Thermal management architectures for rack based electronics systems

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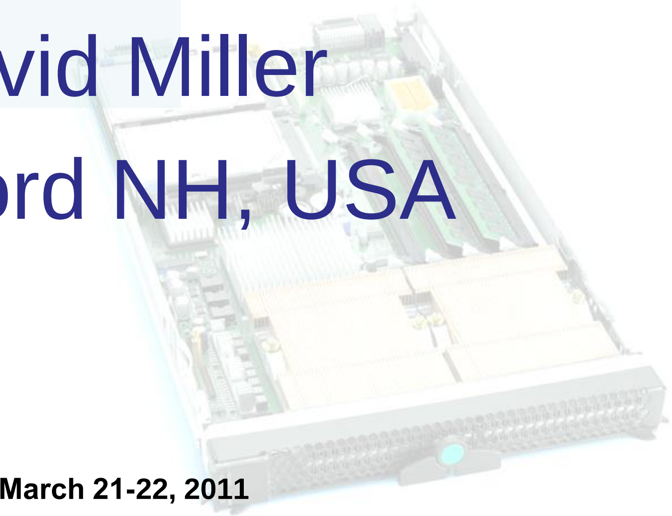

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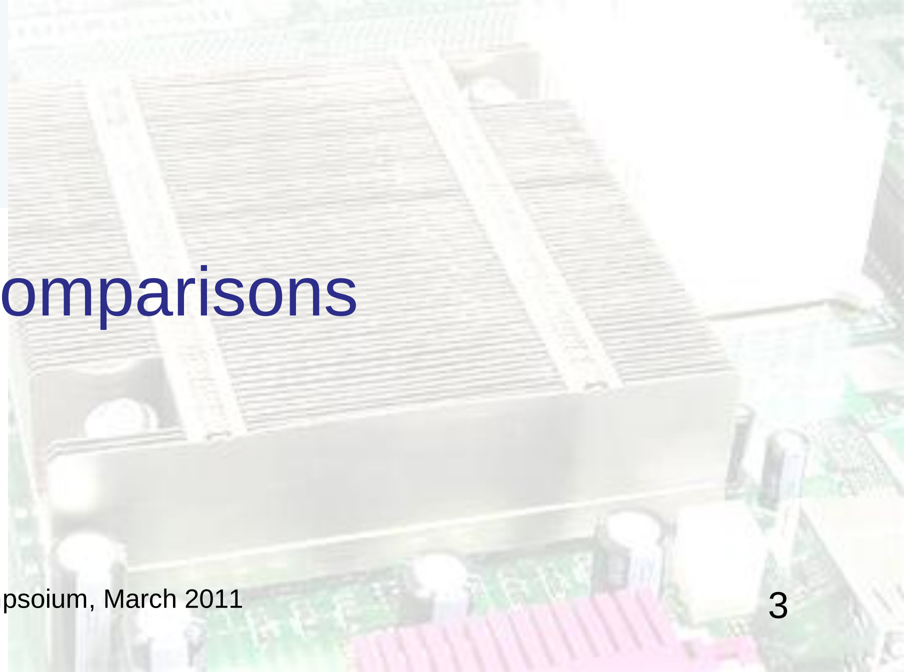
Abstract

