CFD Analysis of Automatic Test Equipment

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ABSTRACT

In many cases the goal of CFD modeling is the accurate prediction of chip junction temperatures within large electronic enclosures that contain numerous boards, flow obstructions, and other thermal/fluid modeling challenges. Although it is often impractical to develop a single, coherent CFD model that accurately predicts both system and board level performance, many electronic enclosures demand such an approach. Automatic test equipment (ATE) for testing semiconductors fits into this category. Reliable operation of ATE is critically dependent on maintaining a stable thermal environment within the test head. The complex architecture of the test head, containing heavily populated boards arranged in a radial manner, make it impractical to accurately predict board and system level performance discretely. This paper documents a successful methodology to model complex systems that require simultaneous system and board level thermal/fluid interactions. First, a CAD model integrating the board and system level geometry was created using Autodesk Inventor 4.0. This CAD model was then imported into a CFD Solver. The CFD solver used was CFDesign 4.1, a finite element fluid flow and heat transfer solver. CFDesign's ability to import geometry using any industry-standard format and quickly prepare it for simulation was the key to creating a CFD model that accurately predicts both system and board level thermal performance concurrently. By employing the above CAD and CFD tools in concert with experimentally validated assumptions, chip junction temperatures were accurately predicted as well as their sensitivities to system level characteristics.

KEY WORDS

CFD, Automatic Test Equipment, FEA, Thermal and Flow Modeling, Computer Simulation, Airflow and Temperature Measurements, Flow Resistance, System Impedance.

INTRODUCTION

Credence Systems Corp., Hillsboro, Oregon, is a world leader in the manufacture of automatic test equipment. The company has found that fluid flow and heat transfer analysis, or computational fluid dynamics (CFD) software could be used to help guide the thermal engineer in devising cooling strategies for its automatic test equipment. One project involved the design of an ATE's air-cooled test head.

The complex architecture of the test head made it impractical to accurately predict board and system level performance discretely. The goal, therefore, was to develop a CFD model that accurately predicts both system and board-level performance concurrently.

SYSTEM DESCRIPTION

Figure 1 shows the complete Automatic Test Equipment system. Of this system only the test head shown in the foreground is of thermal concern.

The test head, shown in figure 2, contains 8 pin modules with electronics and equipment to distribute and interface power and signals to the device under test (DUT). Each of these pin modules contains 8 pin cards and a distribution board for a total of 72 cards. The pin cards are arranged in a radial manner in 5° intervals around a central inlet.

Air is drawn in at the top of the test head through an opening. The air then passes through the wedge-shaped channels formed by each pair of cards and exits through 16 fans mounted at the perimeter of the test head. Each fan produces 85 cfm at the given system impedance.

Figure 3 shows a typical pin card used in the test head. The key thermal concerns are the eight drivers which dissipate 1.5 W each, eight comparators which dissipate 1.0 W each, and eight timing chips which dissipate 2.25 W each. The preferred die junction temperature is between 85° C – 90° C and the worst case allowable ambient air temperature is 30° C. The θ_{jc} is around 1.5°C/W. The test head dissipates a total of 8 kW.

THE CFD MODEL

Geometry and mesh

The modeling approach exploited the cyclic symmetry of the card layout. Fig. 4 shows the geometry of this wedge-shaped domain. Two adjacent cards, the test head centerline, and the outer wall of the test head enclosure bound the domain. The intent of this model was to characterize the flow field within a single card slot and to predict the case temperatures of the principal components

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modeled. The heat dissipated by the driver, comparator, and the timing chips, constitute the key sources of thermal loading on the pin card.

The model shown in fig. 4 was created using a commercially available CAD package [1]. This CAD representation was directly imported into the CFDesign modeler [2]. With very few steps, this model was then converted into a fully meshed finite element CFD model.

