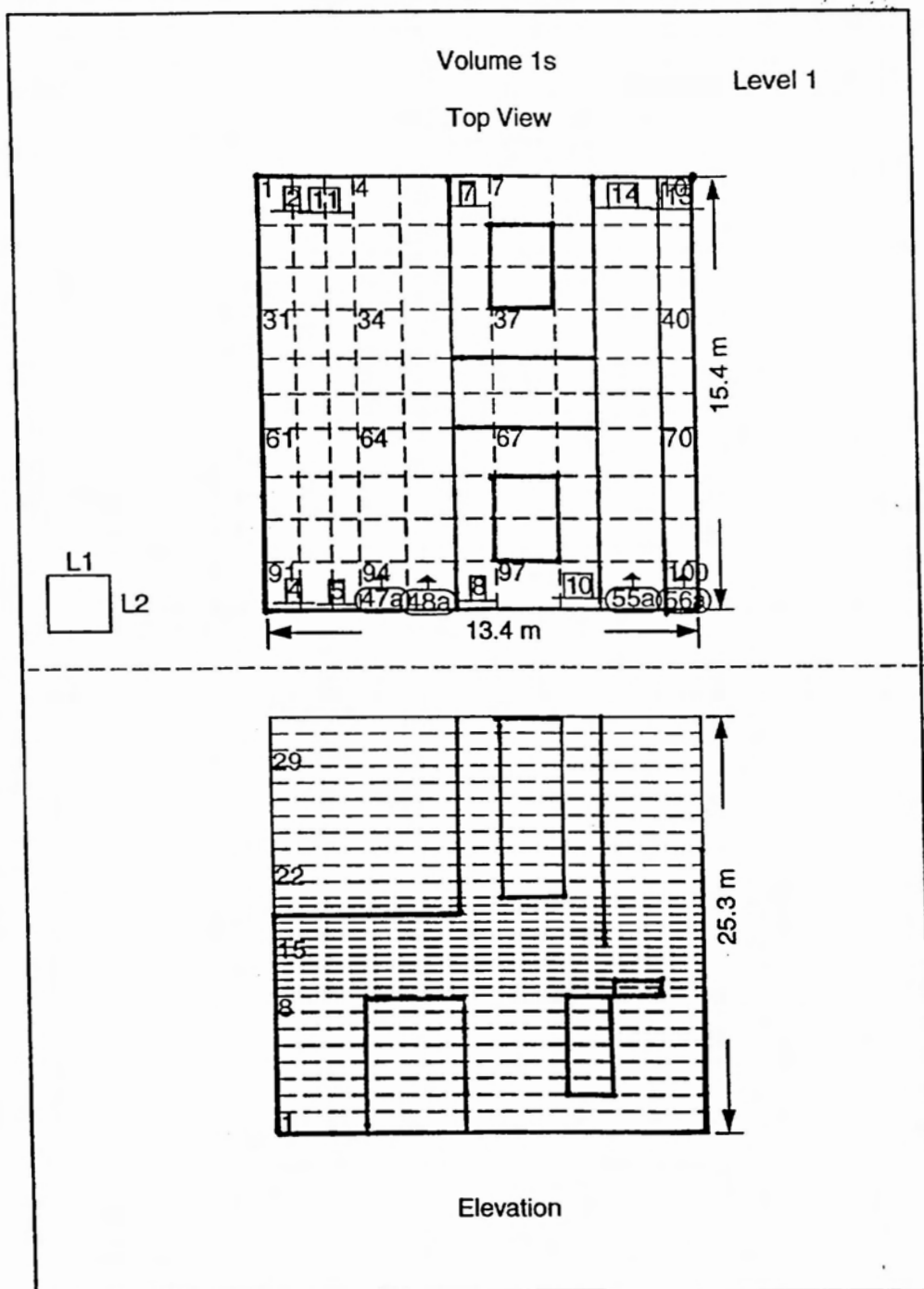


Figure 8 GOTHIC Nodal Diagram of R-108 and R-509 (2356 cell Model)

