Westinghouse Electric Corporation **Energy Systems**

Box 355
Pittsburgh Pennsylvania 15230-0355

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U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: MR. T. R. QUAY

SUBJECT: AP600 WGOTHIC NODING CONVERGENCE STUDIES

Dear Mr. Quay:

The attachment to this letter provides a report on WGOTHIC computer code noding and convergence studies performed in support of the AP600 PCS design basis analysis methodology. The results of the noding studies support the conclusion that the noding used to analyze the AP600 is adequate and conservative. The noding and convergence study results will be included in the WGOTHIC Applications Report which is scheduled for completion in June, 1996. The attached report is provided at this time to support NRC activities toward completion of the AP600 Supplemental Draft Safety Evaluation Report.

Please contact John C. Butler (412-374-5268) if you have any questions concerning this submittal.

John C Butler for
Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

/nja

Attachment

cc: T. Kenyon, NRC (w/o Attachment)
D. Jackson, NRC (1A)
E. Throm, NRC (1A)
J. Kudrick, NRC (1A)
P. Boehnert, ACRS (1A)
B. A. McIntyre, Westinghouse (w/o Attachment)

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ATTACHMENT TO NTD-NRC-96-4634

WGOTHIC Noding Studies in Support of the AP600 Evaluation Model

EXECUTIVE SUMMARY

A study of the noding for the AP600 and the convergence of the WGOTHIC code has been performed and is summarized in this report. The results of the "simple model" noding studies indicate that the WGOTHIC code converges to a unique solution. The bare shell models link the simple models to the complete AP600 models and indicate that the noding patterns used to model the above deck region are conservative with respect to pressure. A comparison of the three AP600 models created by different groups shows that the solution is insensitive to modeling differences, including noding resolution, that arise as different people interpret the same problem. Finally, the comparisons to the Large Scale Tests indicate the both lumped parameter and distributed parameter models are conservative for use in analyzing the AP600 containment.

All of these results and sensitivities taken together provide the basis for concluding that the WGOTHIC code converges as noding resolution increases. They also support the conclusion that the noding used to analyze the AP600 is adequate and conservative.

INTRODUCTION

The GOTHIC code[1,2] package is a state-of-the-art program for modeling multi-phase flow. The GOTHIC code has been developed through a long history from other qualified thermal-hydraulic computer codes (as shown in Figure 1).

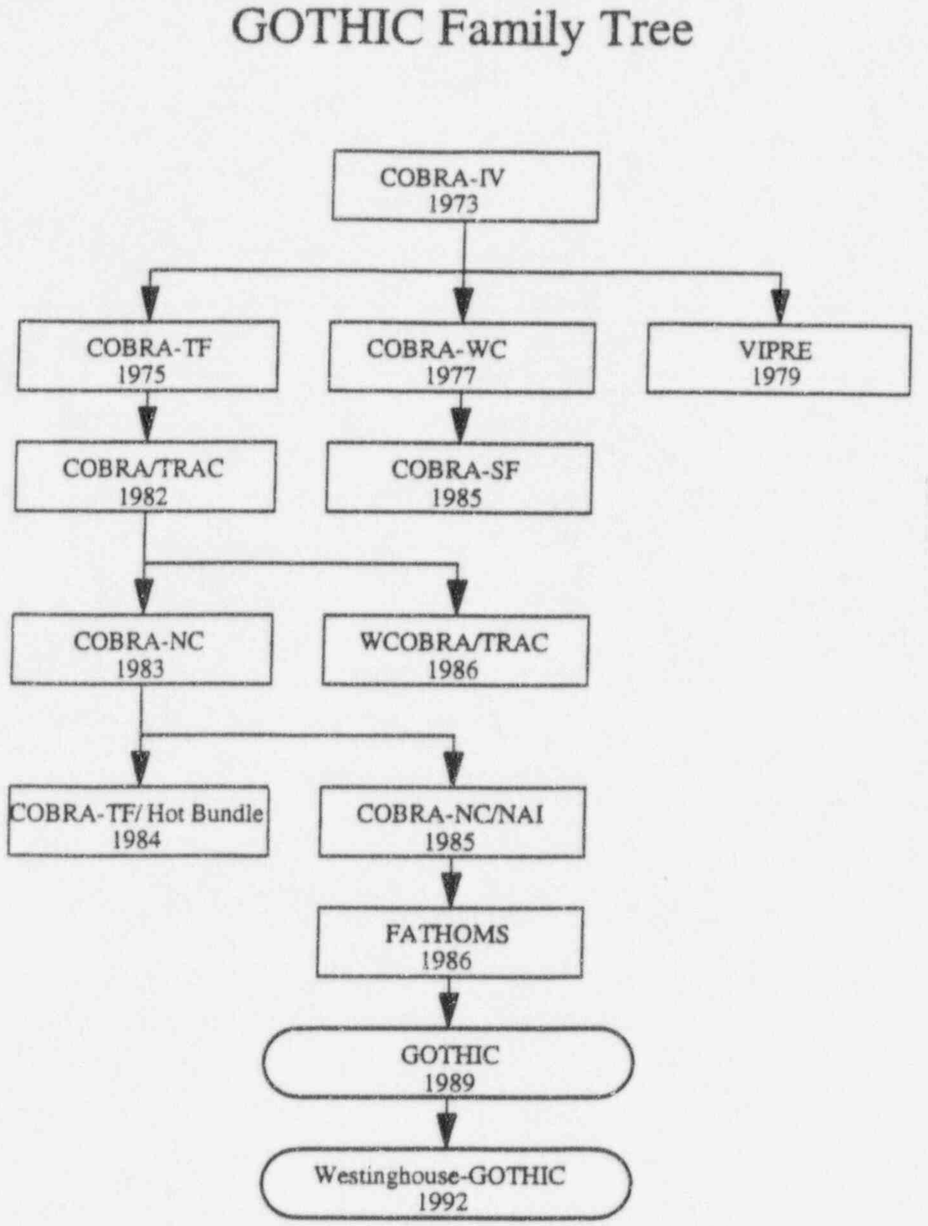


Figure 1: Summary of GOTHIC Historical Development

GOTHIC solves the integral form of the conservation equations for mass, momentum, and energy for multicomponent, two-phase flow. The conservation equations are solved for three fields; continuous liquid, liquid drops, and the steam/gas phase. The three fields may be in thermal nonequilibrium within the same computational cell. This would allow the modeling of subcooled drops falling through an atmosphere of saturated steam. The gas component of the steam/gas field can be comprised of up to eight different noncondensable gases with mass balances performed for each component. Relative velocities are calculate for each field as well as the effects of two-phase slip on pressure drop. Heat transfer between the phases, surfaces, and the fluid are also allowed.

The GOTHIC code is capable of performing calculations in three modes. The code can be used in the lumped-parameter nodal-network mode, the two-dimensional mode, and the three-dimensional distributed parameter mode. Each of these modes may be used within a single model and all are used for the AP600 analyses.

The original GOTHIC code package provided almost every feature needed to model the systems being designed for the AP600. The features that were not available were those needed to model the Passive Cooling System (PCS): the passive containment shell cooling system designed to remove the post accident energy from inside of containment. In order to model the PCS it was necessary to add the capability to model condensing and evaporating films, include a film tracking model, incorporate wall-to-wall radiation, and add heat and mass transfer correlations that extended from free convection through mixed convection and into forced convection. These features were added and the resultant code was called Westinghouse-GOTHIC or WGOTHIC.

These new features were consolidated in a new component that was added to the code. This new component is called a "Clime" and it consists of thermal conductors that perform the heat and mass transfer calculations and are explicitly coupled to GOTHIC lumped and/or distributed parameter volumes. The GOTHIC volume provides the boundary conditions for the heat and mass transfer calculated by the climes.

In applying this new code to the AP600 it is necessary to demonstrate that the code and models converge to a unique solution and that the results are not particularly sensitive to modeling differences that would occur if two experienced modelers separately created models of a given problem. In order to establish this, it is necessary to show that the code predictions will converge as more detailed representations of a given problem are analyzed. Once this has been completed it must be shown that the noding used for a given problem is either conservative or has converged to the final answer. The rationale for accepting conservative results is based on run-time constraints and physical computer limitations. Once it is indicated that the code converges and that the noding is adequate it must be established that the code is not particularly sensitive to differences, that are attributed to modeling, that would arise as two different analysts each set up an accurate model of the given problem. These issues are addressed below for WGOTHIC and its application to the AP600.

