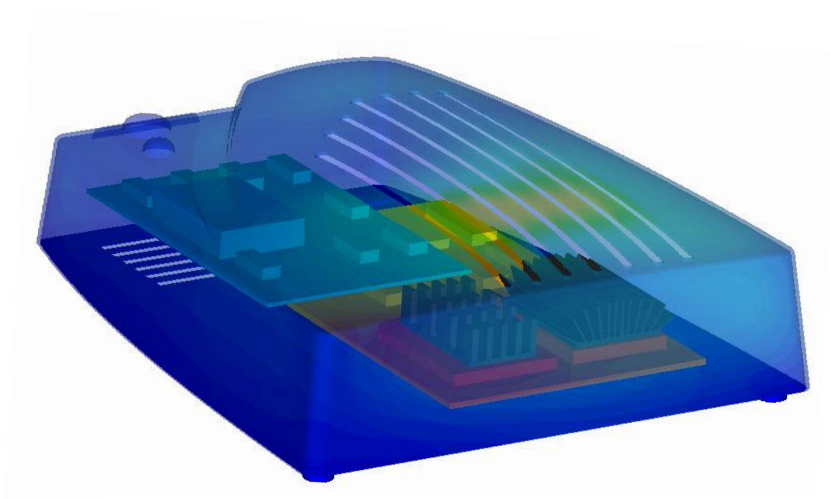
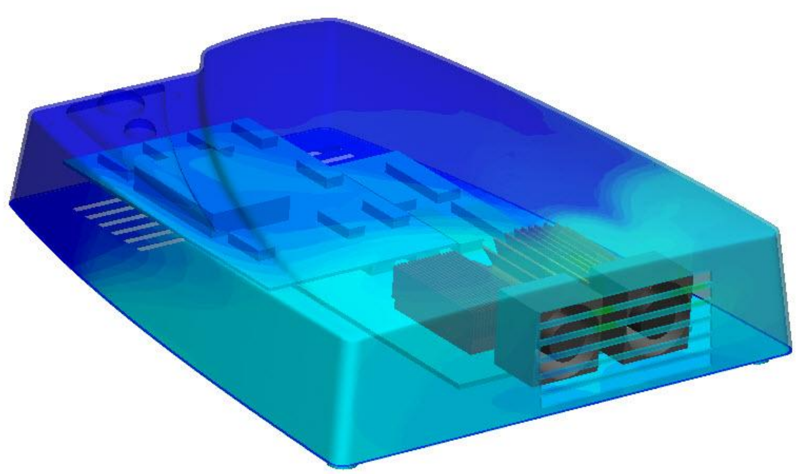
GDC Group Inc. Engineering Design Insight Report

Electronic enclosure D.O.E.



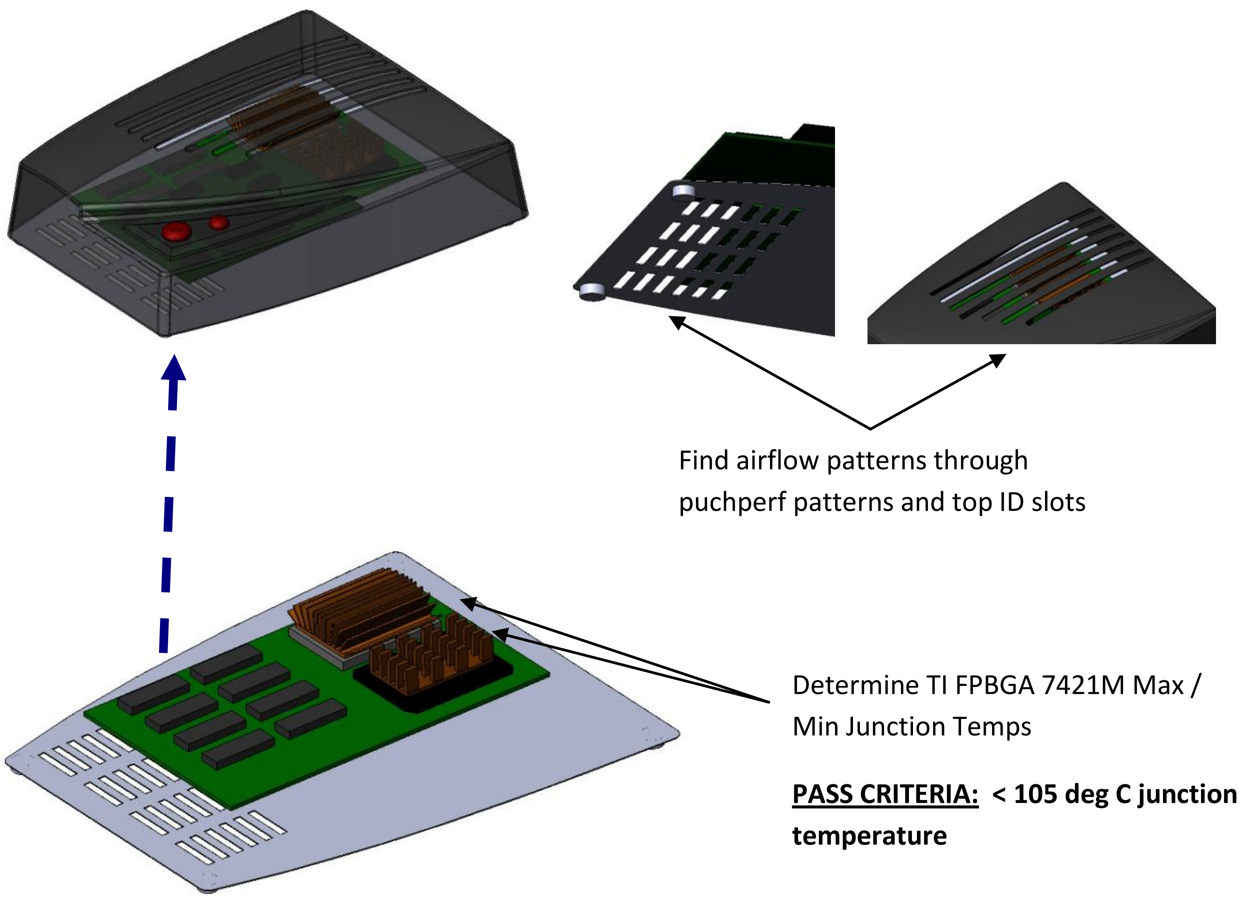
Initial Design Supplied to GDC Group Inc.



Revised Functional Design Supplied from GDC Group Inc. based on simulation insights and interaction w/ Client

Executive Summary:

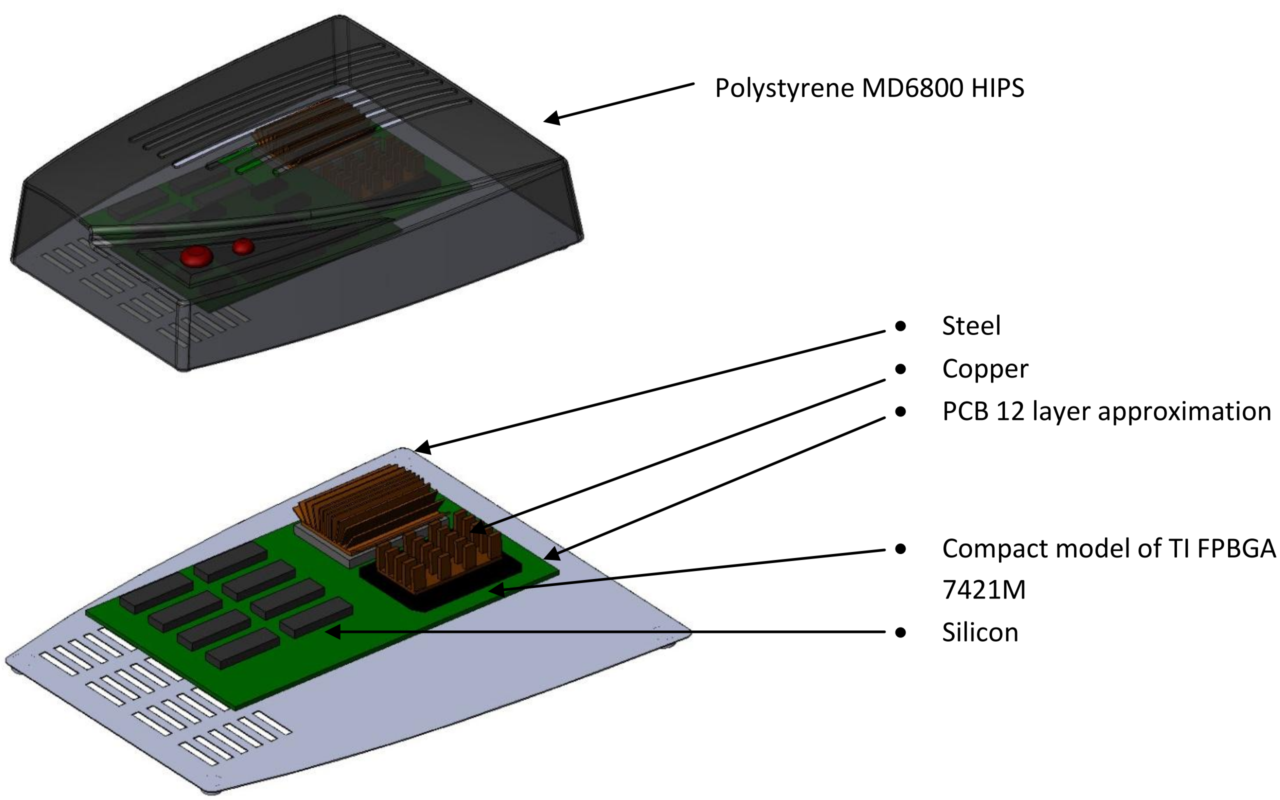
- From CAD model supplied, virtually prototype electronics cooling performance before physically prototyping
- Establish thermal characteristics of initial design including:
  - FPBGA processor maximum junction temperature
  - Validation of a natural convection cooled design
  - Airflow patterns / system impedance
  - Verify grill opening in bottom punch/perf pattern and plastic industrial design housing are sufficient to meet design goals
- Review initial results and optimize design based on simulation insight.
- **Revise design as necessary with GDC Group engineers and Client interaction**



Operating Conditions Simulated:

Initial Revision as supplied by client:

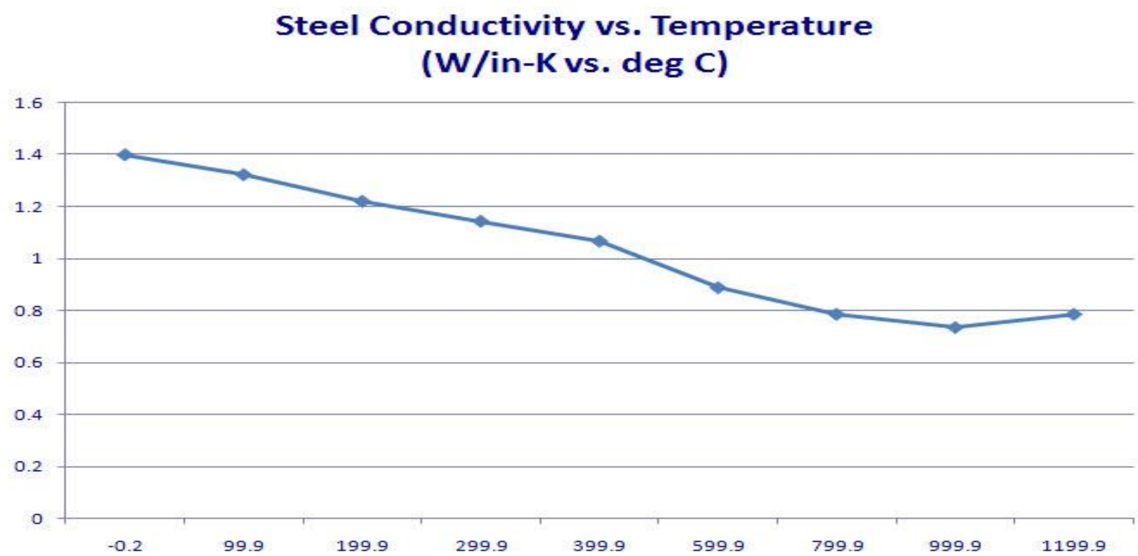
- Ambient temperature: 25°C
- Room air at sea-level surrounding product
- Product sits on an insulated (adiabatic) table surface
- TI FPBGA 7421M Specifications:
    - Steady-state power loading of 20 watts
    - Compact Thermal Modeling parameters: theta J_b = 0.65 C/W, theta J_c = 40 C/W
- EEPROM's Specifications:
    - Steady-state power loading of 0.5 Watts
    - Simulated "Silicon Constant" material
- Top case material: Polystyrene MD6800 HIPS
- Bottom case plate: Steel
- PCB's: simulated 12-layer approximated of anisotropic thermal conductivity
- Heatsinks: Copper with variable conductivity based on temperature



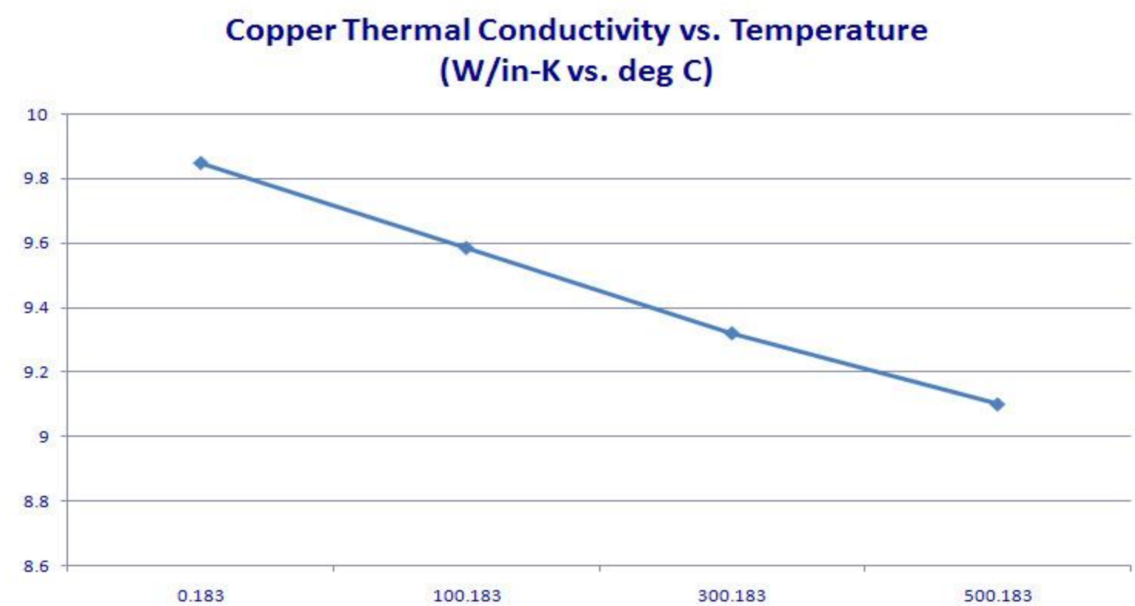
Material Details:

Please note: As this is a steady-state analysis some unecessary physical properties are not listed such as specific heat, density, etc.

- **Steel**:



- **Copper**:



- **PCB 12 layer material:**
  - K(x) = 2.1757 W/in-K
  - K(y) = 0.008476 W/in-K
  - K(z) = 2.1757 W/in-K

- **Silicon:**
  - K(isotropic)= 3.7592 W/in-K

- **Polystyrene MD6800 HIPS:**
  - K(isotropic) = 0.0006858 W/in-K

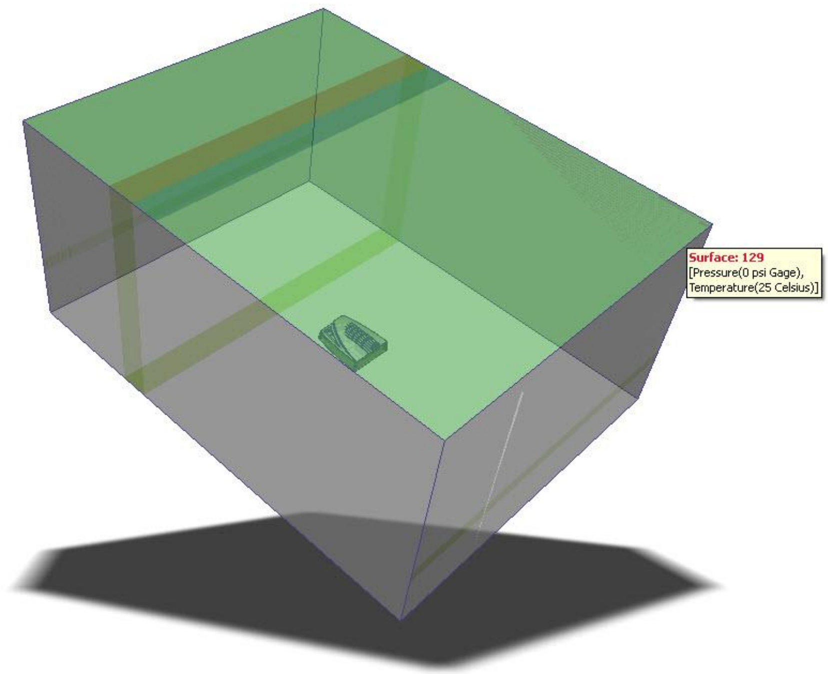
- **TI FPBGA 7421M Compact Modeling Values:**
  - theta J_b = 0.65 C/W,
  - theta J_c = 40 C/W

Operating Condition Application Details:

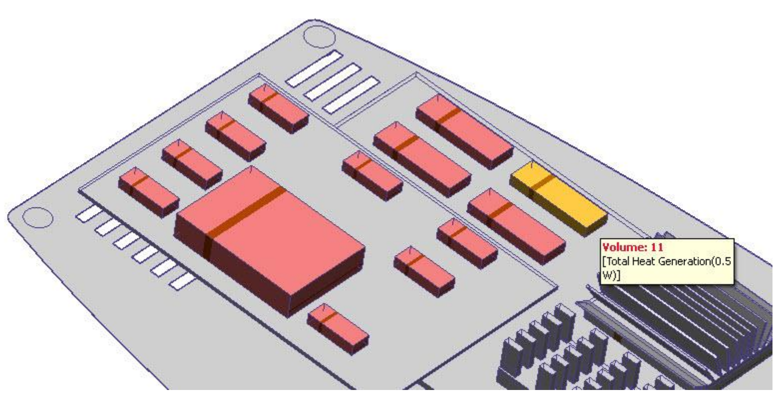
Initial Revision as supplied by client:

GOAL: try to use natural convection as only means of removing heat (no fans) to achieve acceptable junction temperatures