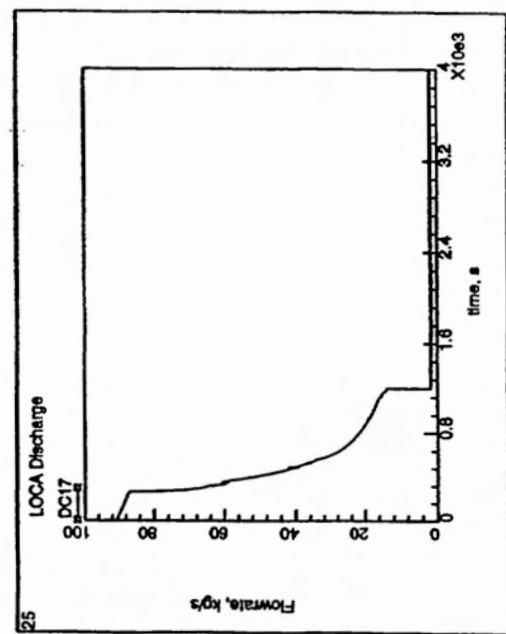


Figure 7a LOCA Discharge Flowrate

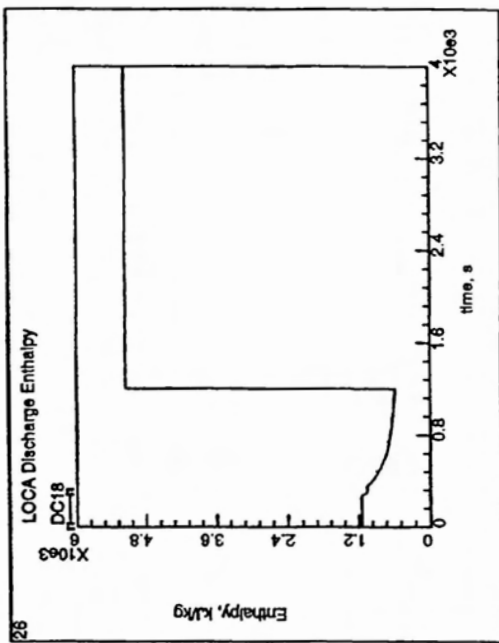


Figure 7b LOCA Discharge Enthalpy

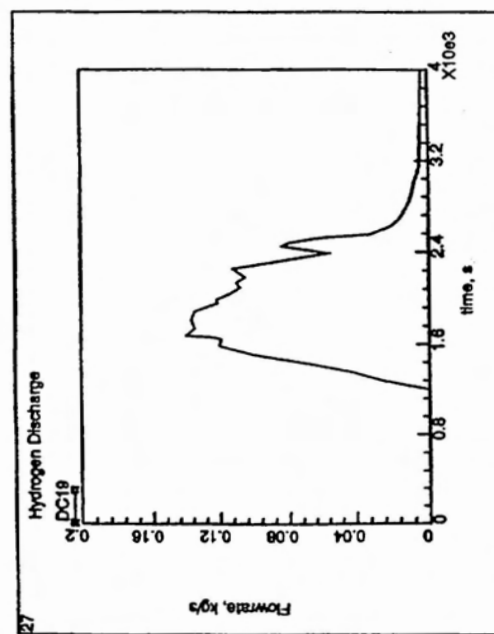


Figure 7c Hydrogen Discharge Flowrate

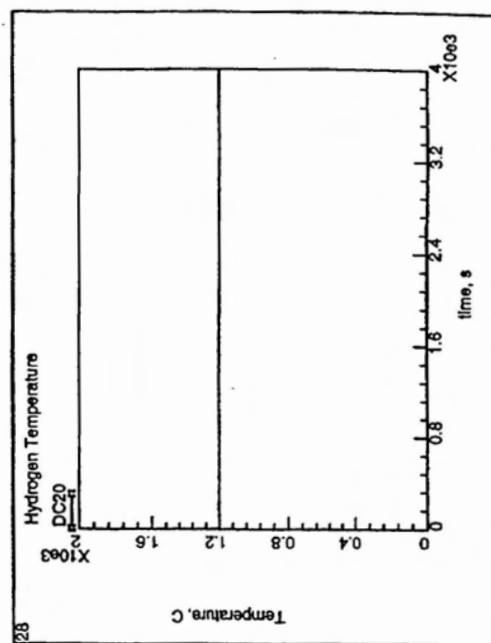


Figure 7d Hydrogen Discharge Temperature

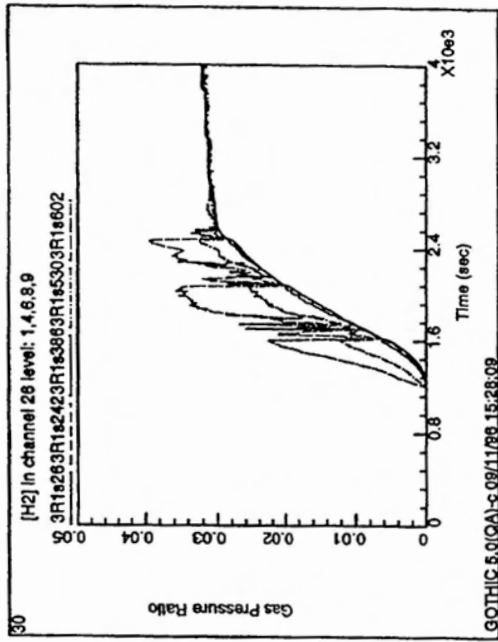