This meshed model would be considered quite coarse by any normal CFD modeling standards. For example, flow passages through the domain were meshed with no regard to the number of elements spanning across the flow channel. In most cases only one element was used to define the edge-to-edge separation. Normally CFD theory, with regard to FEA methods, would recommend a minimum of 5 nodal points (four 4-node tet elements) from edge-to-edge across the flow channel. The CFD solver used in this investigation [3] has the unique ability to inflate or enhance the coarse mesh near walls. Walls, in this context, refer to surfaces of the FEA model where airflow encounters turbulence. The mesh inflation creates a multi-layered mesh of six-node wedge elements using the initial surface mesh as a template. The number of layers and their thickness' are user-defined. The end result allows the user to create and use an incredibly coarse FE mesh (minimizing computational pre-processing and data storage tasks) and yet obtain high quality CFD results.

Thermal and flow modeling

The thermal load on each chip, as described earlier, was applied as a volumetric heat generation. The chip packaging was simplified down to a monolithic solid having the thermal properties of a silicon die [4]. The chip solids were then meshed in such a way that a direct conduction path was established with the pin cards.

The pin card was modeled as a standard 12-layer FR-4 printed circuit board with geometry specific orthotropic thermal properties.

The air inlets and fan outlets were defined next as shown in Fig. 5. A zero static pressure boundary condition was applied at the inlet. At the fan outlet, measured air velocity values as well as fan curve data were applied in separate simulations.

Determining system impedance

Static pressure losses through the complex flow channels inside the test head could not be easily arrived at by calculation. Relying upon air velocity measurements as well as an iterative process utilizing results from the CFD simulation, an estimate was made. The flow resistances due to the air inlet grill and the finger guards at the fan outlets were easily computed [5].

EXPERIMENTAL VALIDATION

Airflow and temperature measurements were made on a fully operational test head to validate the results of the CFD simulation.

Airflow measurements

The air velocity between cards is location specific. The pin cards located near the corners see lesser airflow between them. Figure 6 shows the locations of the airflow sensors (CAFS-220 probes from Cambridge Accusense) on a one-quarter model of the test head. Figure 7 shows the average velocities at these locations.

Temperature measurements

As mentioned earlier the key thermal concerns are the eight drivers (Tritons) which dissipate 1.5 W each, eight comparators (Nyads) which dissipate 1.0 W each, and eight timing chips (Neptunes) which dissipate 2.25 W each. Initial attempts to place thermocouples on all of these chips resulted in inaccurate temperatures. Placing too many thermocouples inside the narrow wedge-shaped space between cards increased the impedance to the airflow. Subsequently three chips were identified as representative of the thermal concerns in the pin card and thermocouples were attached to them, see figure 8. Figure 9 summarizes the average temperatures measured on these chips on different pin cards.

RESULTS & DISCUSSION

The CFD modeling and simulation process matured over successive correlation between empirical data and the simulation results. Three cases are described here which highlight the significant milestones crossed in reaching the final results.

Case1 – The airflow boundary condition was assigned using the total airflow into the test head and dividing it by the total number of card slots. This model was useful in providing a first value in the iterative process used to determine system impedance. It did not however provide good temperature predictions.

Case 2 – System impedance based on the results of Case 1 were included. Also included were the flow resistances due to the air inlet grill and the fan outlet finger guards. Results obtained compared well with the measured values.

Case 3 – This model is mostly similar to Case 2 with the exception of the air velocity boundary condition was modified to represent a pin card located near the test head corners.

The results of these CFD simulations are summarized in fig. 10. These values were then compared with the empirical results. This is shown in fig. 11. The simulation predictions compared well with the measured temperatures and were in the worst case within 13.0°C and in the best case within only 3.0°C.

CONCLUSIONS

The results proved to be very useful in making design decisions regarding board layout based on the board-level thermal characterization and in sizing and selecting fans for air cooling based on the system level flow characterization. Work currently underway on Credence Systems next generation tester is reaping the benefits of this study.