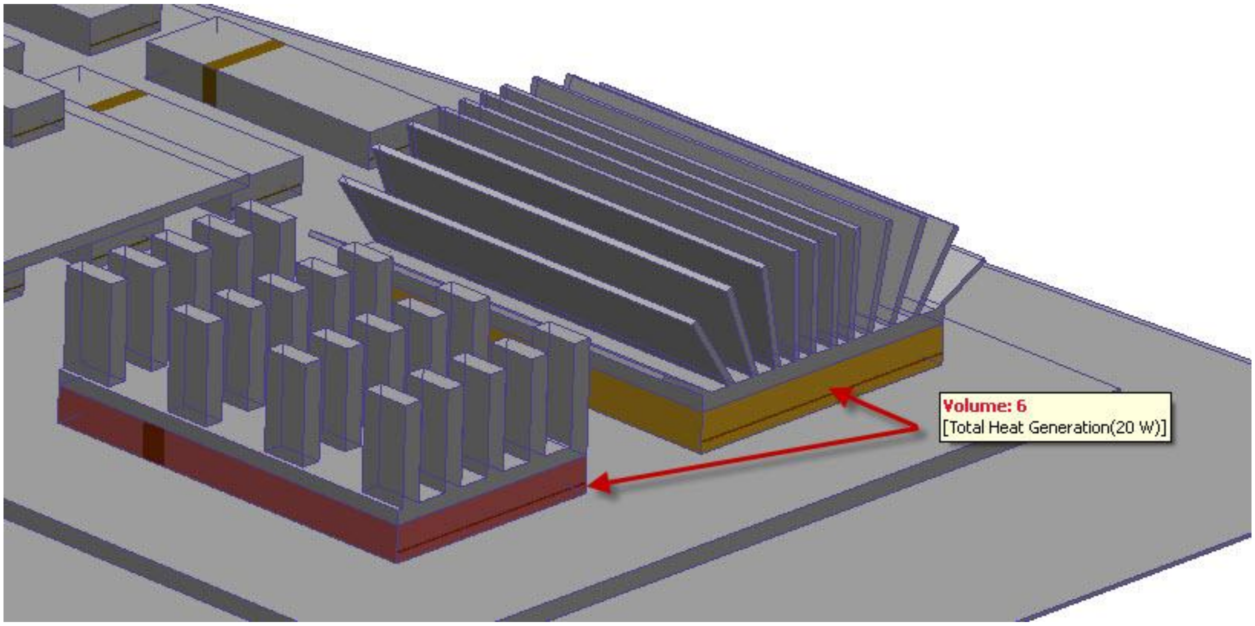
- Ambient room air set to 25 deg C



- EEPROM chips set to output a constant 0.5 Watts each

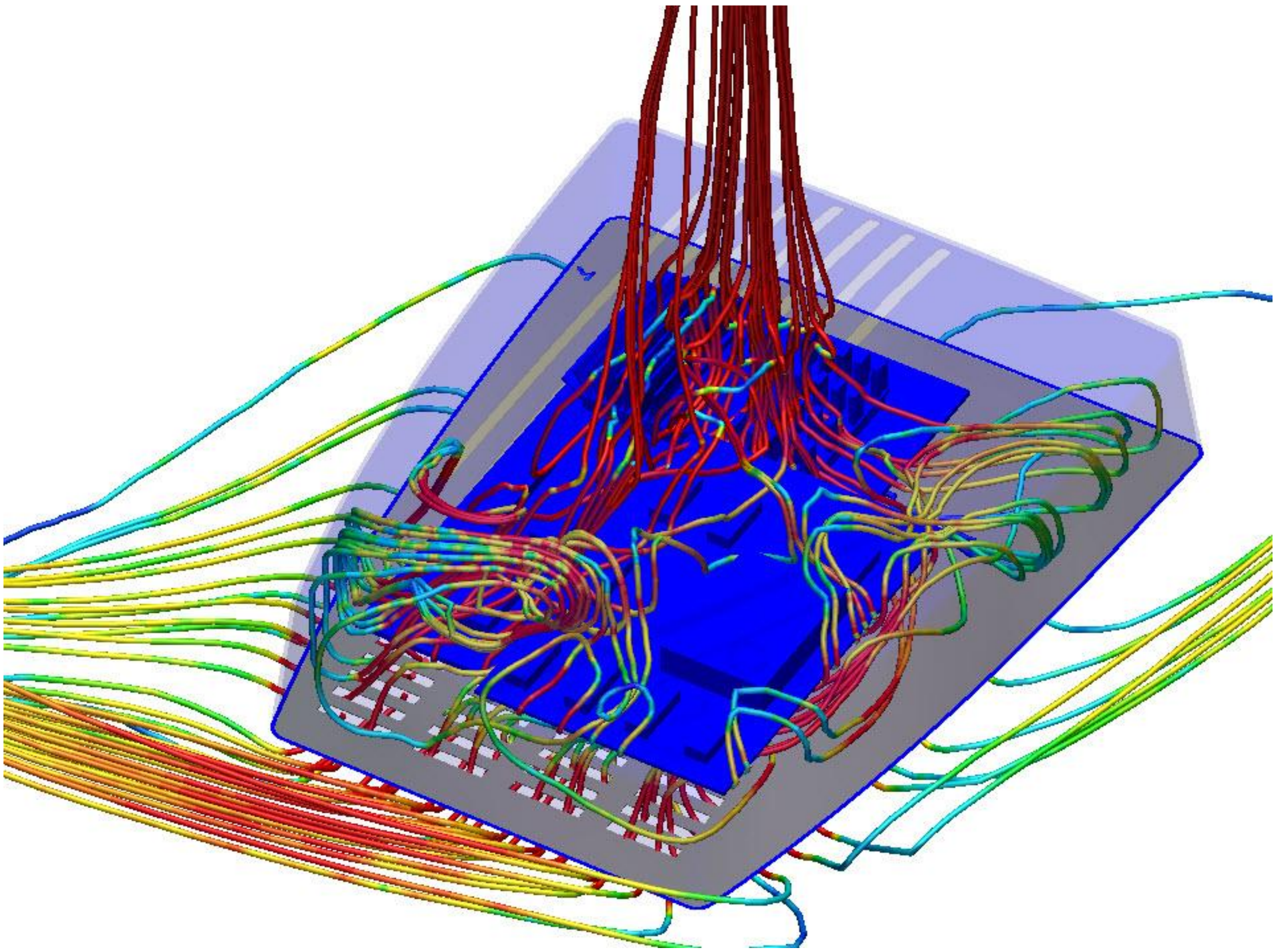


- TI FPBGA 7421M chips set to output a constant 20 Watts each



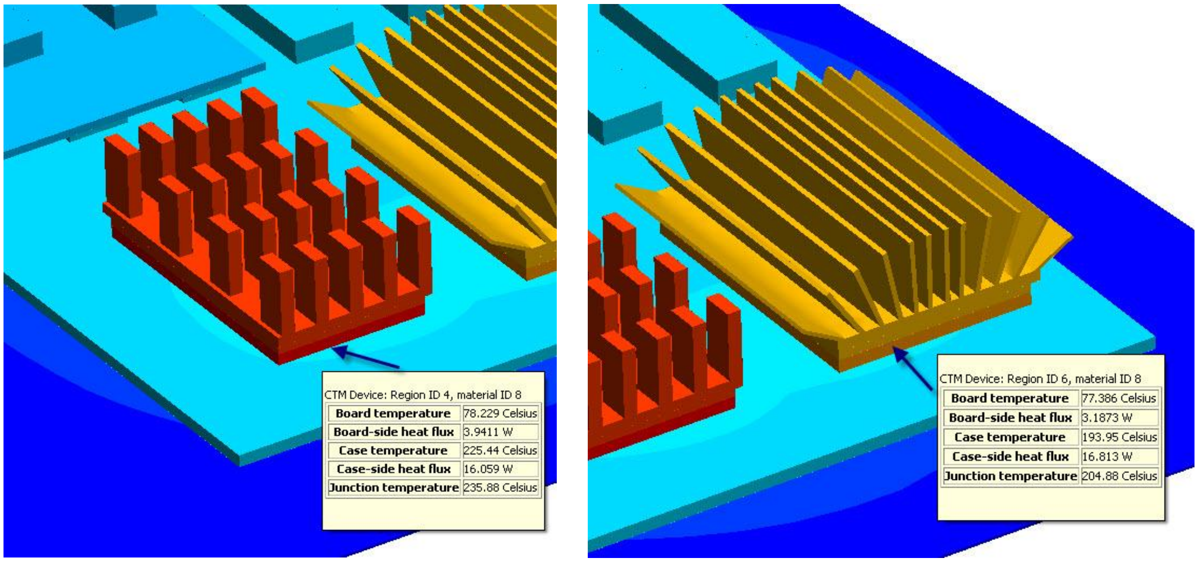
- As natural convection nearly always produces extremely slow moving air (i.e. very low Reynolds numbers), laminar flow was used

<u>Initial Revision Results:</u>



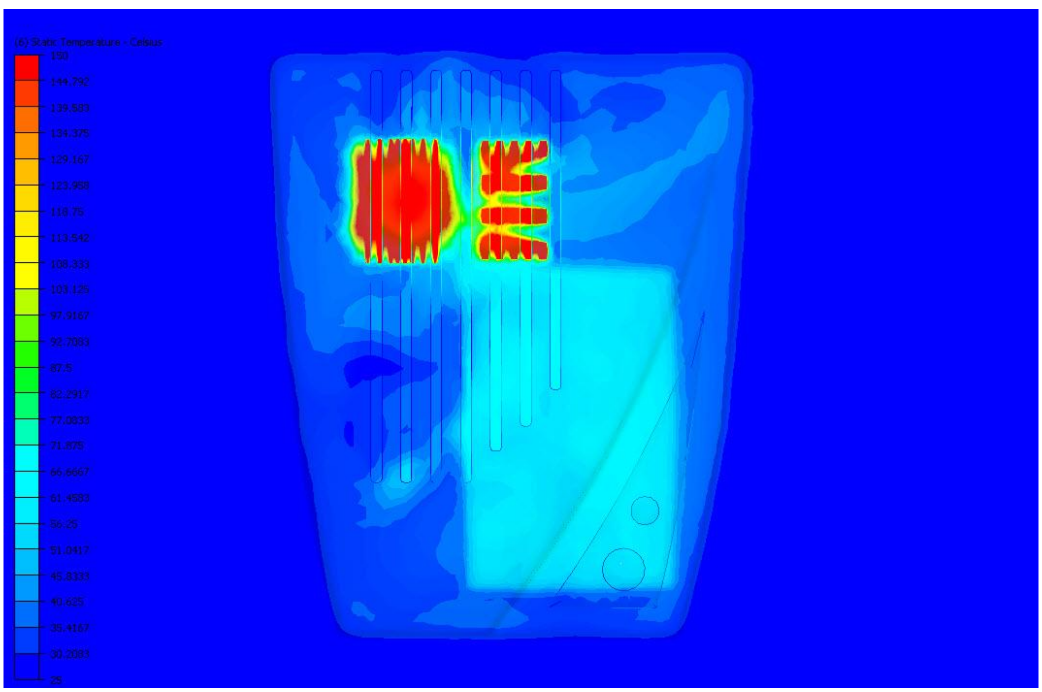
Pathline traces colored by velocity showing patterns of airflow through slots.

***<u>Insight</u>*: "chimney" plume effect from hot chipsets, but majority or air is stagnant in front of enclosure. Configuration of slots may fix this issue.**



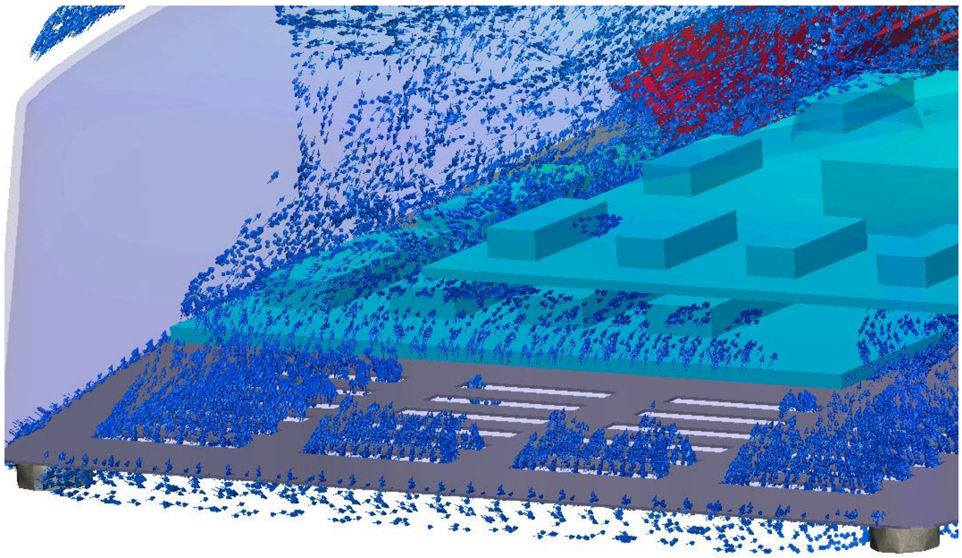
Compact model of TI FPBGA results show completely unacceptable junction temperatures (235 deg C and 204 deg C, respectively).