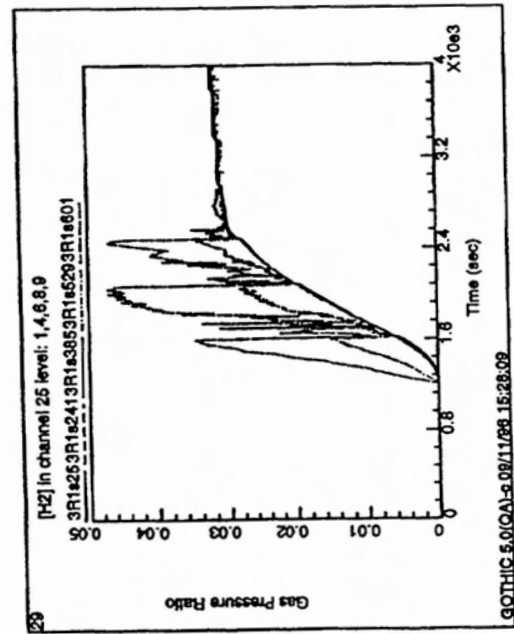
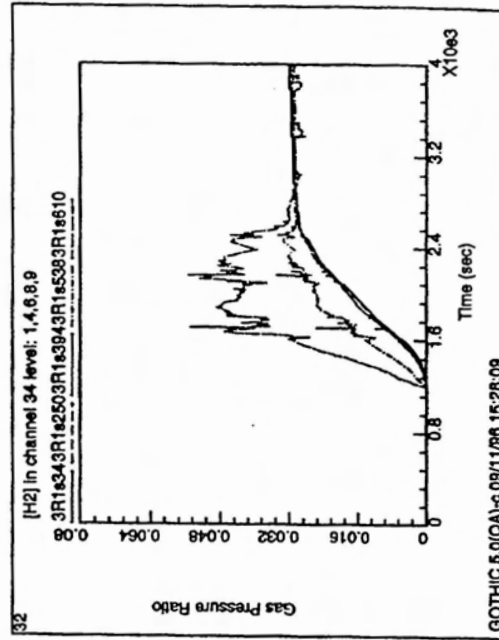
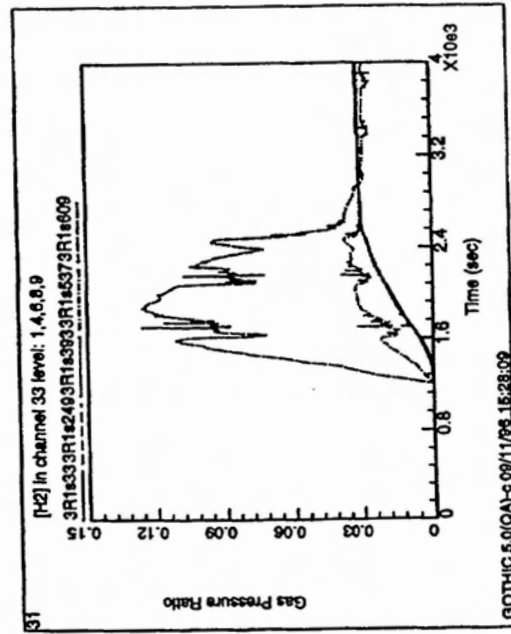


Figure 8a,b,c,d Hydrogen concentration



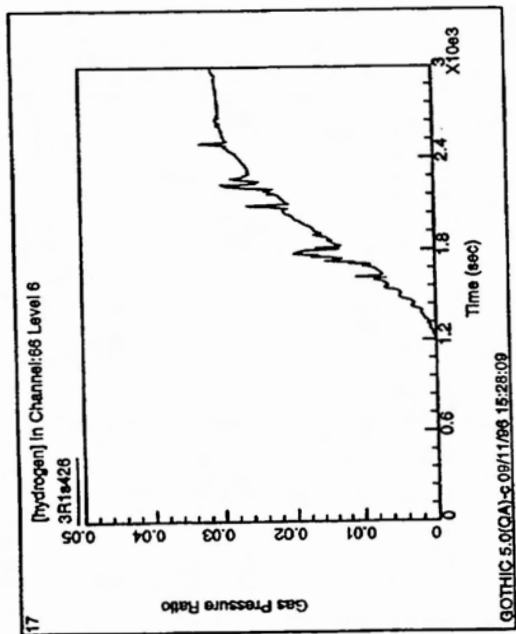
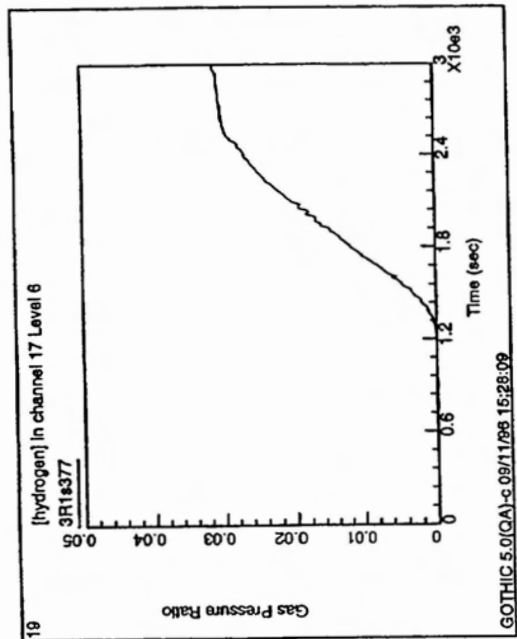
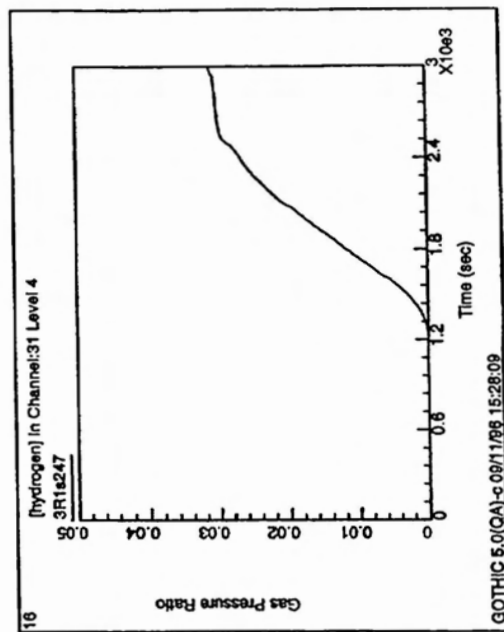
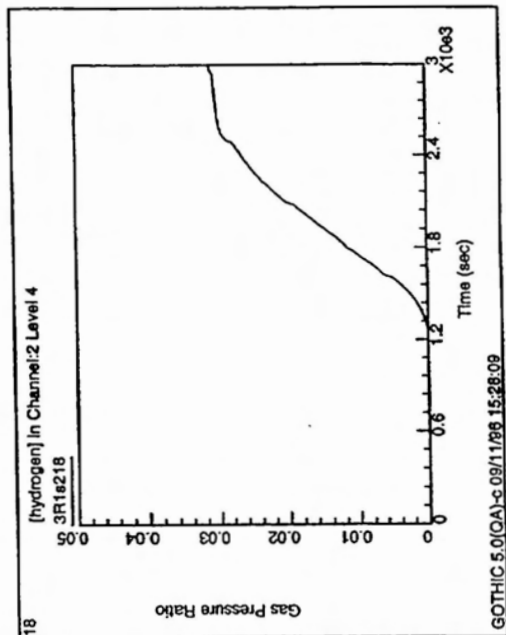