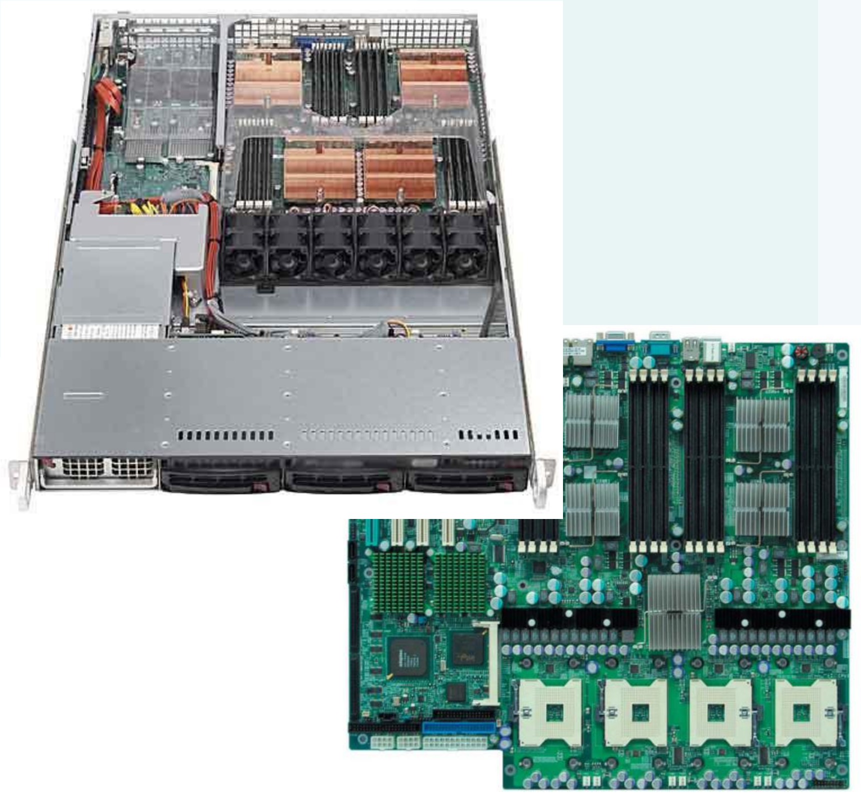
Cooling architecture options are studied for rack based electronics such as computer servers or router line cards. For the purposes of this investigation, individual servers or line cards are assumed to be of the horizontal pizza box style with a few high power modules such as CPU's or high power ASICS and a number of other lower power packages, memory, I/O chips etc. A number of system architectures for cooling the high power modules are considered and the corresponding performance levels that can be achieved are evaluated. In the first, fairly conventional cooling architecture, a “keep in volume” is allocated around each high power module for local air cooled heat sinks. In the second option, volume for air cooled fin surfaces is provided above the card footprint within the server volume but remote from the high power modules such that a single or two-phase heat transport means is required to transport heat from the modules to the fins in the remote location. In a third option, the heat transport loop at the card level transfers heat from the high power modules to a rack level liquid cooling system that dissipates heat to air flowing through the rack. In a fourth architecture, the heat transport loop at the card level connects to a rack level liquid cooling system that exchanges heat with circulating liquid supplied by a cooling system external to the rack. These options are selected to provide a broad look at cooling design possibilities and tradeoffs. Cooling architecture choices are more limited within racks that contain a variety of servers made by different vendors. The more powerful architectures are feasible within racks where a single vendor owns all the functions and has complete flexibility to consider rack level design tradeoffs.

Outline

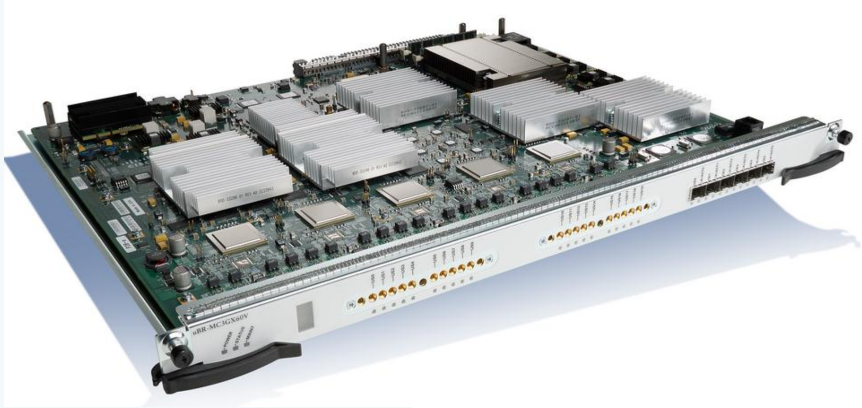
- Typical products of interest
- Layout & design specs considered
- Architecture options
  - Constraints
  - Conceptual models
- Thermal Assessment
  - Methodology
  - Performance metrics & comparisons
- Wrap up