ACKNOWLEDGEMENTS

The authors would like to thank Jeff Monroy, Director of Engineering, Credence Systems Corporation for his permission to present this paper. The author, Venkat Gaurav, would also like to thank his manager, Scott Withee, for his support and guidance and also his co-author, George Laird, for his valuable efforts in successfully completing this work.

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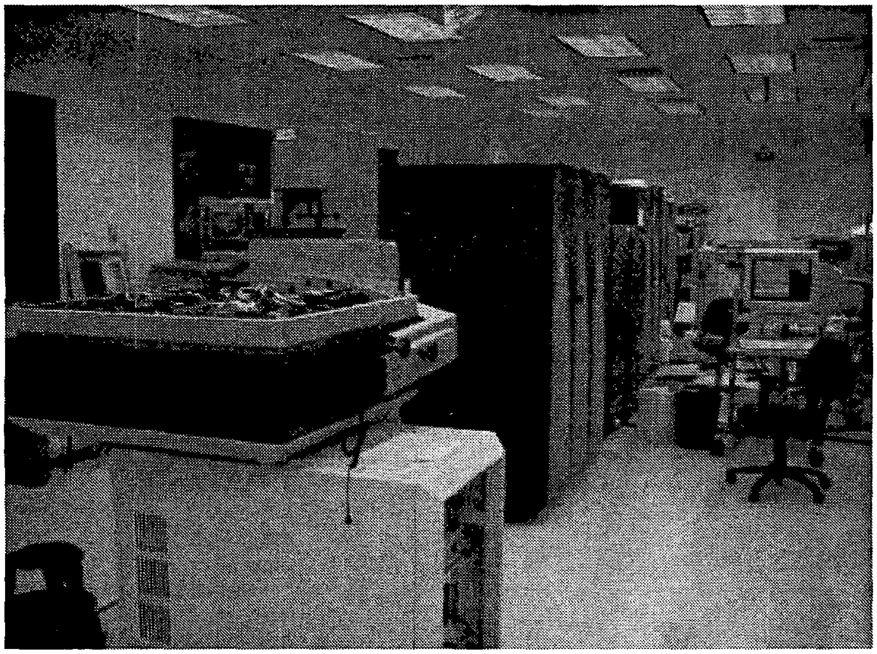


Fig 1. – Credence's Quartet 1 ATE system.