Figure 9a,b,c,d Hydrogen concentration



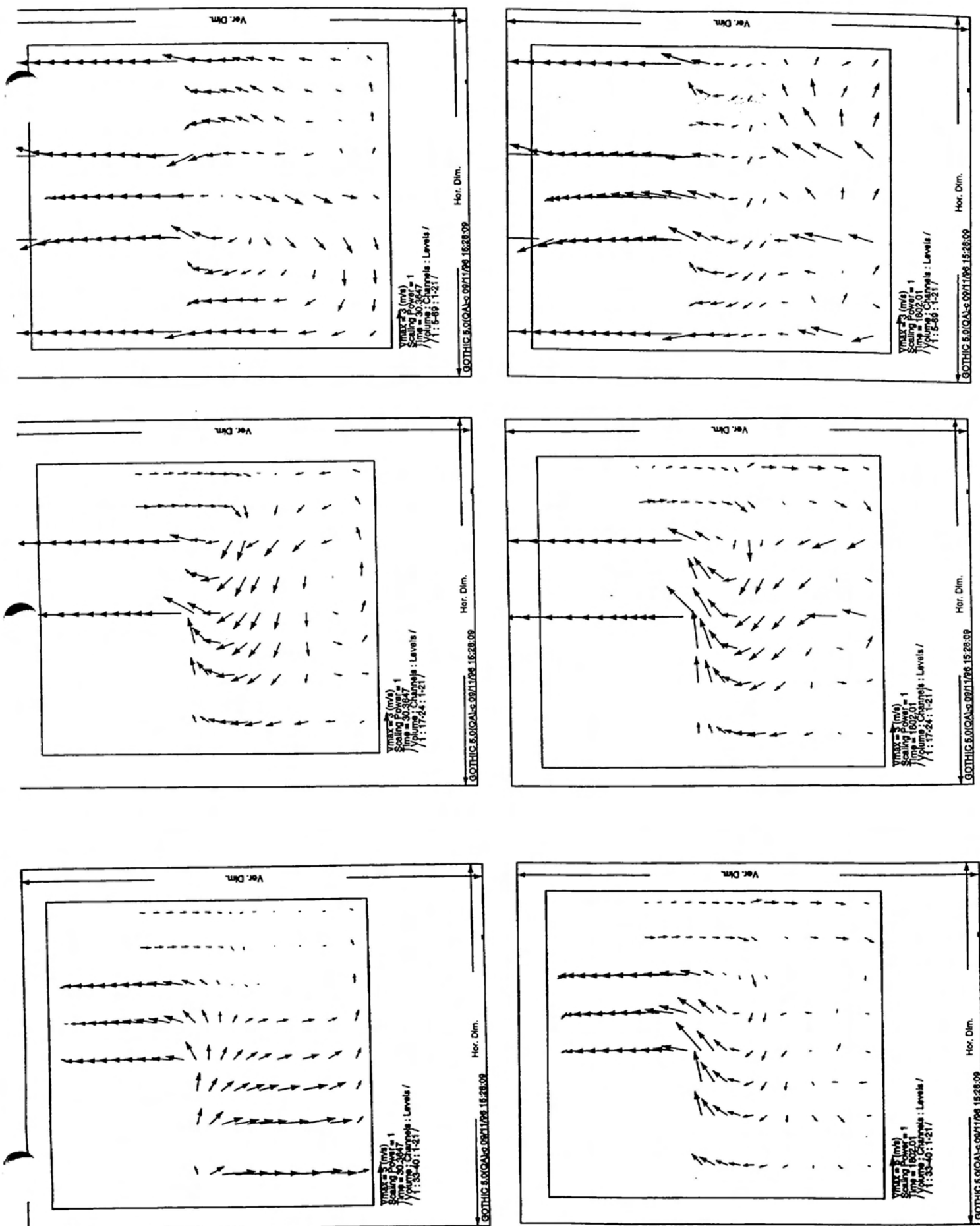


Figure 10a,b,c,d Predicted Velocity Profile of the Vapour Phase at various Locations