Typical products of interest

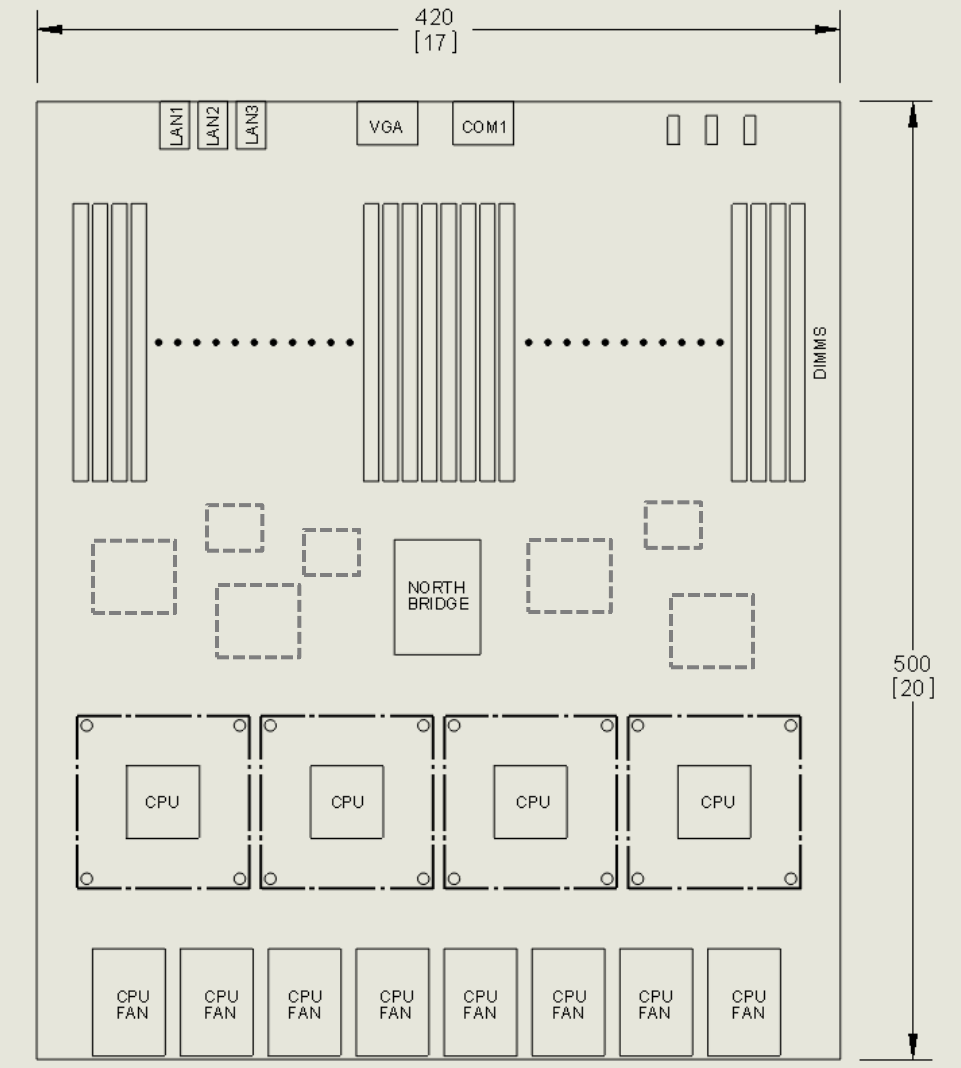


Servers …

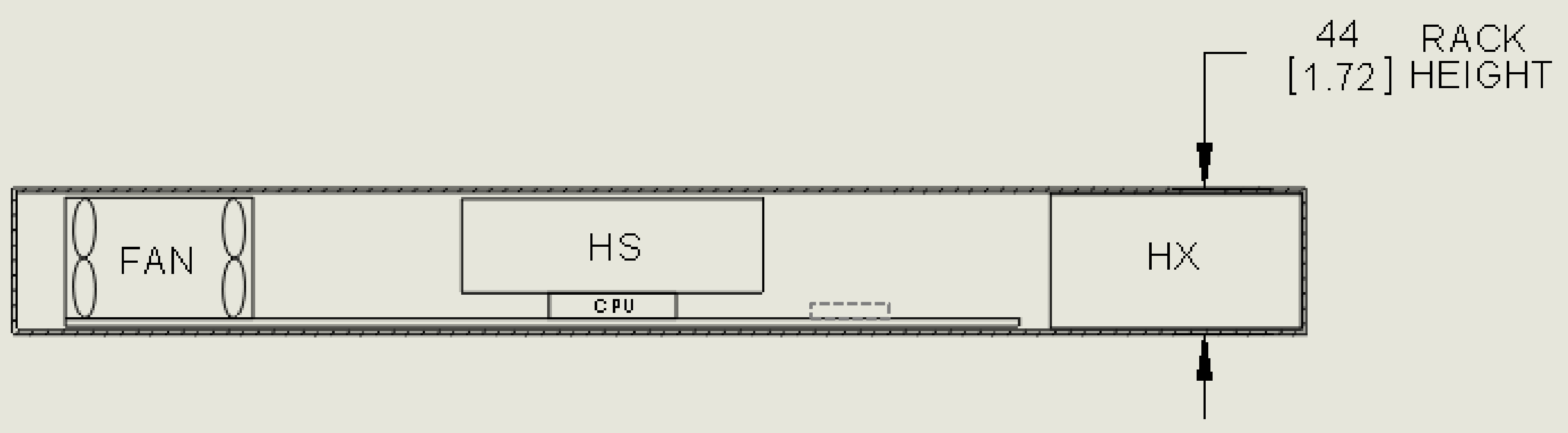


Router line cards …

Simplified layout considered



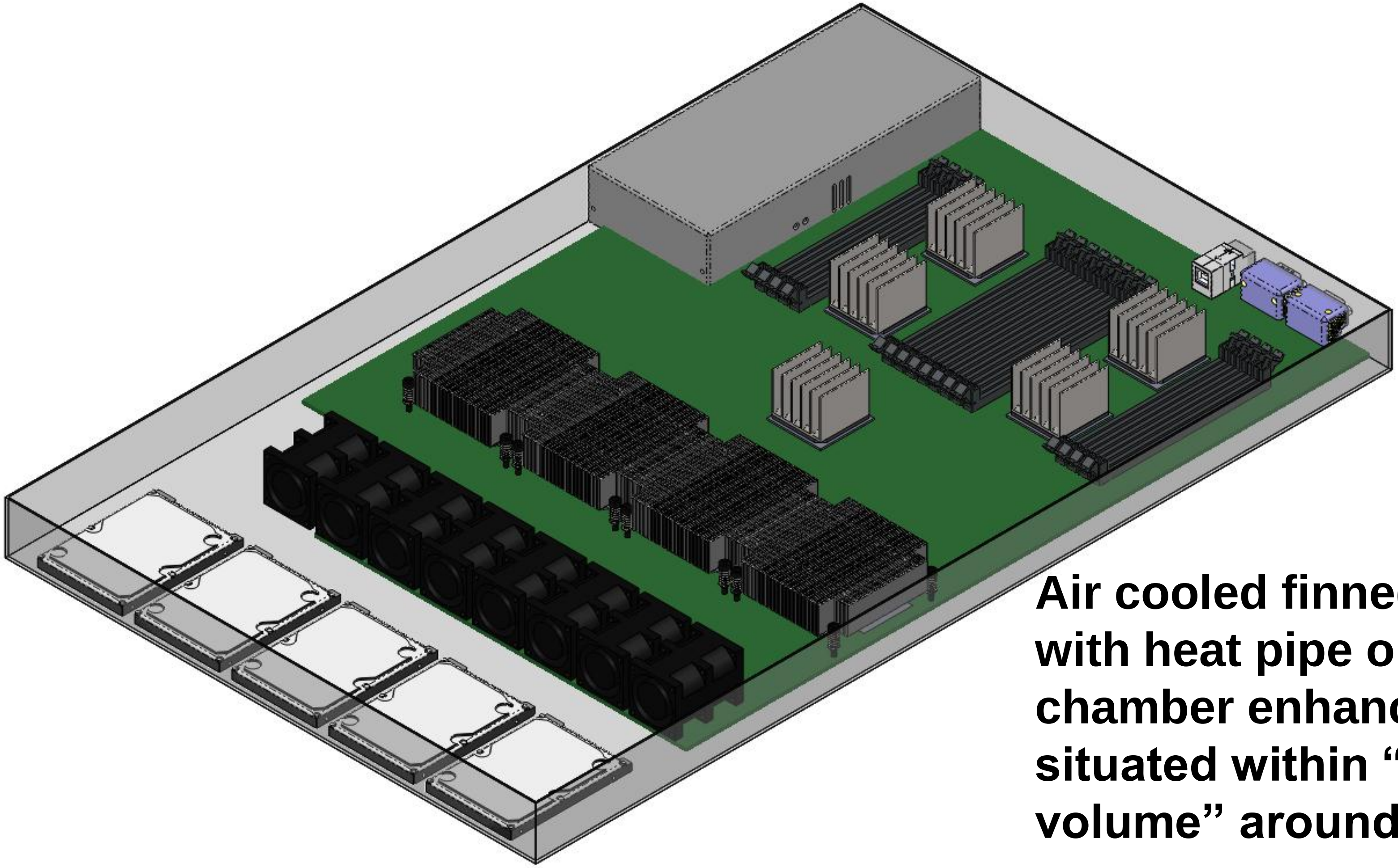
Simplified layout considered



Cooling Architectures

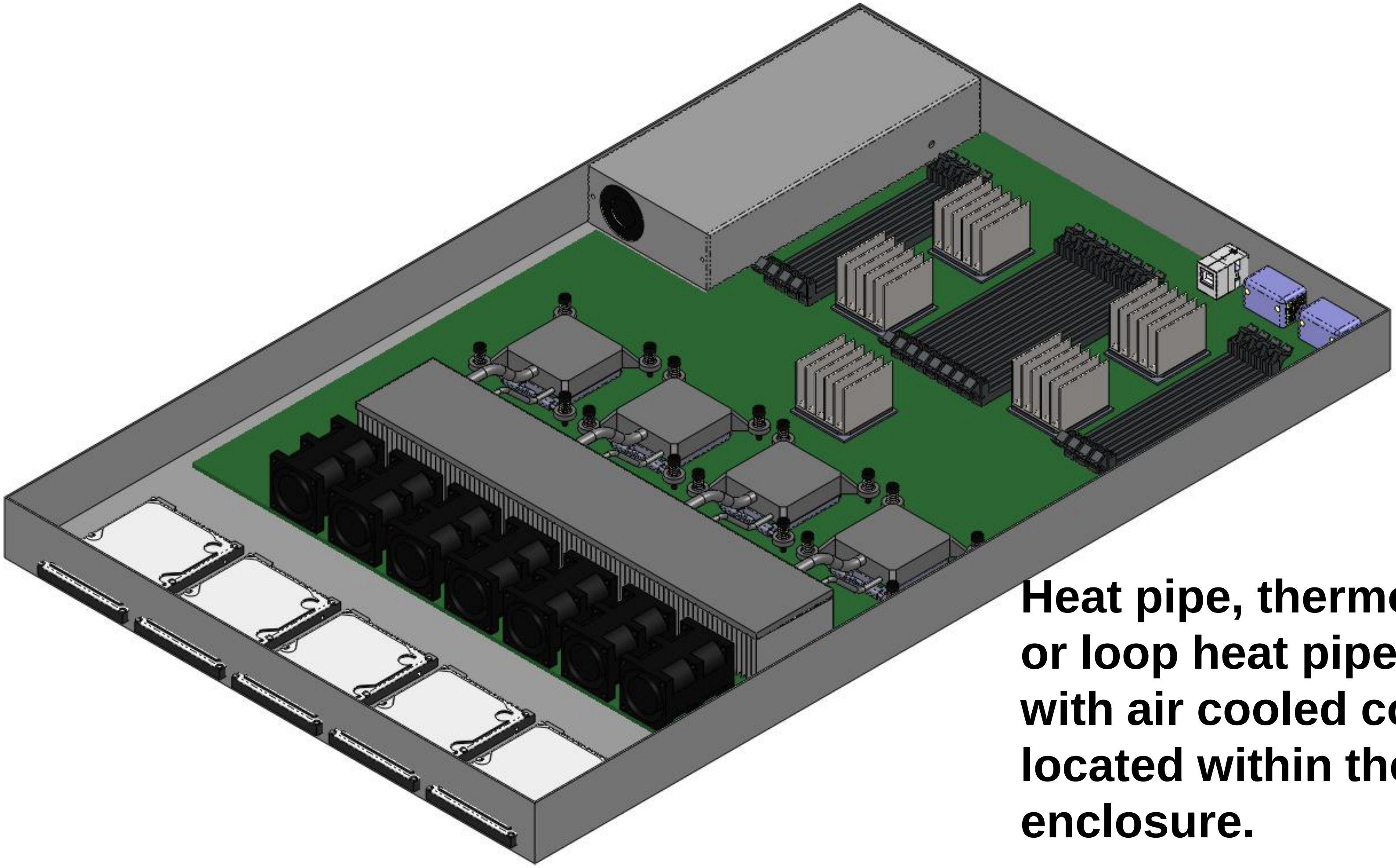
1. Air cooled heat sinks are located on heat sources within “keep in volumes” allocated around each high power module
2. A single or two-phase heat transport means is provided to transport heat from the high power modules to a remote air cooled heat exchanger located above the card footprint within the server volume.
3. A single or two-phase heat transport loop at the card level transfers heat from the high power modules through a conduction connection to a rack level liquid cooling system. The rack level liquid cooling system can dissipate heat to air flowing through the rack or to chilled water supplied by a room level utility.
4. A single phase heat transport loop at the card level connects through liquid couplings to a rack level liquid cooling system. The rack level liquid cooling system can dissipate heat to air flowing through the rack or to chilled water supplied by a room level utility.