***Insight*: Slow moving airflow, slot placement, and possibly heatsink configuration must be changed.**



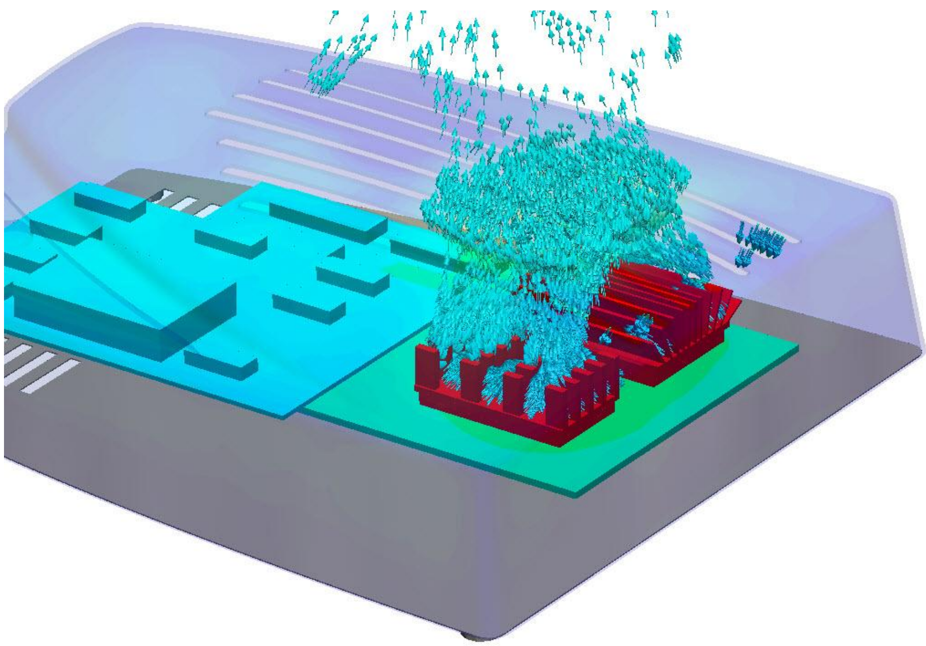
Top view cross section of thermal profile. Heat is not spreading as efficiently as possible

***Insight*: More punches in sheet metal bottom plate may increase airflow**



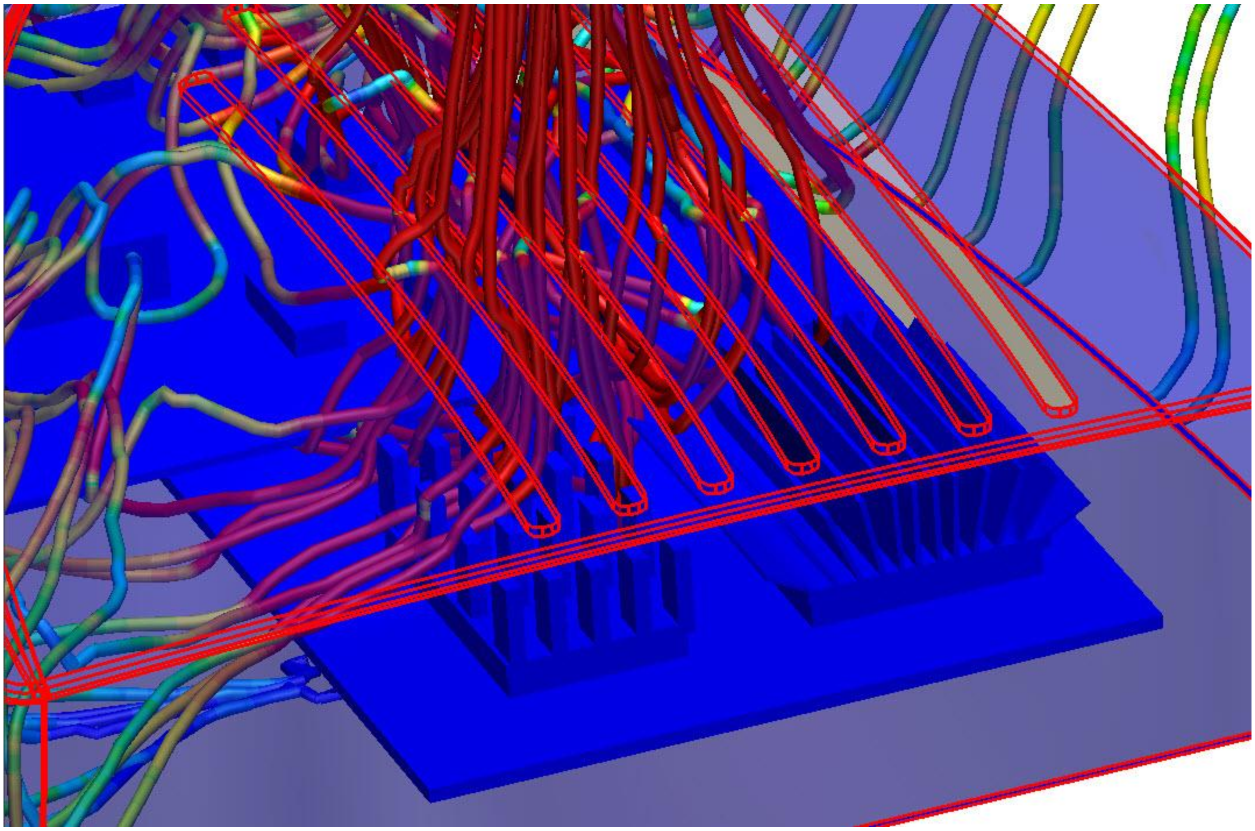
Close up view of 2.5 in/s velocity surface. Note that not all slots are actually necessary.

***Insight*:** **Front punches in bottom plate are not as effective as possible. More punches in back of plate near heat sources may be more effective.**



Close up view of 7 in/s velocity surface. Note that little airflow is going through heatsinks.

***Insight*:** **Increase in airflow through geometry changes / slots in top case and different heat sinks may help decrease overall temperature.**



Close up view of traces going through heat sinks. Note that little airflow is going through heatsinks.

***Insight*: Increase in airflow through geometry changes / slots in top case and different heat sinks may help decrease overall temperature.**

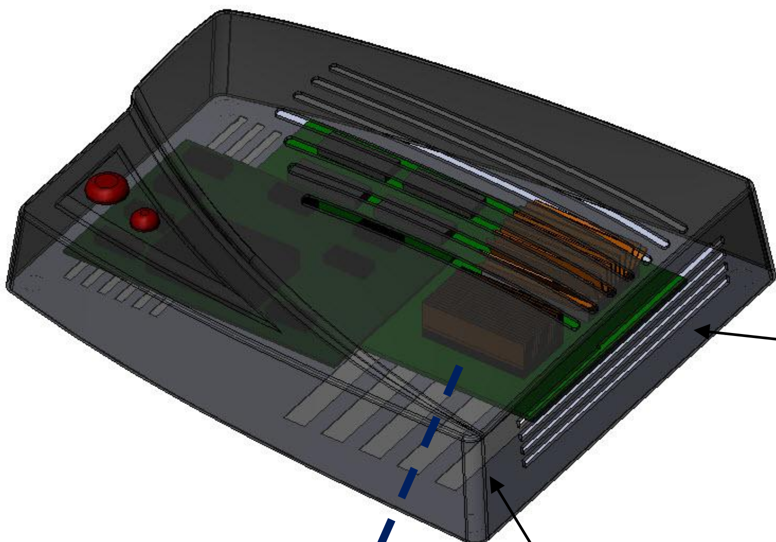
VERDICT:

FAIL: natural convection with given heat loading, heatsinks, and packaging geometry will not pass 105 deg C max junction temperature.

Second Revision as modified in collaboration w/ Client:

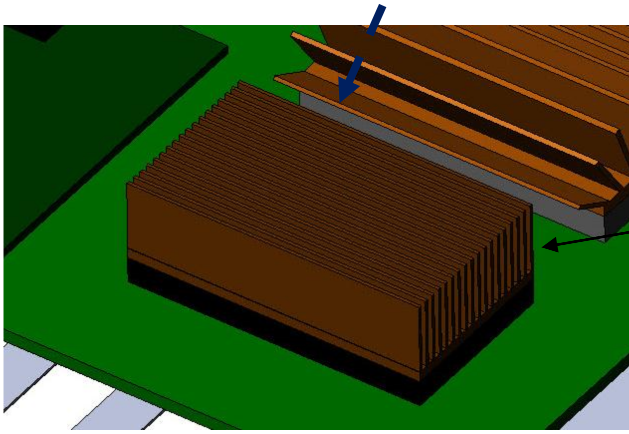
GOAL: try to use natural convection as only means of removing heat (no fans) to achieve acceptable junction temperatures

NOTE: All of the same conditions applied to Revision 1 were applied exactly to Revision 3