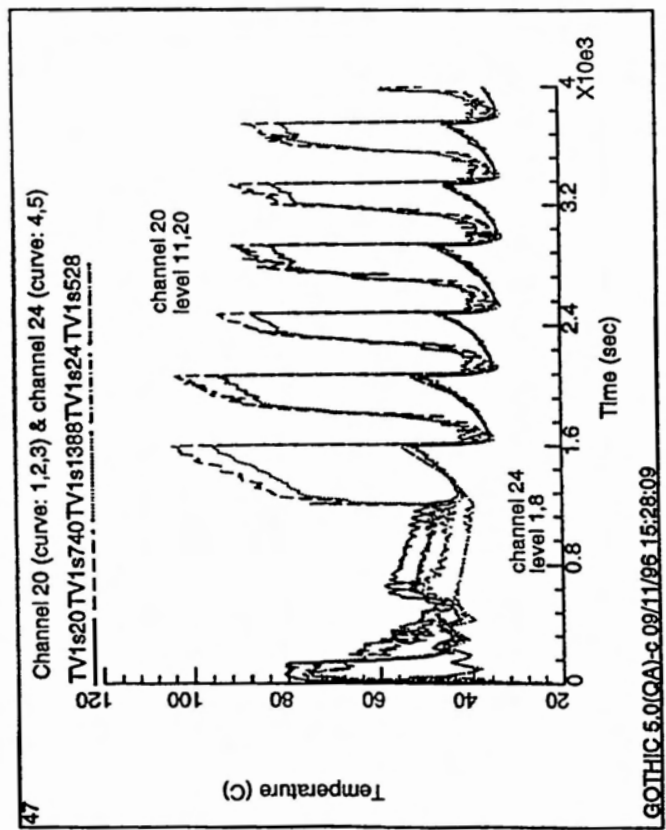


Figure 11a Predicted Temperature in R-108/508 and R-501/108A

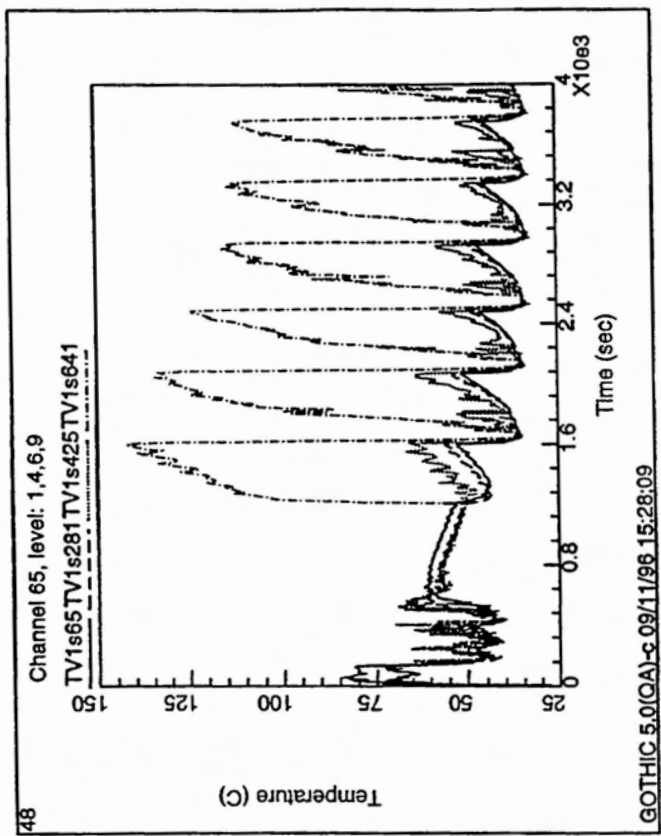


Figure 11b Predicted Temperature in R-108

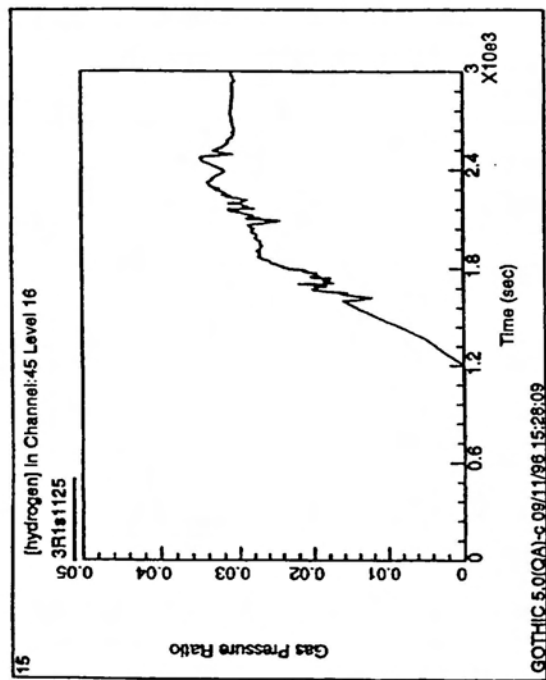


Figure 12a Predicted $[h_2]$ in Channel 45 Level 16 (coarse grid model)