1: Heat sink mounted directly on CPU



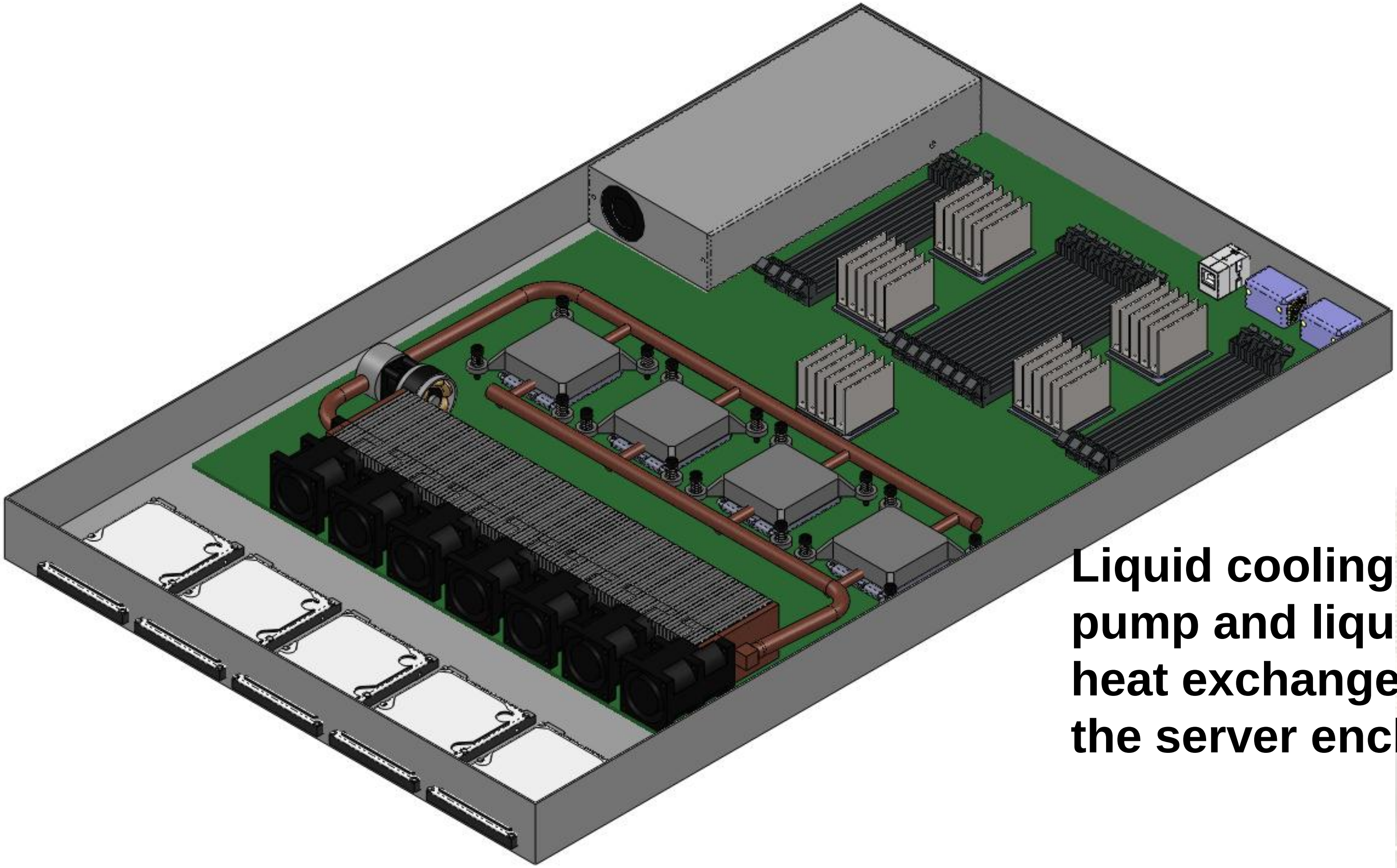
Air cooled finned heat sink with heat pipe or vapor chamber enhanced base situated within "keep in volume" around module.