In the following sections the convergence of the WGOTHIC code and the acceptability of the noding used to model the AP600 are studied. The first section, on the simple model, examines a slice of the AP600 containment above the operating deck in detail and is used to demonstrate that the WGOTHIC code converges to a unique solution. In this study an ordered mesh is successively refined and used to analyze containment pressure response assuming only the steam mass and energy releases from a double ended cold leg loss of coolant accident. In the next section, the section on the bare shell models of only the above-deck region, irregular noding as was used in the AP600 SSAR analysis lumped and distributed models is studied. This is done to determine the adequacy of the noding used in the SSAR analyses. The third section on the complete AP600 models compares models of the same problem, the complete AP600 model, built by three different groups. This section addresses modeling differences that could be attributed to an analyst's interpretation of the problem being studied as well as sensitivities to break location and wall obstructions. The final section discusses sensitivities of the WGOTHIC code calculations to noding variations as compared to the test results obtained from the large scale test facility. This section provides a basis for determining the accuracy of the code's calculational results and is used to confirm the applicability of the selected evaluation model noding for use in AP600 containment integrity calculations.

BARE SHELL NODING STUDIES - Two-Dimensional Parallelepiped Models

In 1995 the Nuclear Engineering Department at Massachusetts Institute of Technology was contracted by Westinghouse to conduct a series of noding and parametric studies. The results of these studies support the acceptability of both WGOTHIC and the noding selected for modeling the AP600.

The first step in studying the convergence of the code was to create a simple model of the AP600 and progressively increase the nodalization of the model while studying the code predicted results for the transient. The first model that was constructed was a simple parallelepiped model of the AP600. The model was based on a 1/32 slice, corresponding to an 11.25 degree arc, of the region above the operating deck.

Seven different models were constructed of this region of the AP600. These models varied the horizontal and vertical mesh through the segment. The table below presents the succession of the two-dimensional models. A schematic of the nodalization study are presented in Figure 2. This figure indicates the paths of identical aspect ratio. This feature is important when studying code convergence since maintaining the same aspect ratio avoids changing gradients across cells which can obscure convergence.

Table 1: Succession of Two-dimensional Parallelepiped Models

Model	Horizontal Mesh	Vertical Mesh
2x4z	2	4
4x4z	4	4
4x8z	4	8
8x8z	8	8
8x16z	8	16
16x16z	16	16
16x32z	16	32

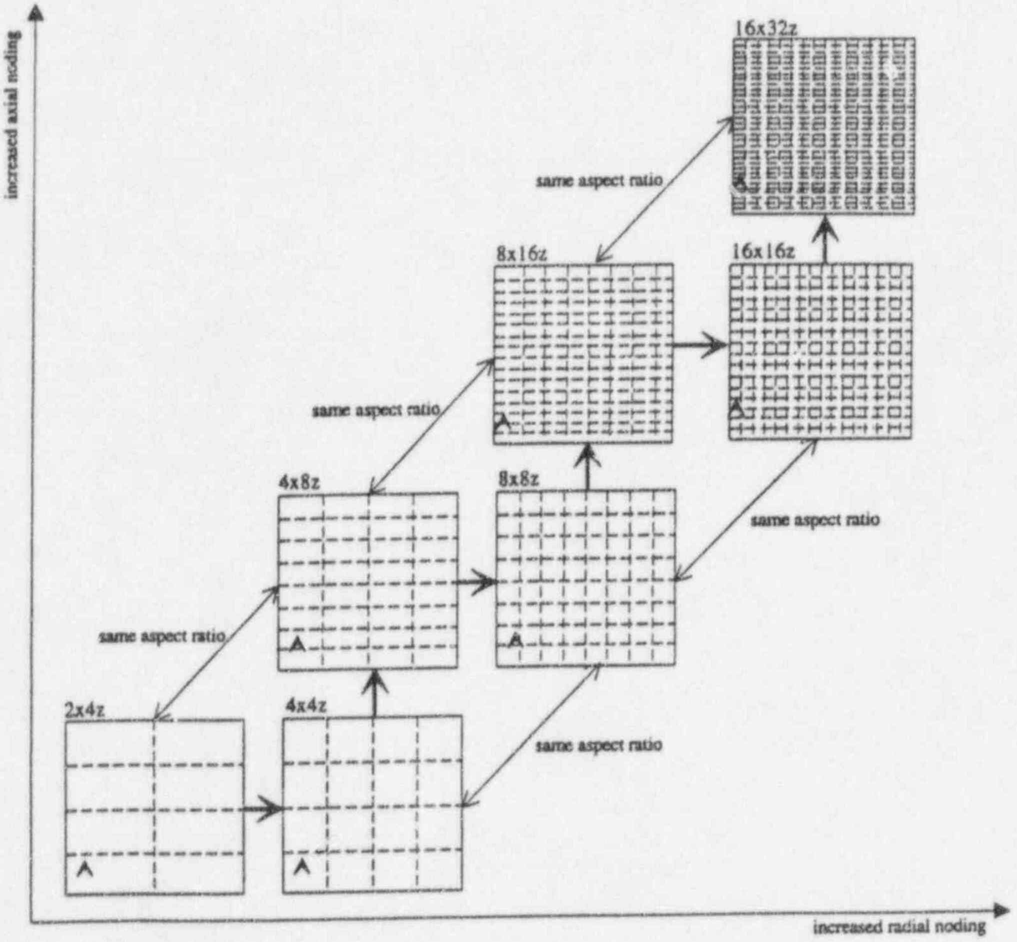


Figure 2: Succession of two-dimensional parallelepiped models

These models were used to study the convergence of the WGOTHIC code. The results that were compared were the pressures, temperatures, wall velocities, recirculation flow from top to bottom, and the steam partial pressures. These results were selected because they are the key parameters of a containment analysis and inputs to the passive cooling features.

These models all included the steam-only component for a large break Loss of Coolant Accident (LOCA), used GOTHIC conductors for the shell assuming a constant outside wall temperature of

120 degrees Fahrenheit, and used Gido-Koestel as the mass transfer correlation. The Gido-Koestel correlation was selected because it includes a dependence on the vapor velocity.

The predicted pressure is important in design calculations because it is the number that is compared to the design pressure of the containment vessel. The results of pressure versus noding are presented in Figure 3 below. This figure clearly demonstrates that the code converges on pressure as the nodalization is increased. By comparing models that maintain the same aspect ratio it can be seen that as the models are refined the pressure transients monotonically approach a lower value indicating convergence toward a solution. It can also be seen that as the nodalization is increased the predicted pressures are lower indicating that the code converges from the top down; that is, fewer nodes result in higher predicted pressures.

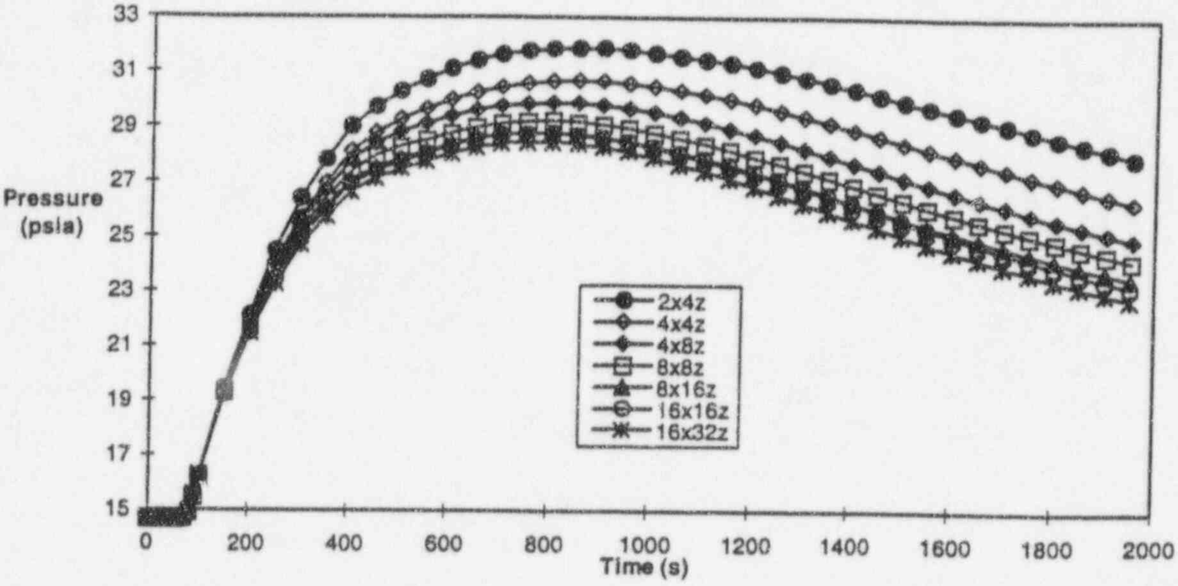


Figure 3: Pressure predictions for two-dimensional parallelepiped models

The results for the temperature comparisons are presented next in Figure 4. Containment temperatures are a basic result of containment integrity analysis. This is a plot of the temperature difference between the top cells and the bottom cells. These results indicate that greater numbers of cells are required in order to predict greater degrees of stratification.