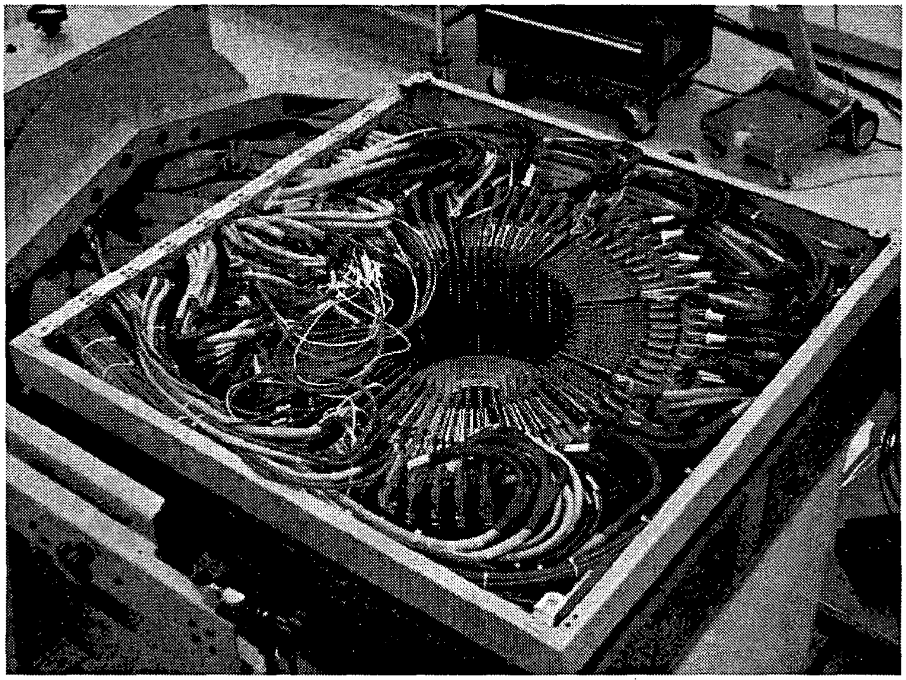


Fig. 2 – ATE test head showing radial array of 72 circuit boards with a total power dissipation of 8 kW. Air enters through the center and is pulled out the sides by 16 axial fans each producing 85 cfm.

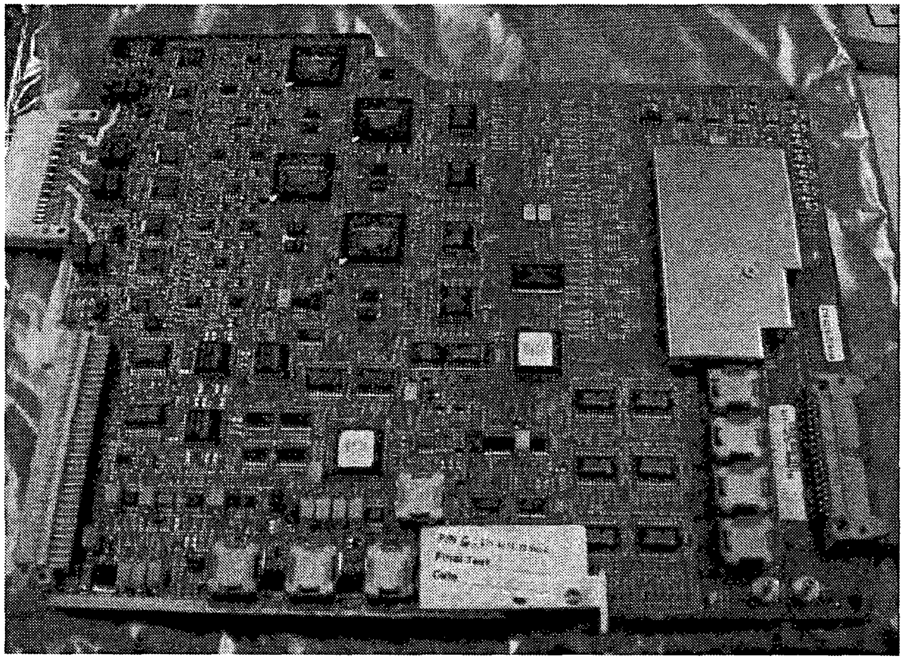


Fig. 3 – A typical pin card.

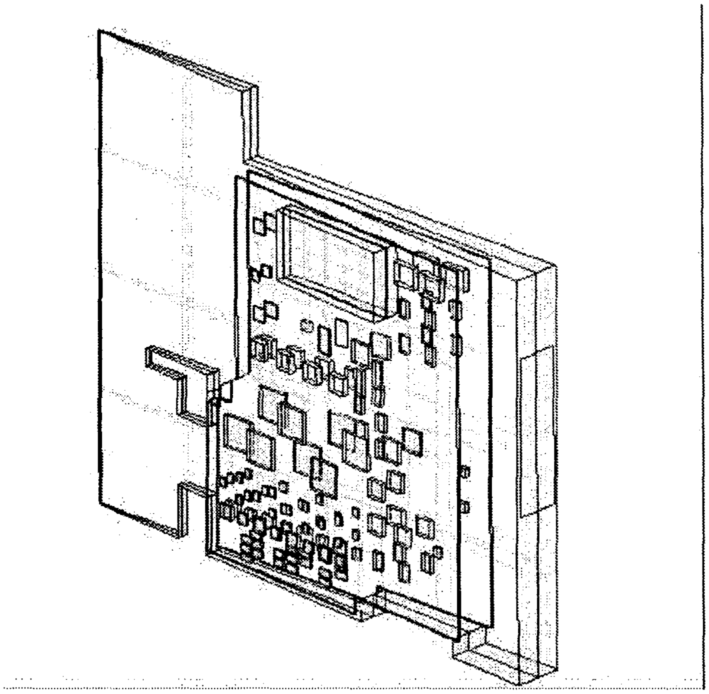


Fig. 4 – Cyclic symmetric geometry with two pin cards embedded within the flow volume. All power generating and flow obstructing chips are represented on the pin cards.