2a: Passive two phase transport w/air cooled HEX on Card



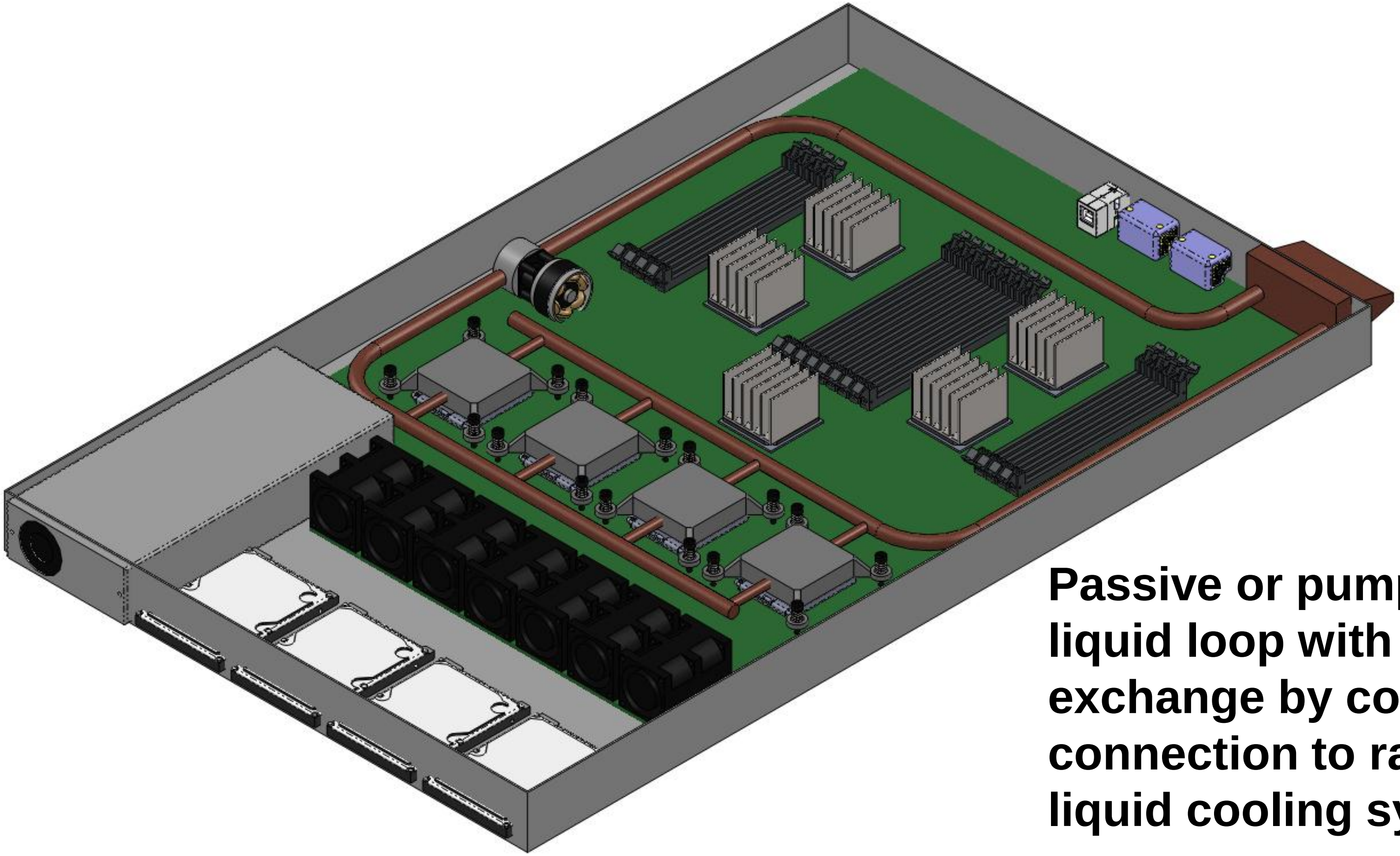
Heat pipe, thermosiphon or loop heat pipe solution with air cooled condenser located within the server enclosure.