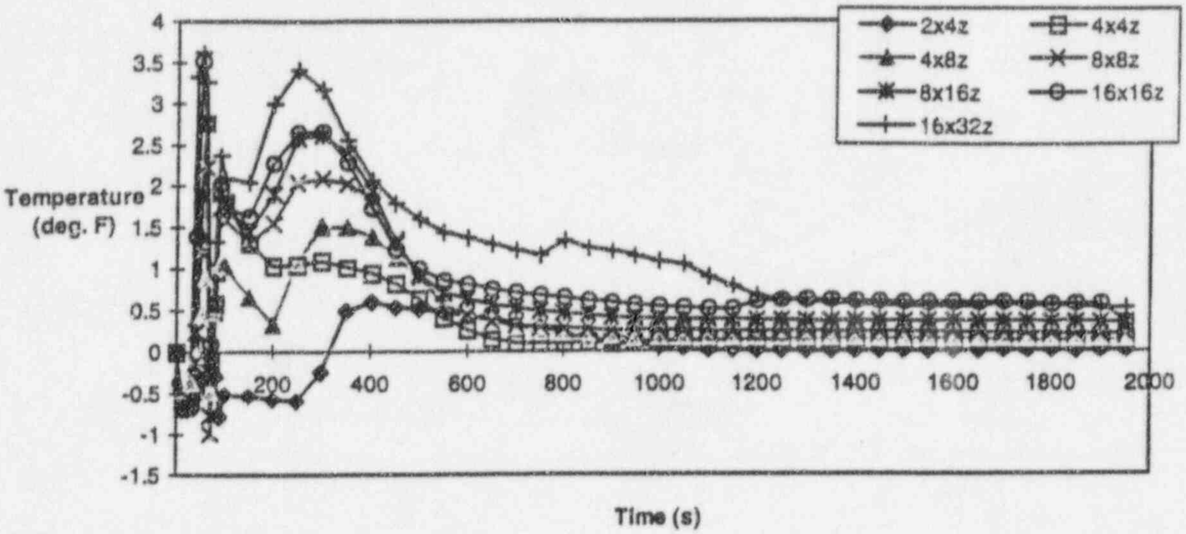


Figure 4: Top-to-bottom temperature differences for the two-dimensional parallelepiped models.

The next aspect of convergence that was studied was the vapor velocities along the walls. This result is not as important in AP600 containment integrity analyses since only free convection heat and mass transfer are used on the inner wall of the containment. Figure 5 presents the results of the vapor velocities at the mid-height elevation of the models. It is seen that as the number of nodes is increased the velocities that are predicted increase. The vapor velocity profile is quite steep near the wall and flat towards the center of the model. As the number of cells is increased greater resolution of the profile is permitted. Although this resolution never approaches the size of the boundary layer the averaging effects that occur across a cell become more dependent on a smaller section of the model, in this case the section nearest the outer wall which has a greater velocity. The fact that larger nodes underpredict velocities is conservative with respect to the heat and mass transfer correlations in the clime models; however, only free convection is used for the inner containment surface for AP600 containment integrity analyses.

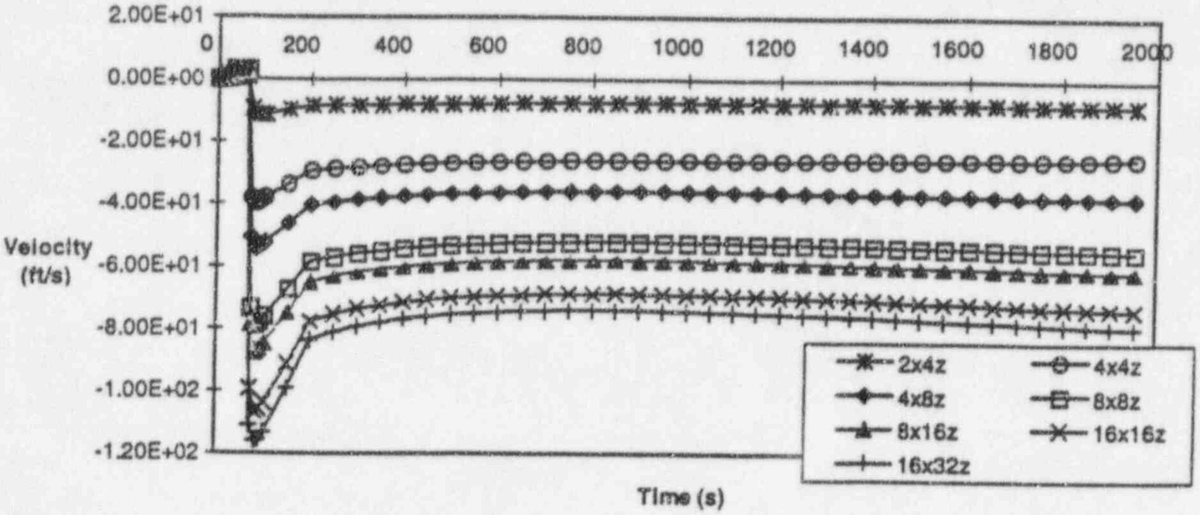
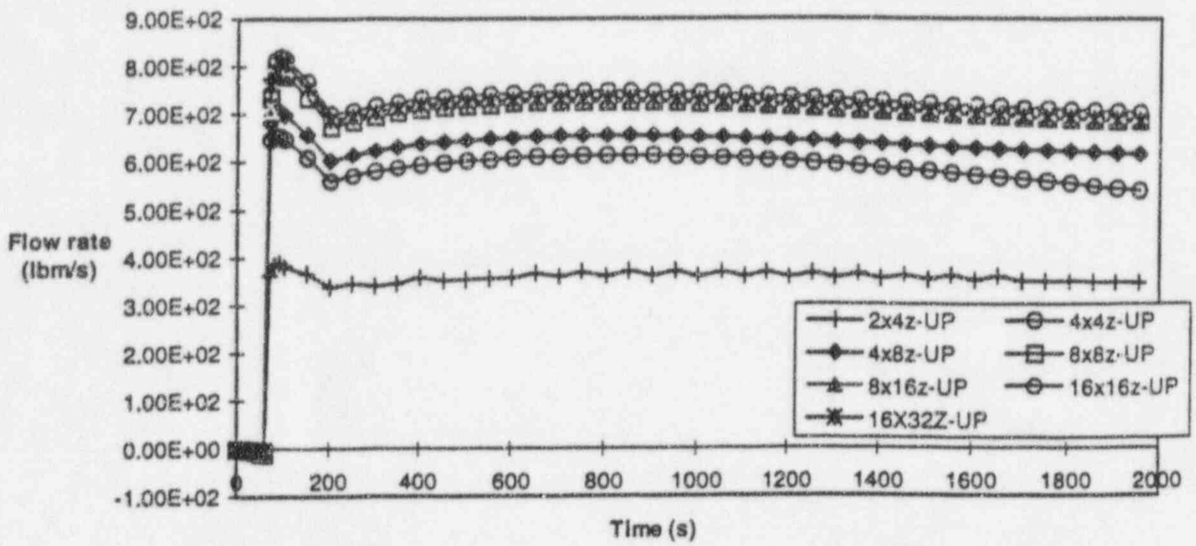


Figure 5: Mid-height near-wall vapor velocities for the two-dimensional parallelepiped models.