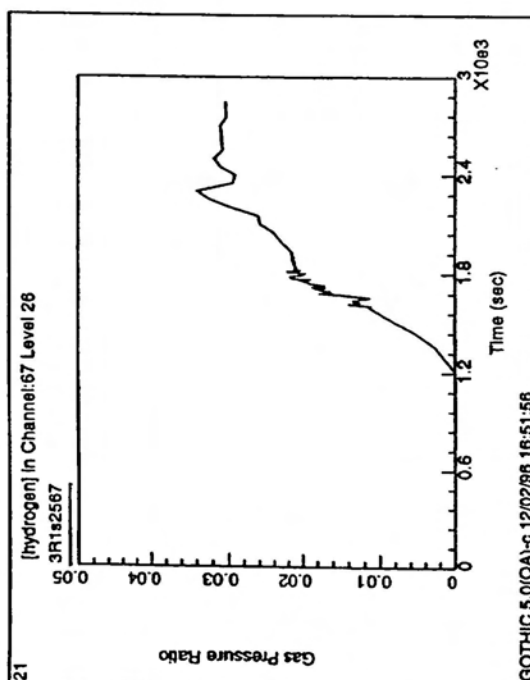


Figure 12b Predicted $[h_2]$ in Channel 67 Level 26 (fine grid model)

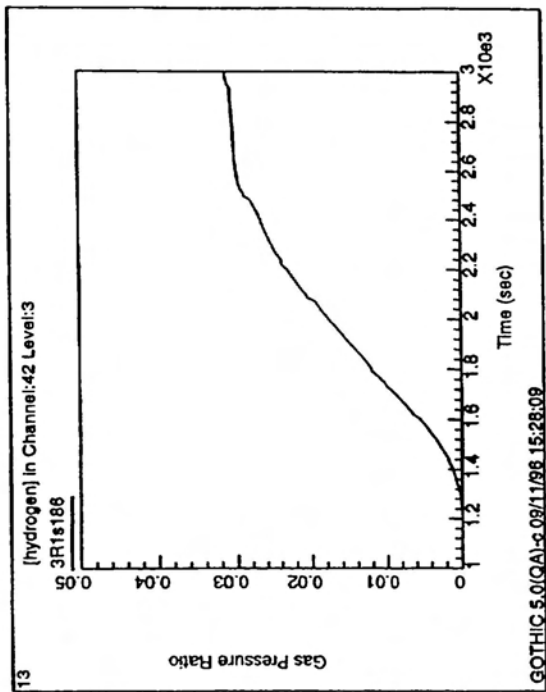


Figure 12c Predicted $[h_2]$ in Channel 42 Level 3 (coarse grid model)

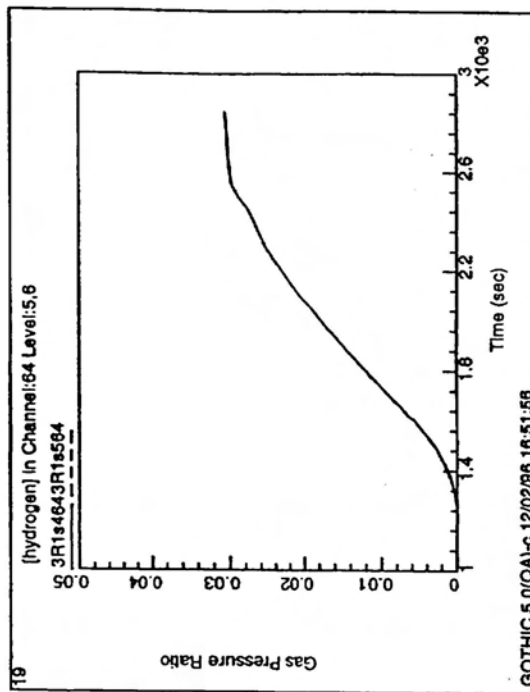


Figure 12d Predicted $[h_2]$ in Channel 64 Level 5, 6 (fine grid model)