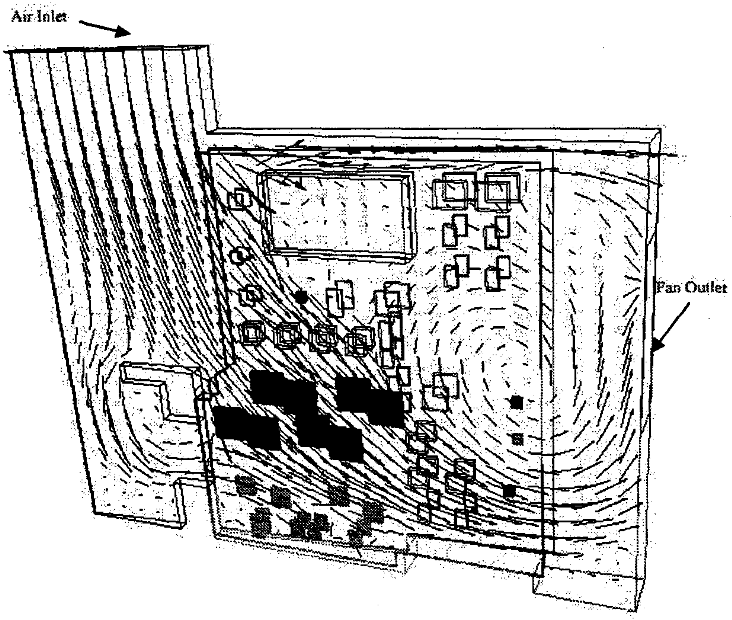


Fig. 5 – Airflow vectors.

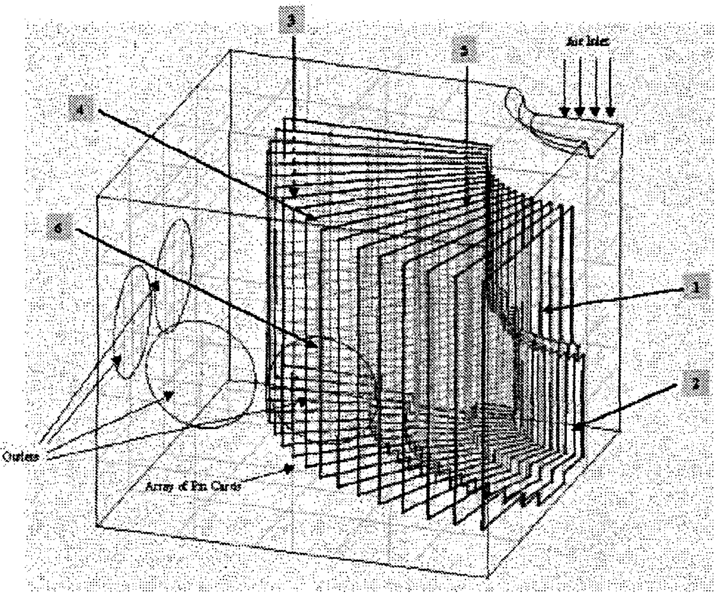


Fig. 6 – Quarter-section model of the test head showing the locations of the air flow sensors 1 through 6.