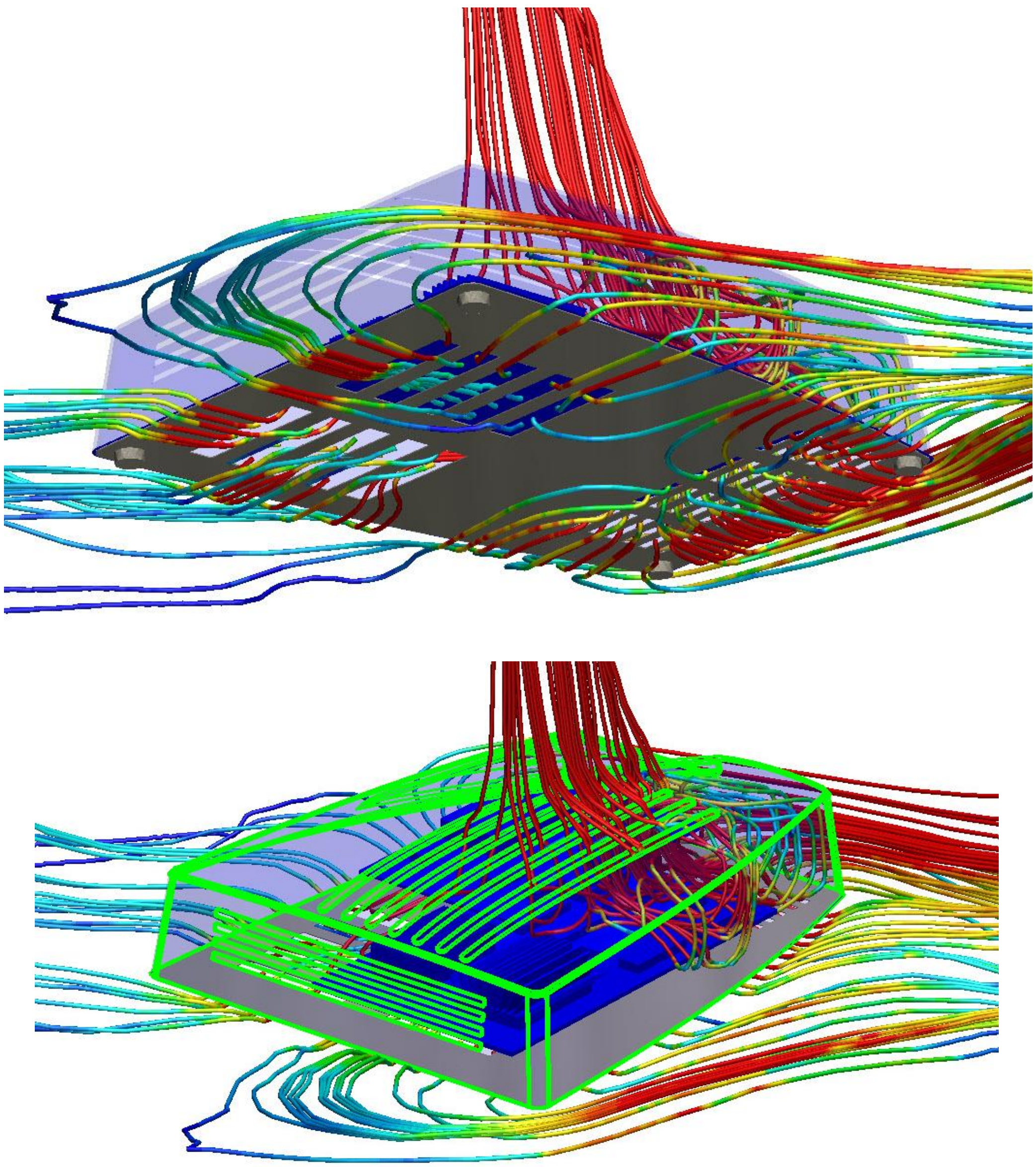
Additional slots added to back of top enclosure

Additional punches added to bottom plate near heat sources



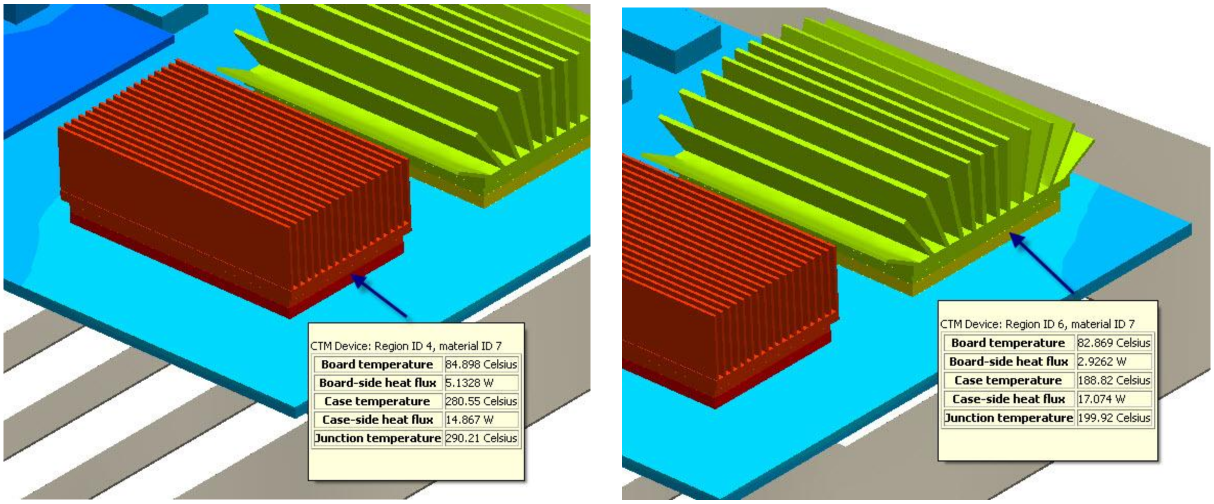
Skived copper heat sink replacing pin fin heat sink on hottest chipset

Revision 2 Results:



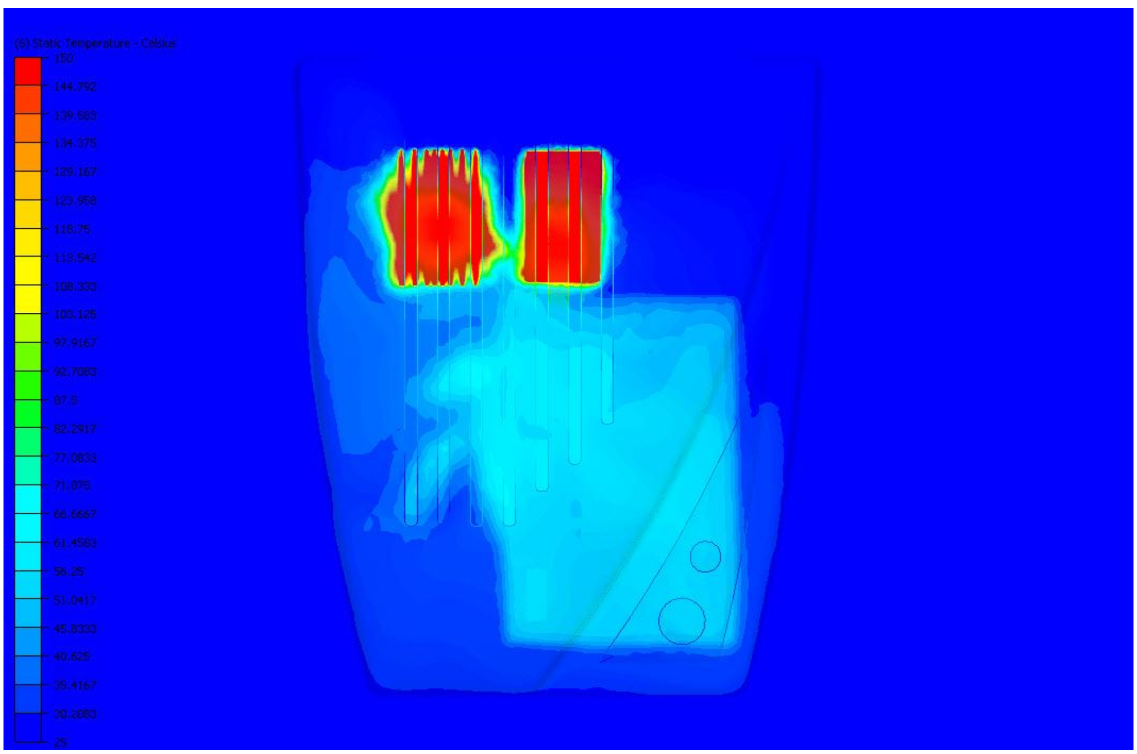
Pathline traces colored by velocity showing patterns of airflow through slots.

***Insight*: Addition of more bottom slots helps, but side slots in top package are nearly useless.**



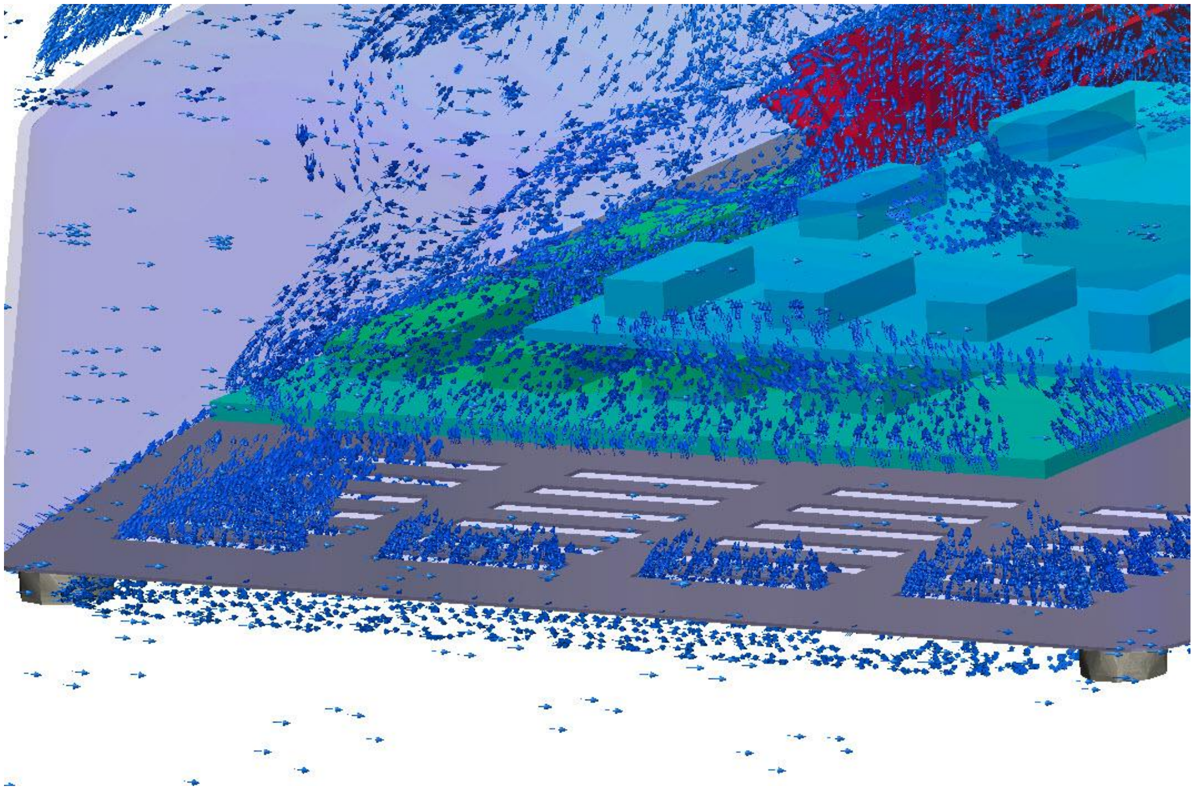
Compact model of TI FPBGA results show completely unacceptable junction temperatures (290 deg C and 199 deg C, respectively).