The recirculation flow is defined as the total vapor flow upwards at the midplane of the model versus the total downwards vapor flow at the midplane. This provides insight into the amount of mixing occurring in the model. Figure 6 provides these flow rates as a function of the model node size. It can be seen that as the number of nodes is increased, the total flows up and the total flows down converge to unique values.

a. Total Gas-phase Up-flow



b. Total Gas-phase Down-flow

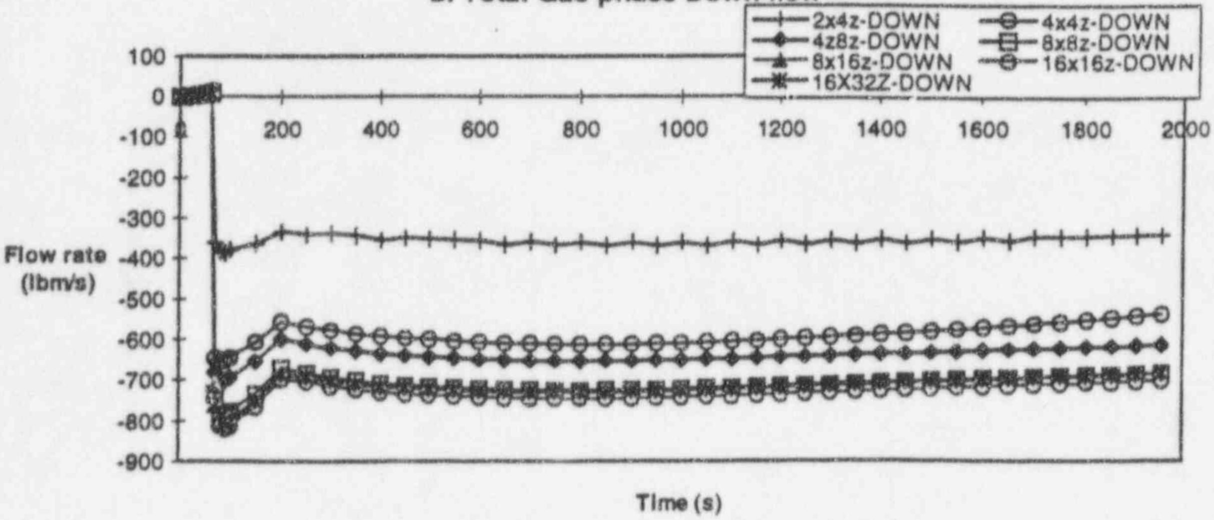


Figure 6: Mid-height global upflow and downflow for two-dimensional parallelepiped models

The concentration of steam versus elevation is an important input to the clime models since that concentration drives the mass transfer from the vapor regions onto the PCS shell. Figure 7 presents the difference in steam partial pressures at the top versus the bottom of the simple models. As the noding is increased in these models the difference in concentration tends to converge at greater values; the cases with fewer nodes are more uniform in concentrations. The absolute values of the differences are quite small in all cases indicating that the simple models are predicting a relatively well mixed region above the operating deck. Differences in steam concentrations that are this small will not have a noticeable effect on the results predicted by the Wgothic code.

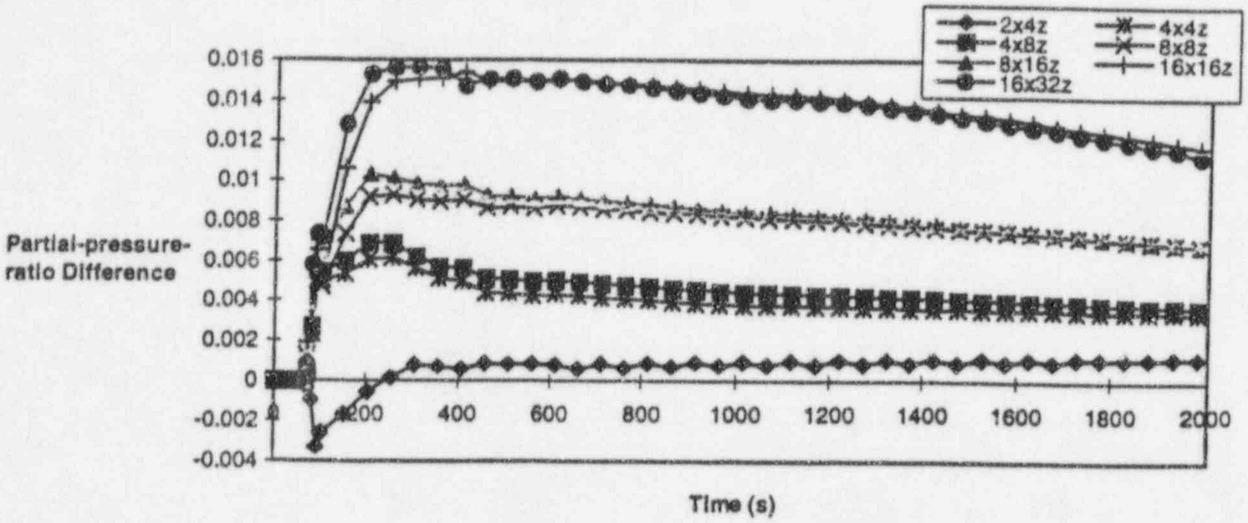


Figure 7: Top-to-bottom steam pressure ratio differences for the two-dimensional parallelepiped models

The two-dimensional parallelepiped model of a sector of the AP600 containment above the operating deck has been studied. The results of this study indicate that the WGOTHIC code does converge to a single solution as the number of cells, or the nodalization, is increased. It is also shown that if the aspect ratio of the cells is maintained, then convergence is easier to identify. The predicted pressures, temperatures, wall velocities, recirculation flows, and steam partial pressures all converge for the simple model that was examined. This supports the conclusion that WGOTHIC does converge and satisfies the first aspect identified earlier in this report for code and model convergence.

BARE SHELL NODING STUDIES - Full Above Deck Models

This portion of the noding study is a transitional step between the simple models described earlier and the more detailed models that represent the entire AP600 containment in full detail. These models will provide results on how the models behave, given that the non-uniform node-size reductions will be used, as opposed to the idealized noding studies done in the previous section.

These models were based on only the above-deck region of AP600. No heat sinks or internal flow obstructions were modeled. The compartments below the operating deck were not included. The GOTHIC conductors were modeled assuming the Guido-Koestel mass transfer correlation with a fixed outside temperature of 120°F. The steam and liquid mass releases associated with a large

LOCA were used as the accident boundary conditions, in contrast to the simple models in the earlier section which only modeled the steam release portion of the LOCA transient. The addition of hot and potentially superheated liquid, which will have the potential to flash as it enters the model, adds to the complexity and volatility of the problem being studied. The nodalizations that were studied are presented in Table 2.

Table 2: Full Above Deck Bare Shell Models

Model	No. Radial Nodes	No. Azimuthal Nodes	No. of Vertical Nodes	Model Corresponds to
1a-112	4	4	7	Westinghouse Lumped
2a-224	4	8	7	
3a-392	7	8	7	
4a-784	7	8	14	

The same pressure, temperature, etc. criteria were used to study convergence with these models. The pressure transients predicted with these models are presented in Figure 8. It is seen in this figure that the predicted pressures drop as the noding increases. The convergence is not as clear due to the variations in cell aspect ratios and the inclusion of the liquid component of the break mass and energy release.

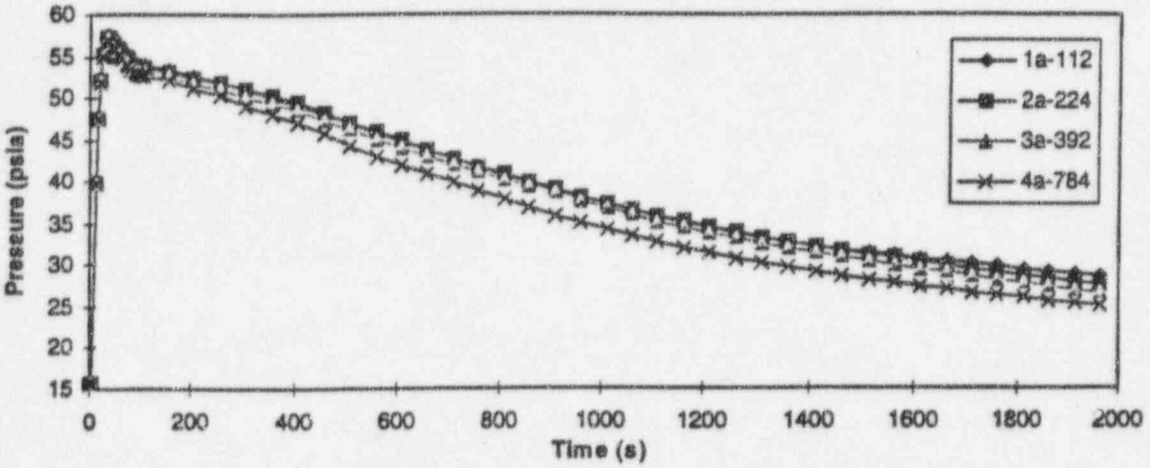


Figure 8: Pressure histories for the above deck models

The temperature transients are presented next in Figure 9. This figure is the top minus bottom vapor temperatures for the four different models. In this figure it is seen that the increased nodalization results in greater temperature differences from top to bottom and greatly smooths the transient response, as was seen in studying the simple models in the earlier section. The changes in the temperature differences from top to bottom occur with a reduction in the volume over which the incoming liquid and steam mass and energy release is averaged, which tempers the effects of the break on the parameter being measured at the top and bottom of the model. Although more difficult to discern, the temperature behavior of the bare shell models is in agreement with the simple models analyzed earlier in which greater degrees of noding are required to resolve the temperature gradient from top to bottom in the containment.