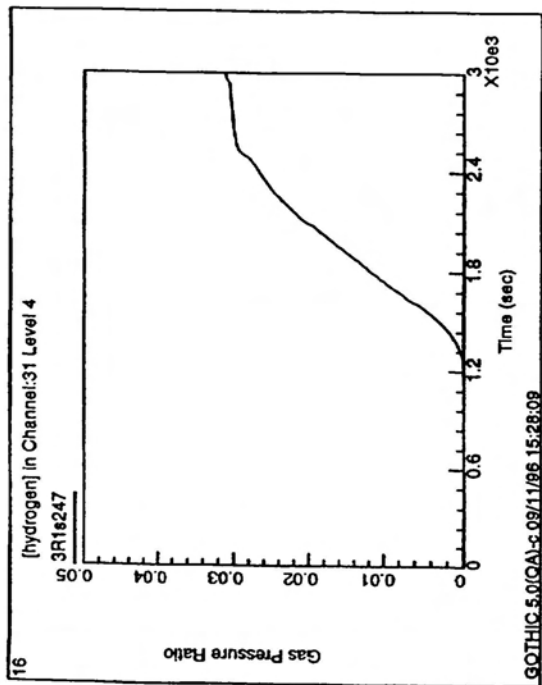


Figure 13a Predicted $[h_2]$ in Channel 31 Level 4 (coarse grid model)

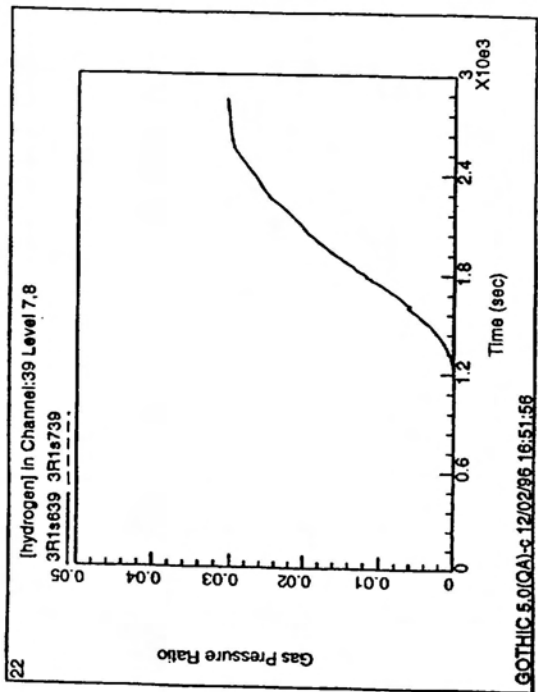


Figure 13b Predicted $[h_2]$ in Channel 39 Level 7, 8 (fine grid model)

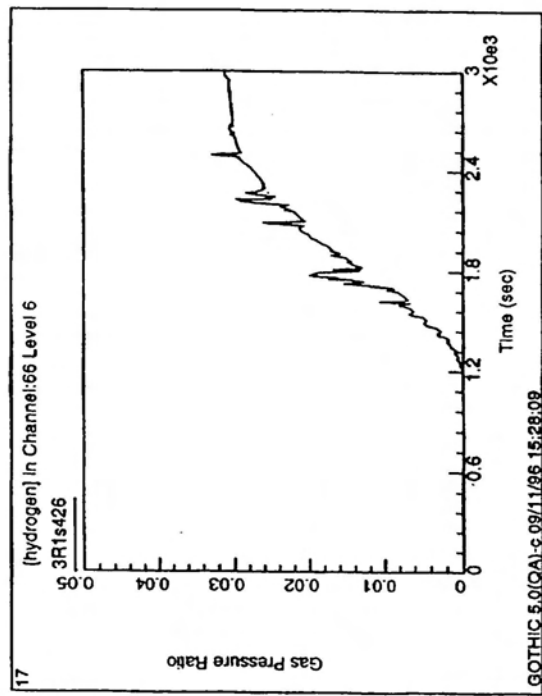


Figure 13c Predicted $[h_2]$ in Channel 66 Level 6 (coarse grid model)

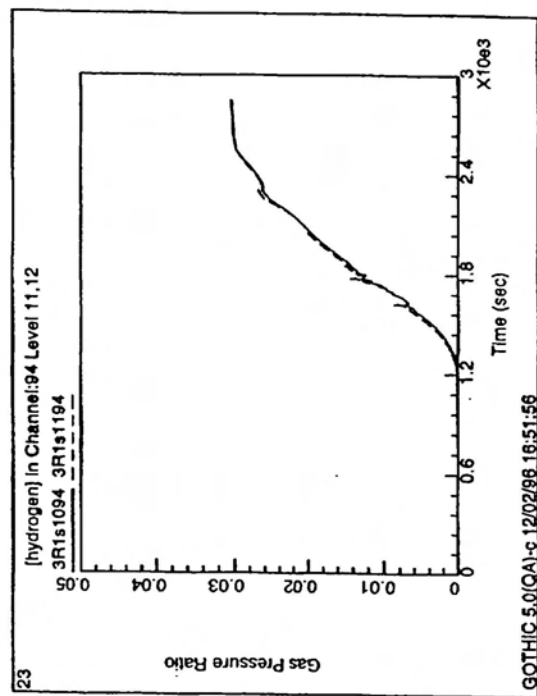


Figure 13d Predicted $[h_2]$ in Channel 94 Level 11, 12 (fine grid model)