***Insight*:** **Changes made to design have actually been detrimental to junction temperatures. Performance has been decreased.**



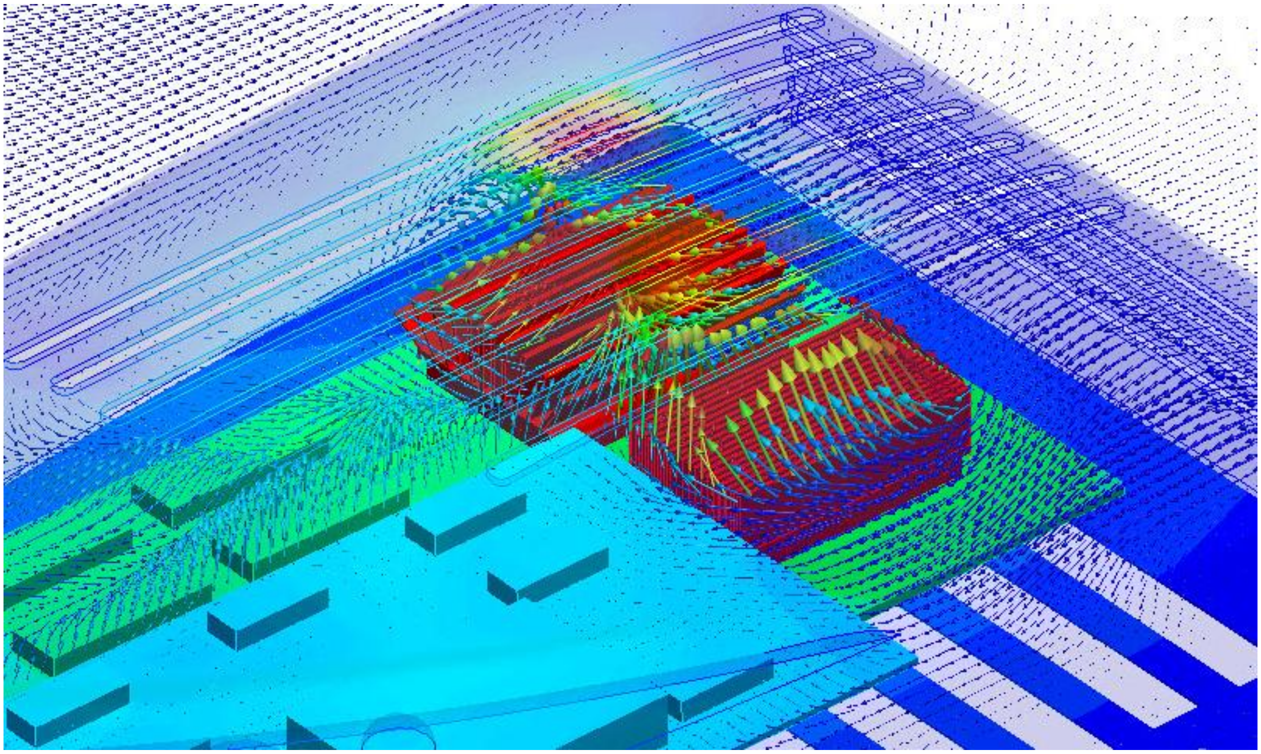
Top view cross section of thermal profile. Heat is not spreading as efficiently as possible

***Insight*:** **More punches in sheet metal bottom did not affect airflow as much as expected**



Close up view of 2.5 in/s velocity surface. Note that fewer front punches are actually useful.

***Insight*: Front punches in bottom plate are not as effective as possible, even with addition of rear punches.**



Close up view of traces going through heat sinks. Note that little airflow is going through heatsinks.

***Insight*: Changes in slot patter have not forced airflow to go through heat sinks as much as necessary to achieve thermal goals.**

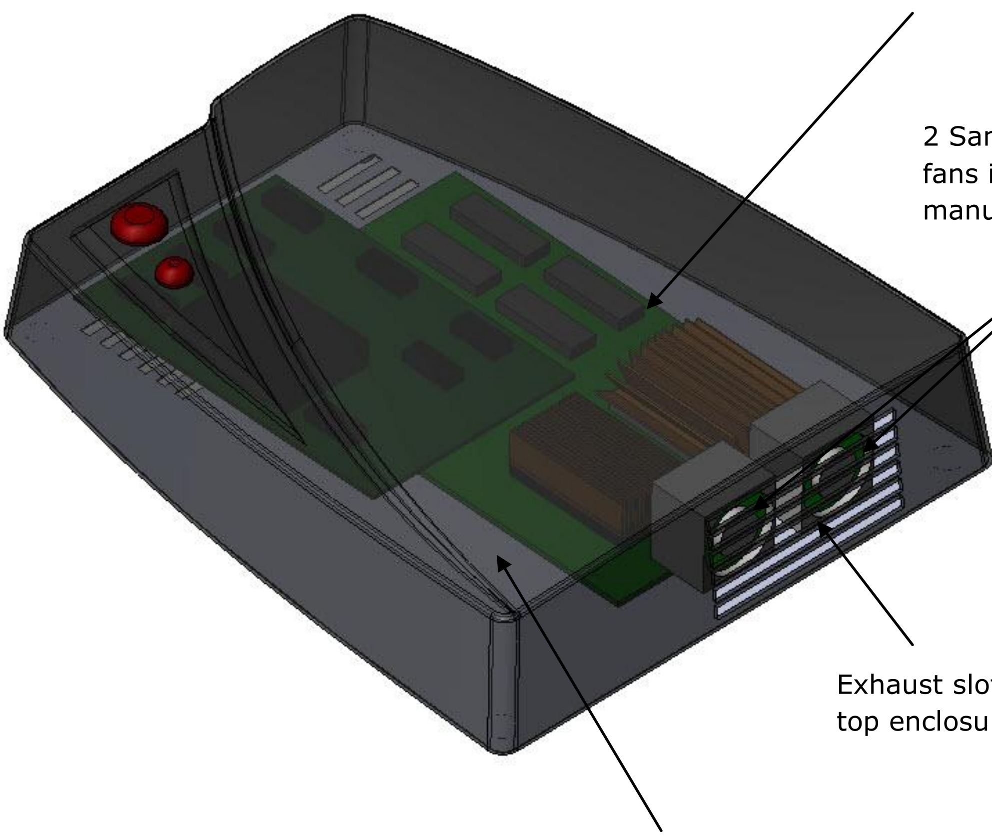
VERDICT:

FAIL: natural convection with given heat loading, heatsinks, and packaging geometry will not pass 105 deg C max junction temperature.

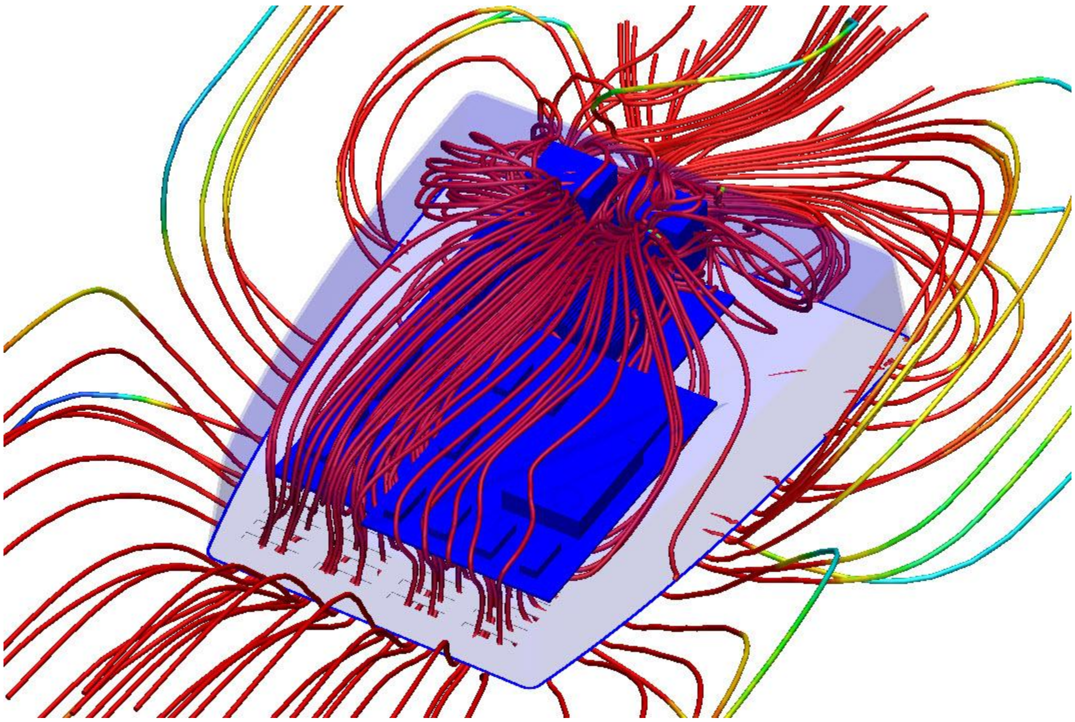
Third Revision as modified in collaboration w/ Client:

GOAL: use of 2 small Sanyo Denki Ace 36 fans pulling air across heatsinks to achieve acceptable junction temperatures.