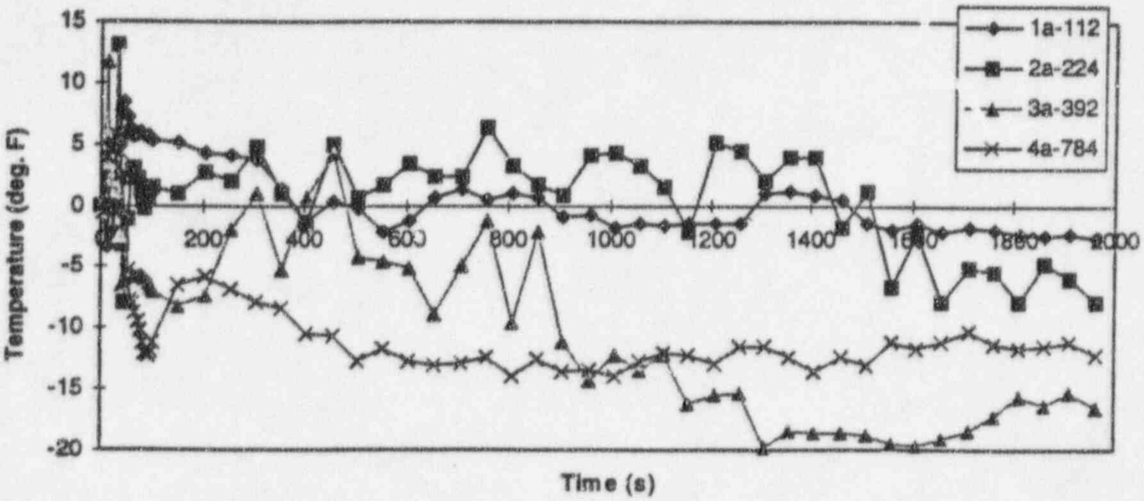


Figure 9: Temperature histories for above deck models

The near-wall velocities are studied next with the above-deck bare shell models. In Figure 10 it is shown that as the number of cells is increased the near-wall velocities increase. Again, this is consistent with the simple models.

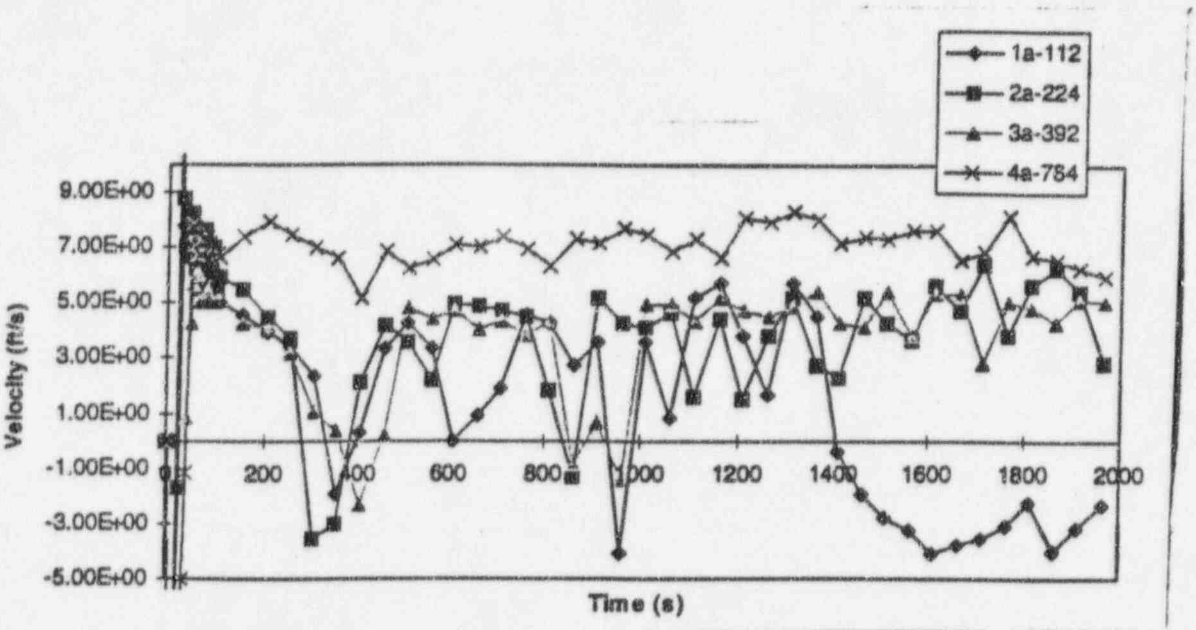


Figure 10: Near-wall velocities for above deck models

The steam concentration gradients are examined next. This graph presents the difference in the steam concentration, or steam partial pressure, from top to bottom in the models. The results of this comparison are less clear than they were for the simpler models. However, as the noding is refined the calculated differences in concentration from top to bottom become more stable and in all cases are predicted to be less that 0.15 psi different in partial pressure. These differences are again quite small indicating a well mixed environment and, based on the pressure results, this magnitude of a difference has very little effect on the predicted pressures.

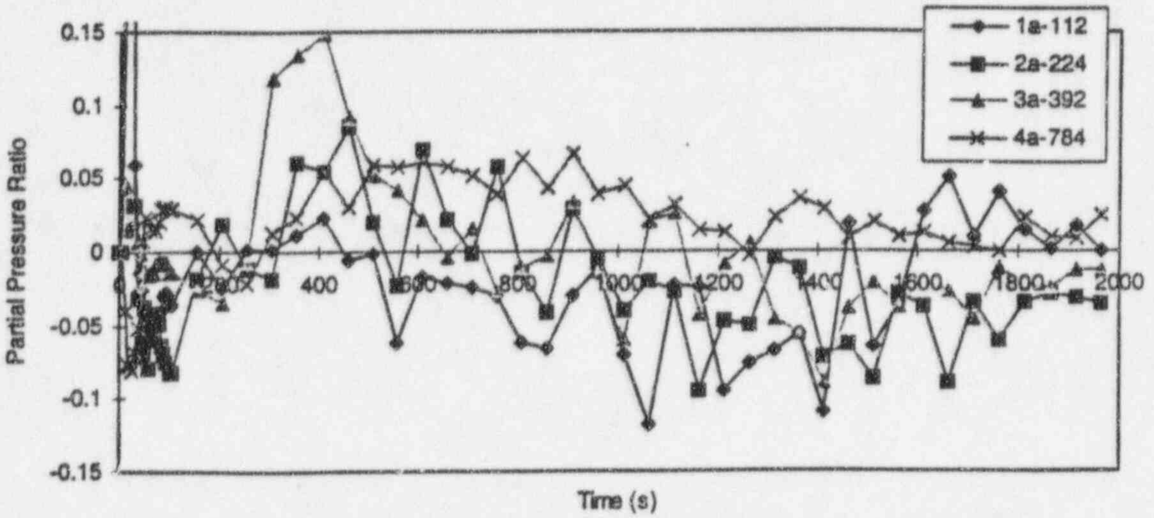


Figure 11: Steam-partial pressure ratios for above deck models

The full above deck models have been studied in the same fashion as the simpler parallelepiped models. The sensitivities to noding that were found for the simpler models are also found for the more detailed modeling of the AP600 above deck containment. The fact that the noding is more irregular in the full above deck models and the liquid contribution of the LOCA is modeled tends to obscure the very clear convergence trends of the simpler models; however, the parameters critical to predicting the heat and mass transfer in the AP600 become more conservative as the number of cells is reduced making coarser models conservative. As the number of cells in the model is increased these critical parameters trend towards a single solution.

COMPLETE AP600 NODING STUDIES

The final set of noding studies performed for the AP600 design involved complete models of the containment. Four models were constructed for this effort. In all of these models the regions below the operating deck were modeled as a network of lumped parameter nodes. All internal heat sinks were considered and the PCS was modeled using the Westinghouse climes instead of GOTHIC conductors.