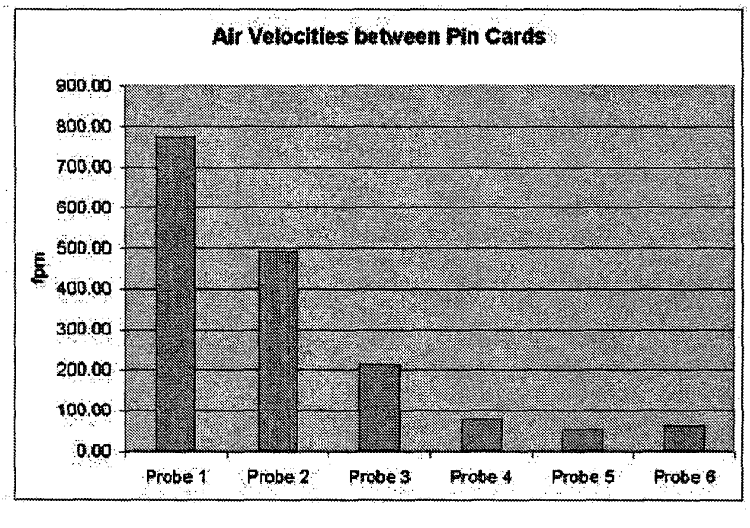
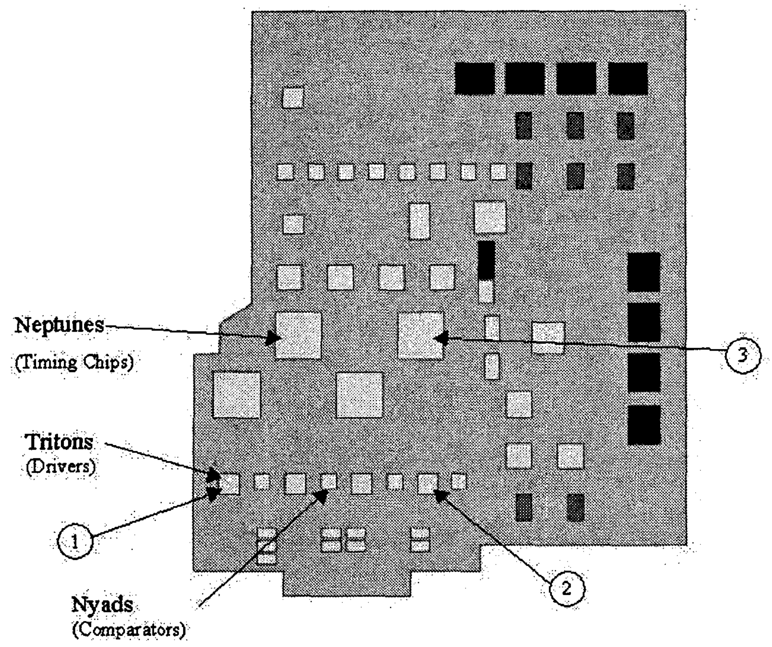


Fig. 7 – Measured air velocities between pin cards



Thermocouples attached at locations 1, 2 & 3.

Fig. 8 – Model of pin card showing thermally intensive chips. Three of these chips were selected for measuring case temperatures using thermocouples.