NOTE: All of the same conditions applied to Revision 1 were applied exactly to Revision 3

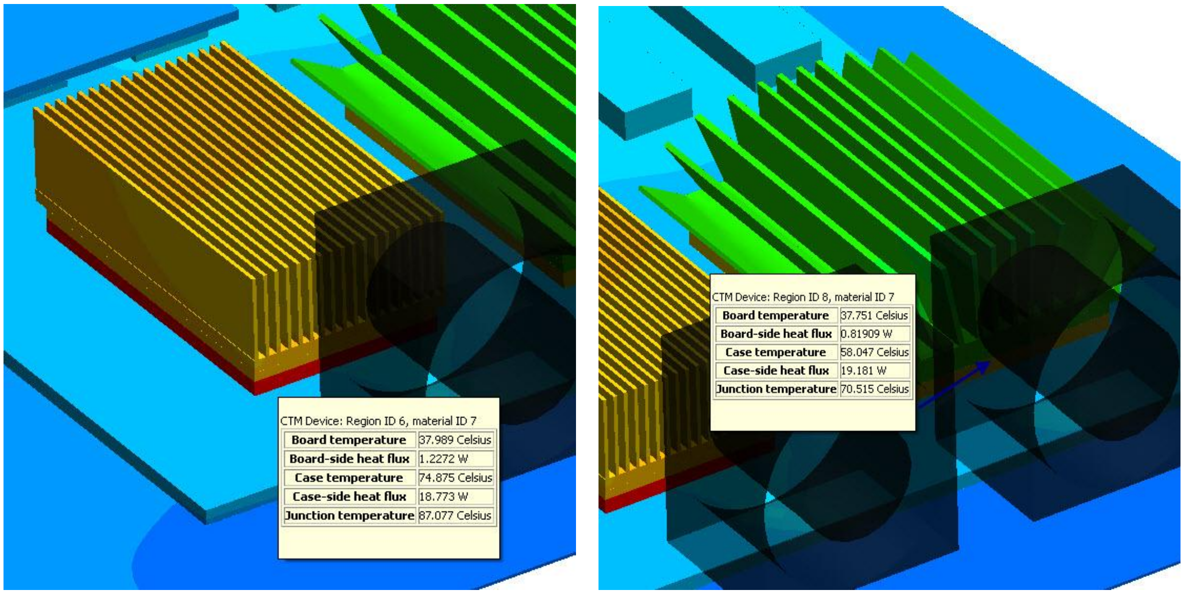


<u>**Revision 3 Results:**</u>



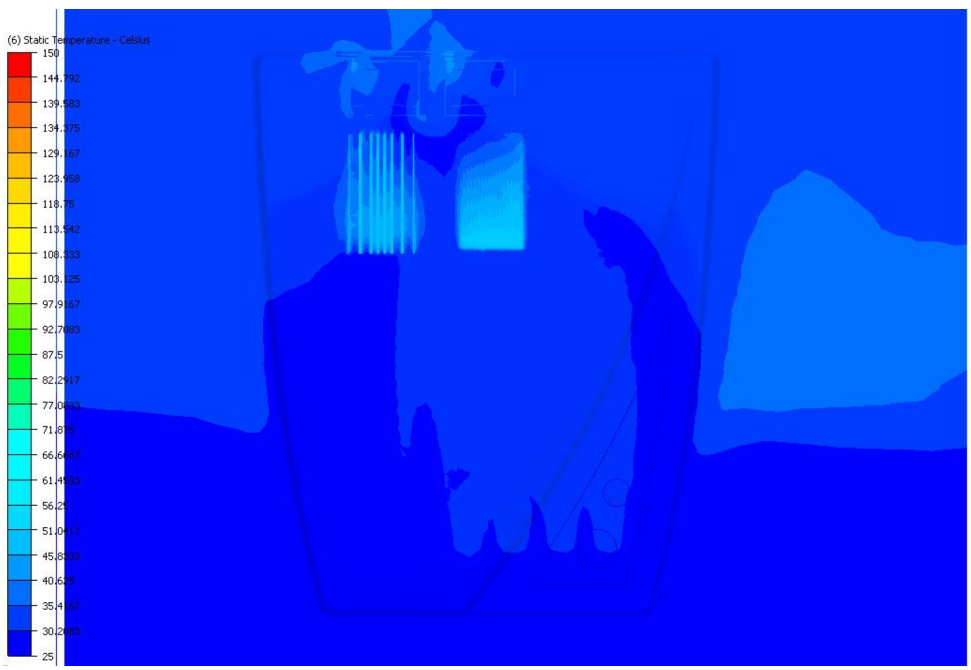
Pathline traces colored by velocity showing patterns of airflow over heat sinks.

***<u>Insight</u>*: Fans are pulling 25 deg C room air into system at about 14.8 CFM each. Note the flow is going exactly where needed.**



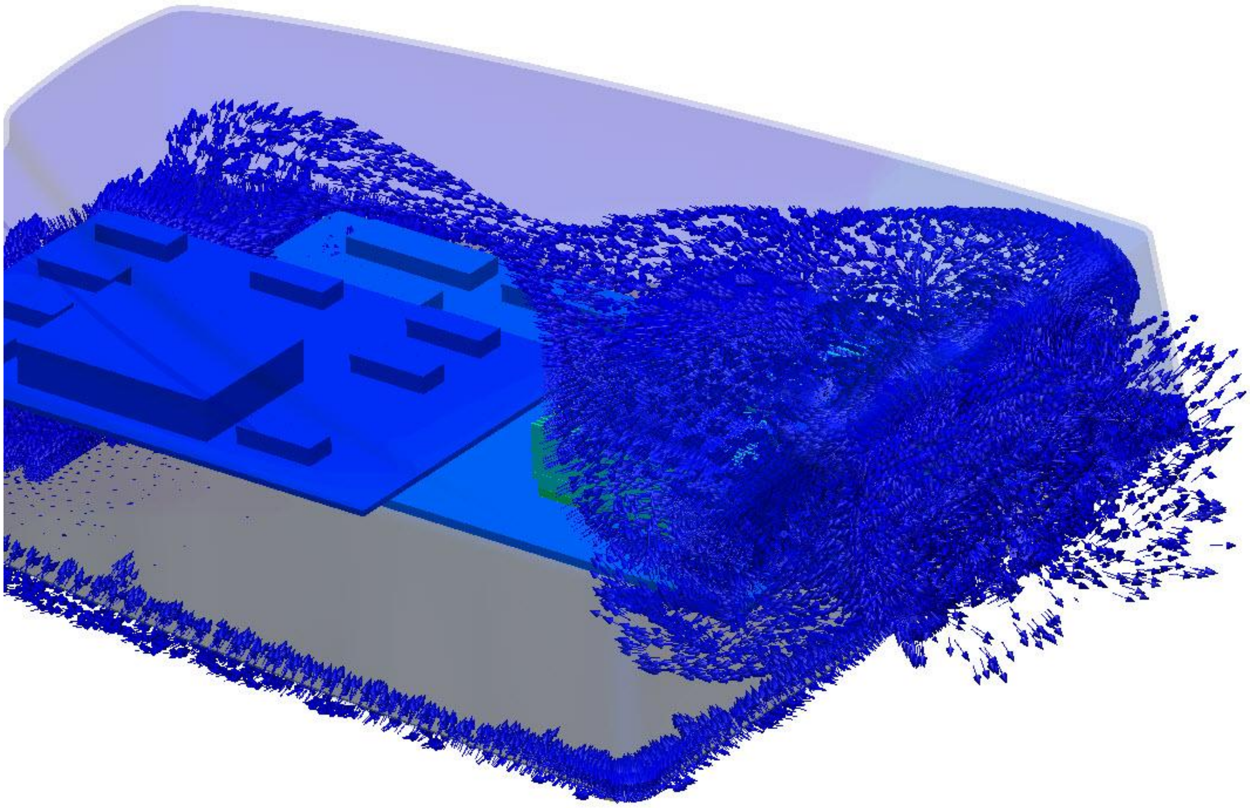
Compact model of TI FPBGA results show ACCEPTABLE junction temperatures (87 deg C and 70 deg C, respectively).

***Insight*: Design with fans is well within thermal goal. Design may be overdesigned at this point.**



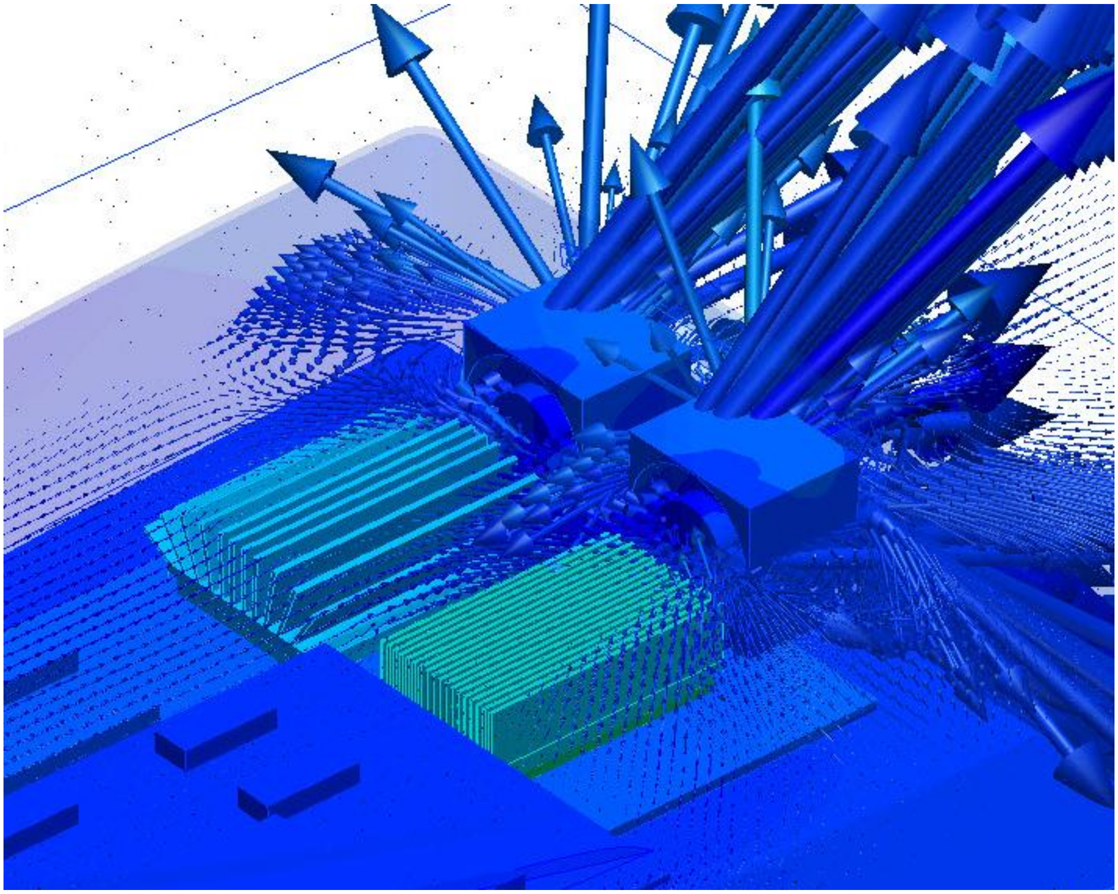
Top view cross section of thermal profile. Temperature is a fraction of previous designs

***Insight*: Fans moving air at high velocity have solved the thermal issues**



Close up view of 30 in/s velocity surface. Note the majority of flow is concentrated exactly over heat sinks.

***Insight*: Visualizing flow everywhere in system has shown where improvements have been made.**



Close up view of traces going through heat sinks. The large vectors near the fans are due to the 14,000 RPM rotational speed and resulting high tangential air velocity.

***Insight*: Fans are small and powerful, but may be too much for this design.**

VERDICT:

PASS: forced convection with given heat loading, heatsinks, and optimized packaging geometry pass 105 deg C max junction temperature.