The first AP600 model is the lumped parameter model developed by Westinghouse. This model is a network of lumped parameter nodes above the operating deck. The second model is a distributed parameter model that is noded based on the Westinghouse lumped parameter model. The third model is a more finely noded distributed parameter model developed by Numerical Applications, Inc. (NAI, the developers of the GOTHIC code) and is used in the SSAR analyses of the AP600.

The noding of this model is based on the distributed parameter evaluation model of the Westinghouse Large Scale Test which is described and validated in Reference 3. The fourth model is a distributed parameter model developed by M.I.T based on the results of their sensitivity studies. The three distributed parameter models are used for the majority of the sensitivities. At the end, comparisons between the lumped Westinghouse model and the distributed representation of the Westinghouse model are made. The noding characteristics of the models are presented below in Table 3.

Table 3: Nodalization of the Complete Models

Model	No. of Radial Nodes	No. of Azimuthal Nodes	Number of Vertical Nodes (above deck)	Notes
Lumped				84 lumped parameter node network
Dist. Westinghouse	4	4	7	based on Westinghouse lumped model
NAI	7	11	9	June 1995 distributed parameter evaluation model
MIT	6	8	7	

The three distributed models were used to analyze the LOCA transient. The results of the pressure comparison are provided below in Figure 12. The pressure traces for all three models are very similar with the exception of the second peak for the NAI model. This difference was found to be the result of inadequate noding through the internal heat sinks in the NAI model. Once the meshing in the heat sinks was refined the pressures came into agreement as is shown in Figure 13.

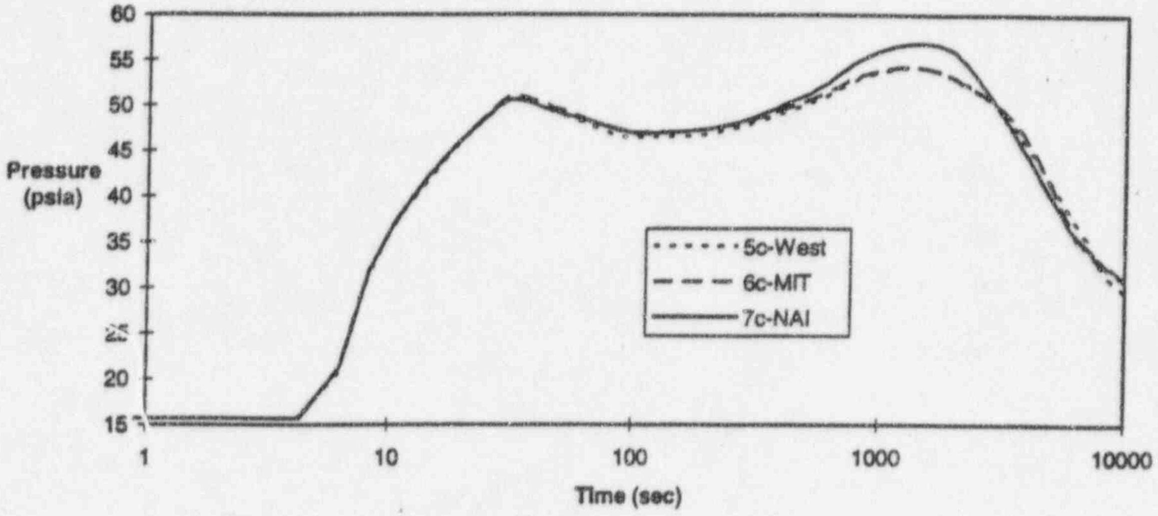


Figure 12: Complete model pressure transients

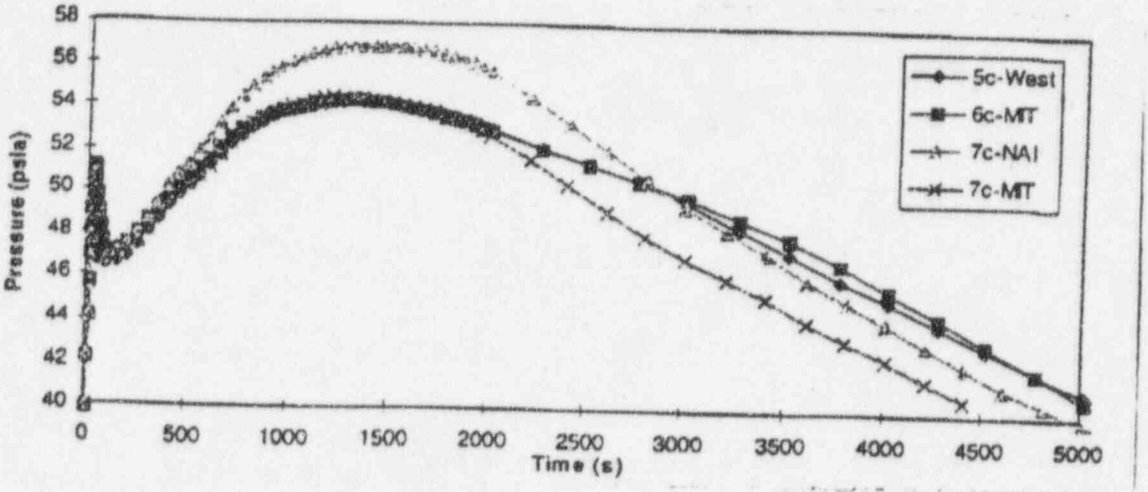


Figure 13: Pressure comparison including revised NAI model.

The predicted temperatures are compared Figure 14. The NAI and the Westinghouse models agree quite well and the NAI model deviates again due to the coarse noding through the internal heat sinks.