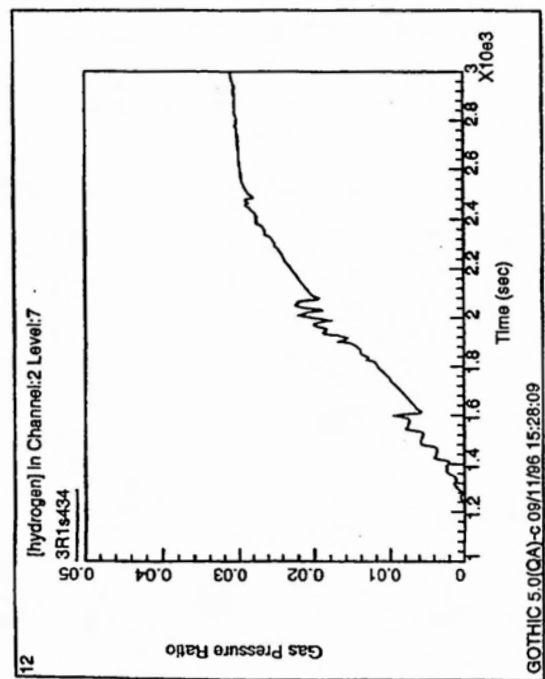


Figure 14a Predicted $[h_2]$ in Channel 2 Level 7 (coarse grid model)

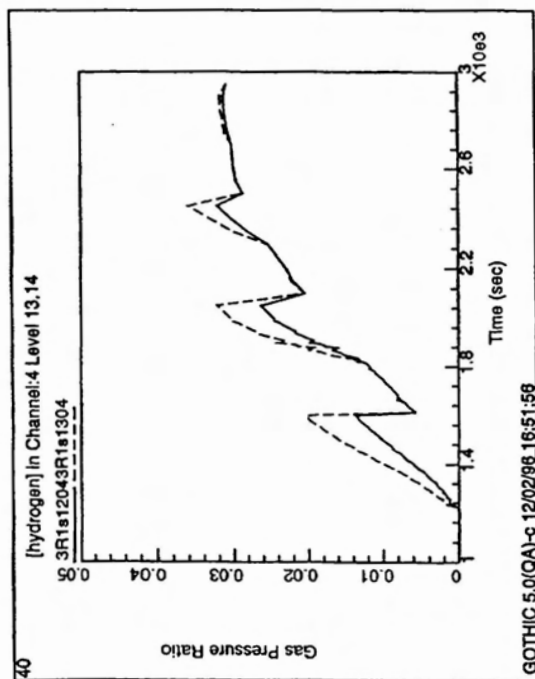


Figure 14b Predicted $[h_2]$ in Channel 4 Level 15, 16 (fine grid model)

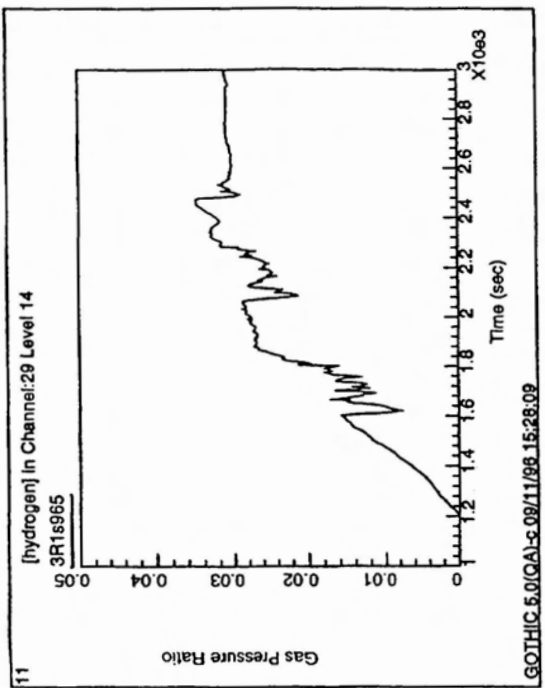


Figure 14c Predicted $[h_2]$ in Channel 29 Level 14 (coarse grid model)

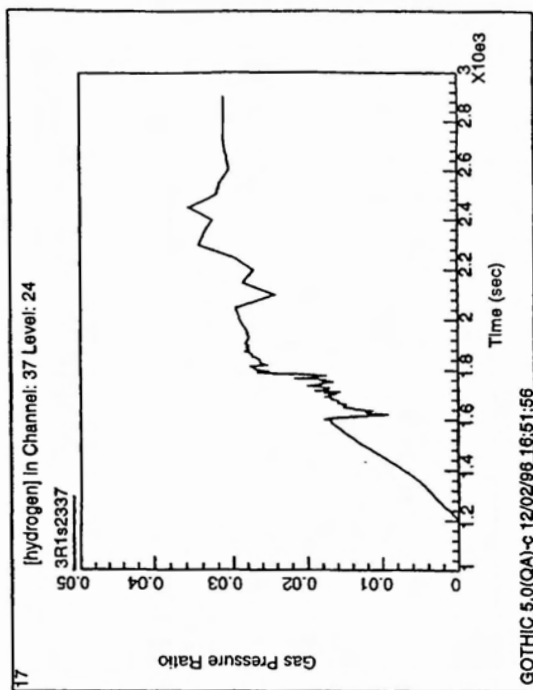


Figure 14d Predicted $[h_2]$ in Channel 37 Level 24 (fine grid model)