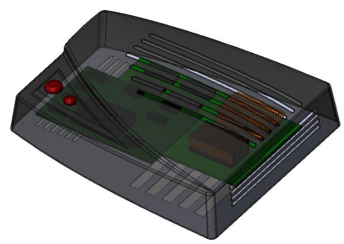
Conclusion:

Design with analysis in beginning of project saved the time and cost of producing many failed prototypes.

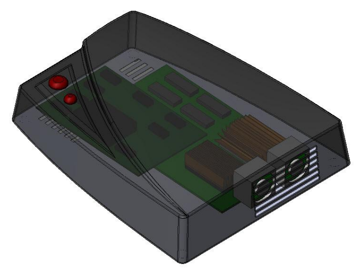
Collaborating with the On-Demand Engineering Team at GDC Group Inc. through meetings online and on-site, changes to the design were made quickly and produced a final working design….*all with zero physical prototype cost*.

The insight-based design progression:

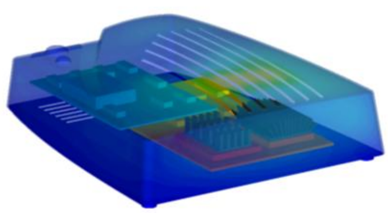
Revision 1

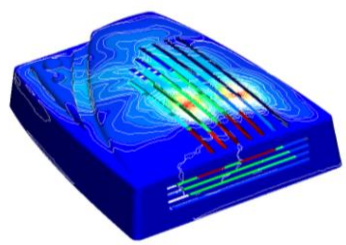


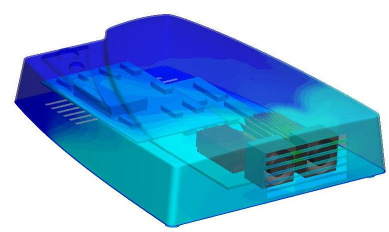
Revision 2



Revision 3







From insight gained the following is suggested (and confirmed in web meeting with Client):

- While this design does pass the criteria, further optimization is likely beneficial to the **cost per unit reduction** of the product, for example:

    - **Perhaps one larger fan will work?**

    - **Can a cheaper heatsink be used?**

    - ***Do we need even need heatsinks* when the fan is used?**

Numerical Simulation Method:

This design study was solved using the full Navier-Stokes and energy governing equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0$$

$$continuity \qquad equation$$

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial x} + \rho v\frac{\partial u}{\partial y} + \rho w\frac{\partial u}{\partial z}$$

$$= \rho g_x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[2\mu\frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right]$$

$$+ S_\omega + S_{DR}$$

$$x - momentum \qquad equation$$

$$\rho\frac{\partial v}{\partial t} + \rho u\frac{\partial v}{\partial x} + \rho v\frac{\partial v}{\partial y} + \rho w\frac{\partial v}{\partial z}$$

$$= \rho g_y - \frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[2\mu\frac{\partial v}{\partial y}\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)\right]$$

$$+ S_\omega + S_{DR}$$

$$y - momentum \qquad equation$$

$$\rho\frac{\partial w}{\partial t} + \rho u\frac{\partial w}{\partial x} + \rho v\frac{\partial w}{\partial y} + \rho w\frac{\partial w}{\partial z}$$

$$= \rho g_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[2\mu\frac{\partial w}{\partial z}\right]$$

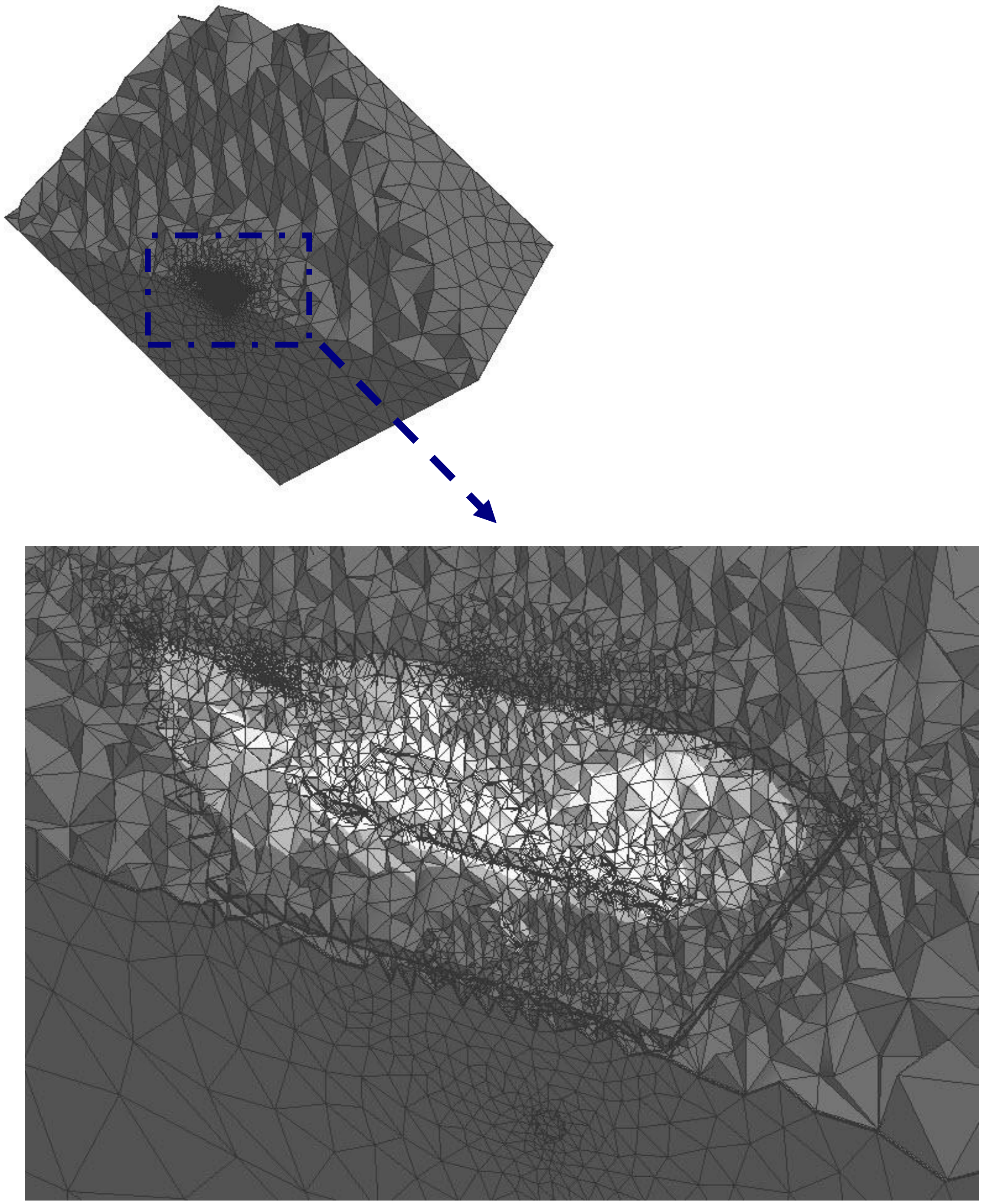
$$+ S_\omega + S_{DR}$$

$$z - momentum \qquad equation$$

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u\frac{\partial T}{\partial x} + \rho C_p v\frac{\partial T}{\partial y} + \rho C_p w\frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left[k\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[k\frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right] + q_V$$

$$energy \qquad equation$$

The method incorporated FEA model descritization (using TET4, TET10, 2D triangular, Hexahedral 8-node, 5-node pyramid, and wedge elements).



The solver incorporated full turbulent behavior of the fluid. Numerically, this involves an isotropic turbulence assumption to form a Boussinesq formation of eddy viscosity and eddy conductivity. This of course assumes inertial forces are small in comparison to forces inflicted by gravity in a buoyancy driven simulation.

The respective eddy viscosity and eddy conductivity equations are as follows:

For eddy viscosity:

$$\mu_t = C_\mu \rho \frac{K^2}{\varepsilon}$$

For eddy conductivity (note that the Prandtl number here is assumed a constant "1"):

$$k_t = \frac{\mu_t C_p}{\sigma_t}$$

To model fluid turbulence the widely accepted standard k-ε model was incorporated into this time-averaged solution.

The respective transport equations are:

For k:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_k$$

For ε:

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}\left(P_k + C_{3\epsilon}P_b\right) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon$$

Walls (any solid coming in contact with the fluid domain including exterior domain walls unless specified otherwise) are accounted for in this solver two ways:

For low Reynolds numbers automatic mesh enhancement (3-10 wedge and prismatic element layers at growon from wall surfaces into domain) values of y^+ from 1-5 are assigned. For higer Reynolds numbers a "Law of the Wall" (incorporated in all major CFD codes) is applied. This Law is as follows:

$$U^{+} = \frac{1}{\kappa}\log y^{+} + B$$

Where inner variables are defined as:

$$U^{+} = \frac{U_t}{\sqrt{\frac{\tau_w}{\rho}}} \qquad y^{+} = \frac{\delta\sqrt{\frac{\tau_w}{\rho}}}{\nu}$$

U_T = velocity tangent to wall

τ_w = wall shear stress

δ = distance from wall

v = kinematic viscocity

To solve the full governing equations an explicit definition of pressure is required and has been derived from the continuity equation. To accommodate the coupled, non-linear, and hyperbolic characteristic of fluid simulation a segregated solver is used to solve each term of the PDEs at every iteration. To minimize the solution runtime and maximize accuracy, a Tri-Diagonal Matrix Algorithm (TDMA) is issued in place of the Gauss-Siedel matrix solver.

The TDMA solver can be expressed as:

$$A_{i-1,j}\phi_{i-1} + A_{i,j}\phi_{i-1} + A_{i+1,j}\phi_{i+1} = \sum_{j \neq i-1, j \neq i, j \neq i+1} A_{i,j}\phi_j + F_i$$

Relaxation is controlled using Galerkin's method of weighted residuals and a variation of the SUPG (Streamwise Upwind Petrov-Galerkin) to manage the advection / diffusion potential. Both under-relaxation and inertial relaxation can be used in this approach of unsteady flows.

References:

- White, F.M., Viscous Fluid Flow, McGraw-Hill, New York, 1974
- Schnipke, R.J., "A Streamline Upwind Finite Element Method For Laminar And Turbulent Flow", Ph.D. Dissertation, University of Virginia, May 1986
- V. Venkatakrishnan, "A Perspective On Unstructured Grid Flow Solvers", NASA Langley Research Center, Hampton, VA 23681