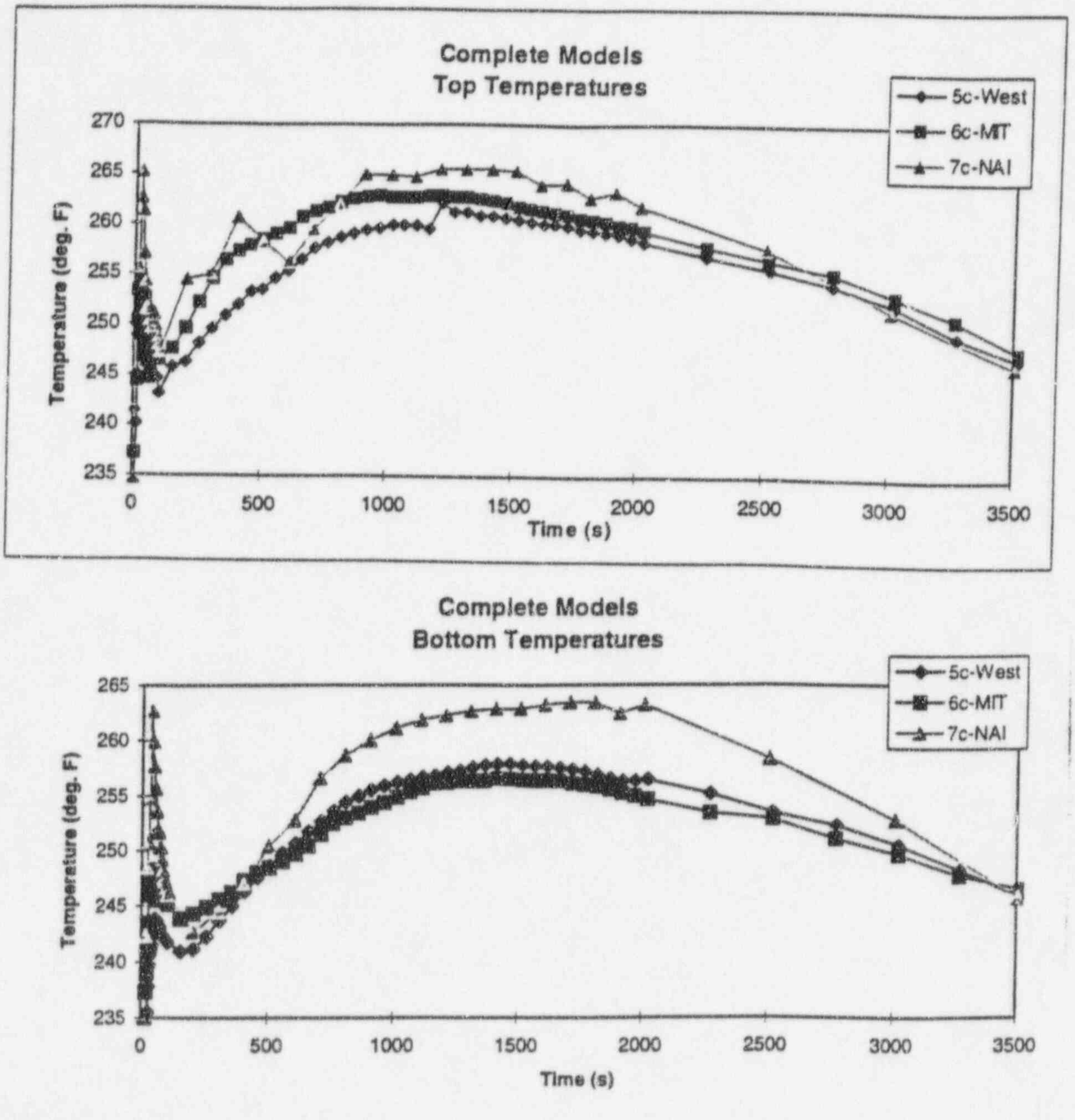


Figure 14: Temperature history for complete models

The wall velocities are compared next. Figure 15 shows that the near wall velocities are dissimilar among all the models. The greatest differences are found in the first few hundred seconds which is before the PCS cooling water flow is actuated (the PCS is assumed to actuate at 660 seconds into the transient). After the first few hundred seconds the velocities converge and are very similar. The velocities adjacent to the PCS wall are used to calculate the forced convection component of the heat and mass transfer in these studies. Since, based on these studies, it is difficult to refine a model to the degree needed to achieve convergence on wall velocities the SSAR analyses supporting the AP600 containment integrity analyses bound the effects of velocity by using only free convection on the inner shell surface and neglect the benefits of forced convection.

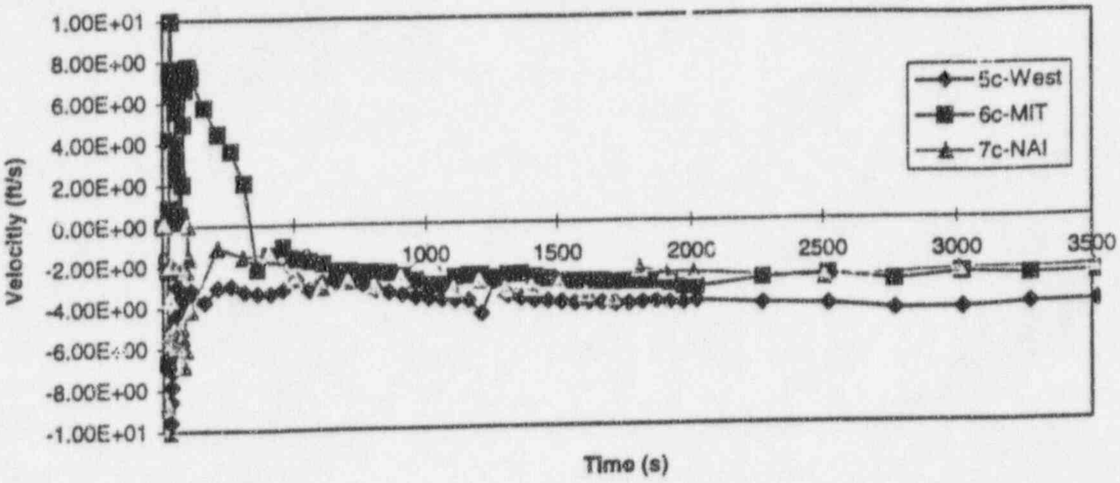


Figure 15: Complete model near wall velocities

The global recirculation flow rates are compared in Figure 16. The convective flow rates are different yet this difference does not result in large differences in predicted pressures. This result is expected since in all three cases the region above the operating deck is essentially well mixed. In addition, based on the AP600 energy partitioning$^{(3)}$, the PCS shell heat capacity is removing about 5% of the energy during blowdown up to a maximum of 35% of the energy by the time of the peak pressure. The external PCS does not become a dominant heat removal mechanism until after the peak pressure is reached since external cooling water flow is delayed.

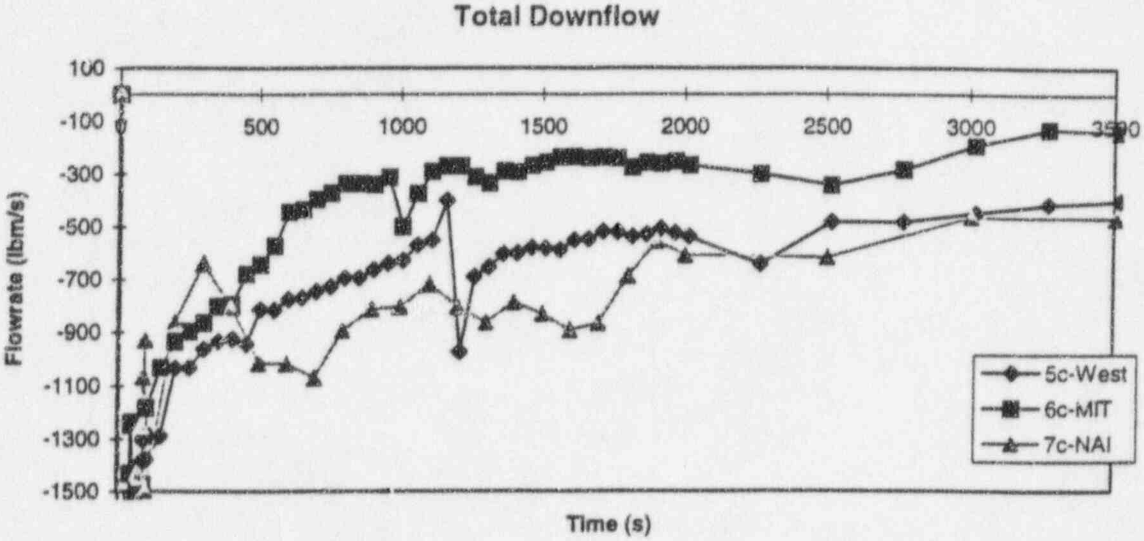


Figure 16: Recirculation for the complete models

The steam concentrations at the top and bottom of the above deck region also differ by amounts greater than those seen in studying the simpler models. These traces are provided in Figure 17. The difference in steam partial pressures from top to bottom are relatively large between the Westinghouse model and the MIT model yet the pressures predicted by these two models are very close. This would indicate that the overall clime heat and mass transfer for the containment are relatively insensitive to concentration differences of this magnitude.

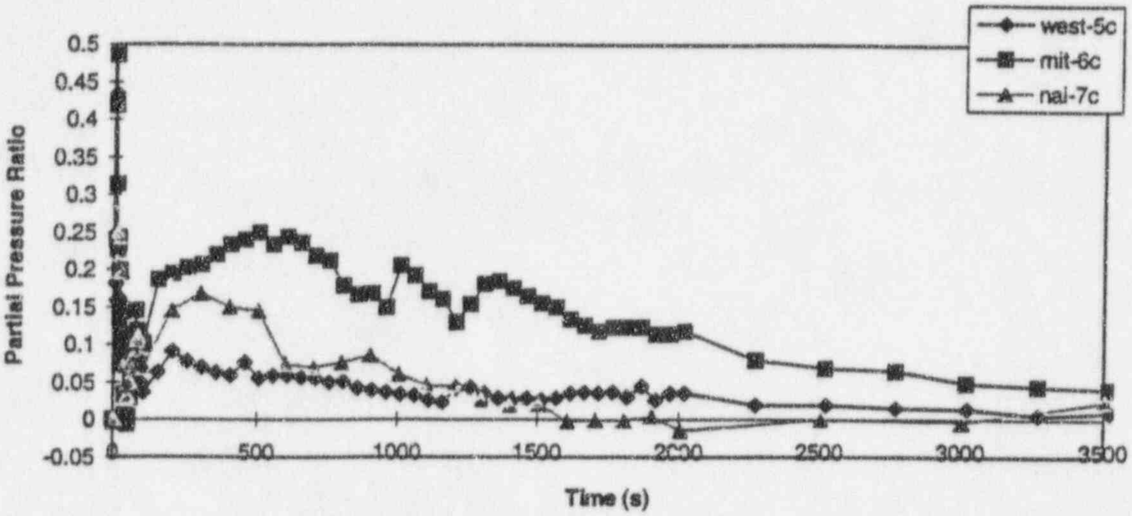


Figure 17: Complete model steam partial pressure ratios

Four completely different models of the AP600 containment were constructed by three different groups. Westinghouse constructed a completely lumped parameter representation of the AP600, MIT created a distributed parameter model of the AP600 based on the Westinghouse noding, MIT created a distributed parameter model based on the results of their noding studies, and NAI developed a model based on the results of the Large Scale Tests performed to support the AP600 evaluation model.