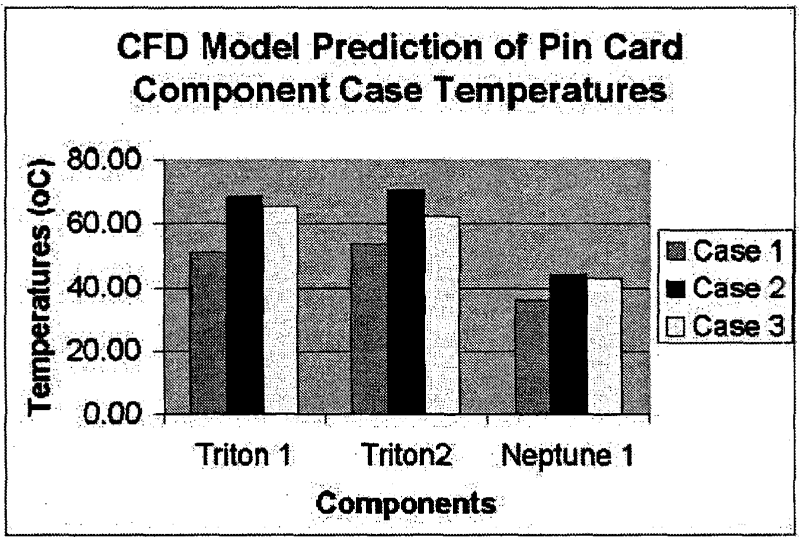


Fig. 9 – Measured values of case temperatures of selected components.

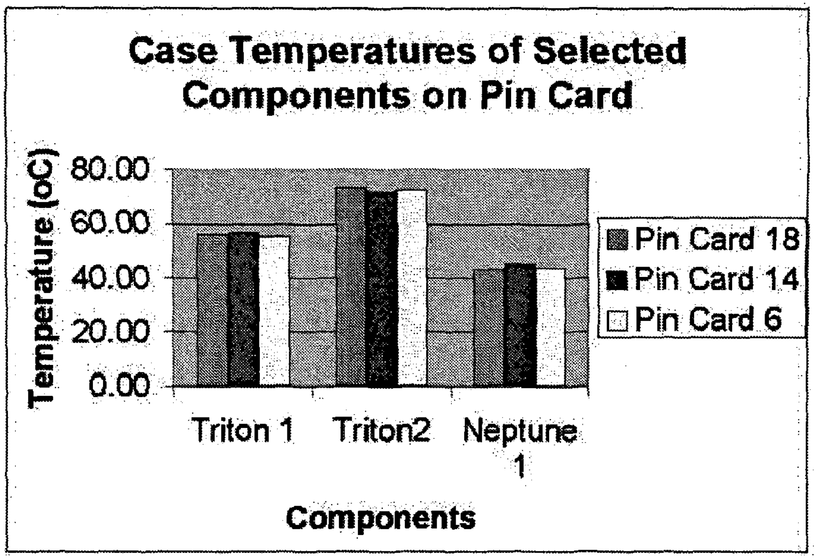


Fig. 10 – CFD model predictions of pin card component case temperatures for all three cases.

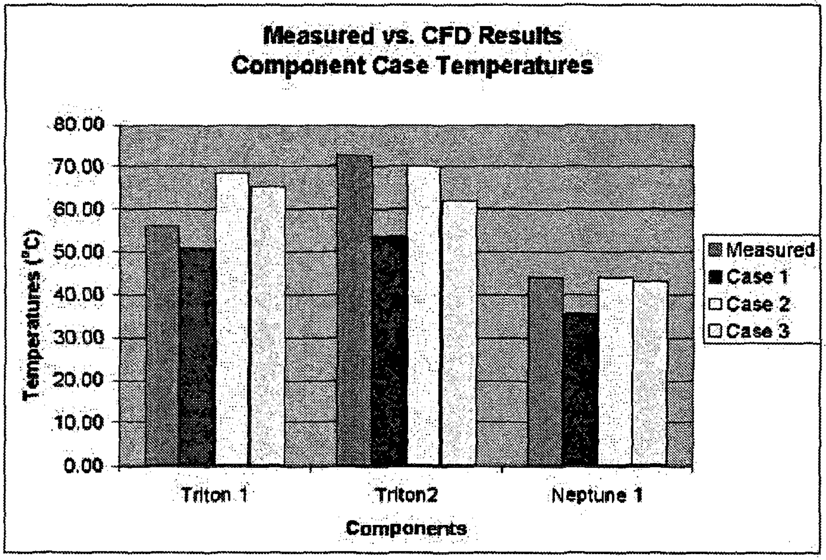


Fig. 11 – A comparison of the measured vs. CFD simulation predicted component case temperatures.