All of these models were found to predict essentially the same pressure transients after the heat sink mesh intervals were corrected in the NAI model. The wall velocities were found to be the most different between the models which leads to differences in steam concentrations between the two models. These differences are minor in light of the fact that the pressures in all models agree very well through the time of the peak pressure. The fact that all four models predict essentially the same results shows that the code is not particularly sensitive to modeling differences that may be attributed to different modelers. The exception to this would be the noding through the heat sinks in the NAI model which were found to be too coarse based on using the Biot numbers for the conductors to determine the appropriate mesh. The meshing for the AP600 evaluation models were established based on the Biot numbers for the conductors.

ADDITIONAL SENSITIVITIES

Additional sensitivities were performed by MIT to study features of the AP600. These sensitivities were for break location and wall-flow obstructions (e.g., crane rail). The results of these sensitivities using the MIT model are presented in Figures 18 and 19 below. In Figure 18 the break is moved to the other steam generator compartment. In Figure 19 the wall-flow obstruction modeling of the crane rail and the internal stiffener are removed.

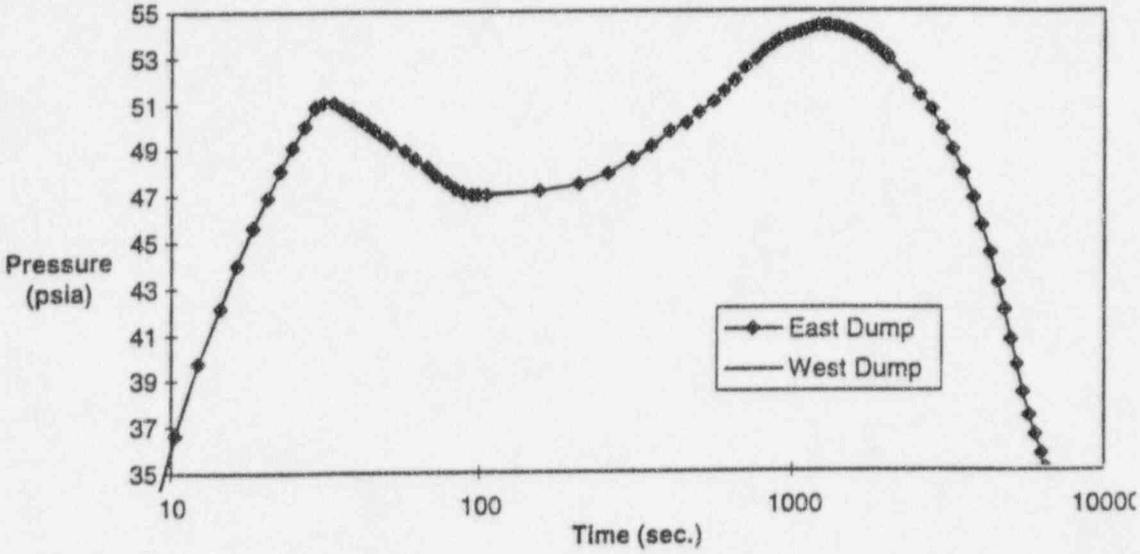


Figure 18: Pressure sensitivity to break release location

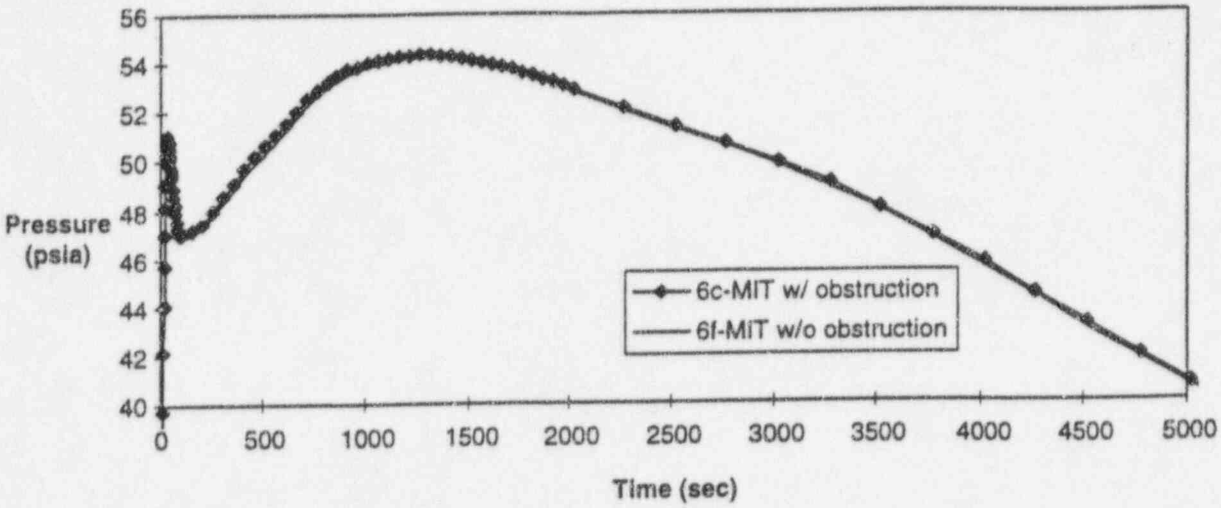


Figure 19: Pressure sensitivity to wall-flow obstructions

These sensitivities indicate that there is no strong sensitivity to break location even though the heat sinks are non-symmetrically located. The inclusion of the wall-flow obstructions has a very minor effect on the pressures which is expected since only free convection is used on the inner PCS surface due to difficulties in calculating the correct near-wall velocity.

This summarizes the results of the AP600 noding studies performed to study the effects of noding and how the WGOTHIC code converges and to assess the adequacy of the noding chosen for the AP600 evaluation model. The results of the MIT simple model studies support the conclusion that the WGOTHIC code does converge to a unique solution as noding is refined. They also support the fact that the code solution converges as the nodalization of the models is increased, this is particularly evident when the aspect ratio between the cells is maintained as the number of cells is increased. This top down convergence means that coarser models are conservative with respect pressure which is the results of a containment integrity analysis. Finally, four different models of the AP600 were constructed by three different groups with noding coarser and finer than that used in the AP600 distributed parameter evaluation model. These models all predicted essentially the same pressure responses for the AP600. These all support the acceptability of WGOTHIC and the evaluation models being used to analyze the AP600.

LARGE SCALE TEST NODING STUDIES

An additional set of noding studies were performed and compared to test results from the Large Scale Tests (LST) performed to support the AP600 design and analyses. These studies are documented in Reference 4. These studies used best estimate boundary conditions, such as actual initial conditions and geometries as opposed to the bounding assumptions made for design basis analyses.

In those noding studies a number of issues were reviewed. Vertical noding above the operating deck was studied as was noding around the broken loop steam generator compartment, noding of open and dead ended compartments, and the angular noding around the containment shell. The results of these studies indicated that the noding around the steam generator compartment containing the break was important. This result was factored into the distributed parameter model of the AP600 created by NAI. The noding used for the lumped parameter comparisons was used to generate the full model of the AP600 in the lumped parameter Westinghouse model discussed in earlier sections.

The results of the LST validation comparisons using nominal inputs are that the lumped parameter model consistently overpredicts the pressures and that in all but two of the eleven cases the distributed parameter model overpredicts the pressures, the other two cases only slightly underpredict the pressures.

Based on the results of the comparisons to the LST results it is concluded that it is conservative to use either the lumped or distributed modeling of the AP600 with the selected noding for containment integrity analyses.

CONCLUSIONS

A study of the noding for the AP600 and the convergence of the WGOTHIC code has been performed and is summarized in this report. The results of the simple model noding studies indicate that the WGOTHIC code converges to a unique solution. The bare shell models provide a basis for extending conclusions from the simple models to the complete AP600 models. The results from the bare shell models indicate that the noding patterns used to model the above deck region are conservative with respect to pressure. The comparison of the complete AP600 models created by different groups shows that the code is insensitive to differences that could arise as different people interpret the same problem. Finally, the comparisons to the Large Scale Tests indicate the both the lumped parameter and distributed parameter models are conservative for use in analyzing the AP600 containment.

All of these results and sensitivities taken together provide the basis for concluding that the WGOTHIC code converges as noding resolution increases. They also support the conclusion that the noding used to analyze the AP600 is adequate and conservative.

References

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