2b: Pumped single phase transport with HEX on Card



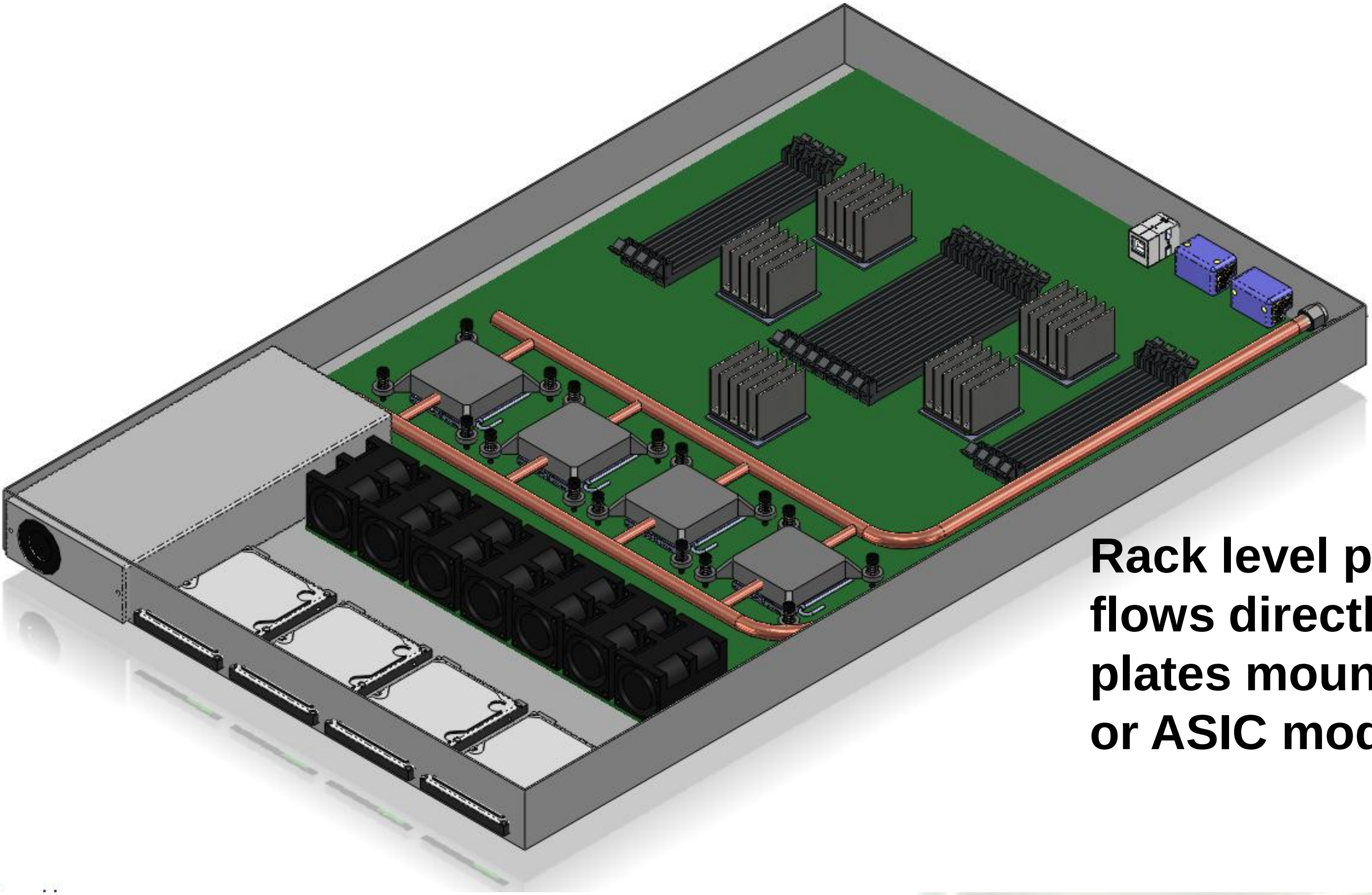
Liquid cooling loop with pump and liquid-to-air heat exchanger within the server enclosure.

3: On Card loop with thermal connection to Rack level cooling system



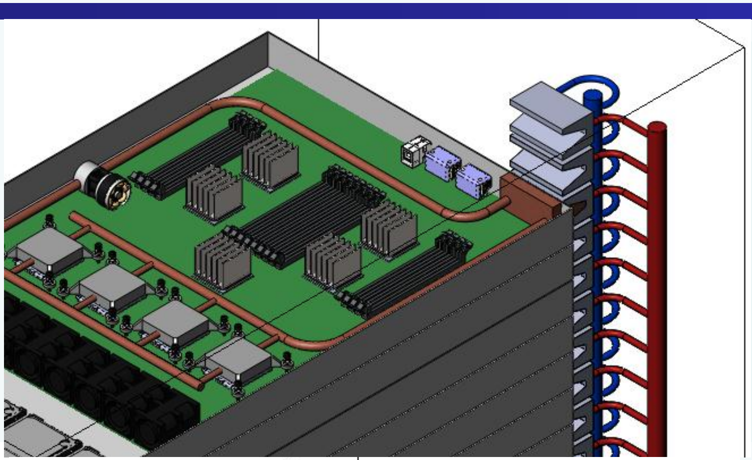
Passive or pumped liquid loop with heat exchange by conduction connection to rack level liquid cooling system.

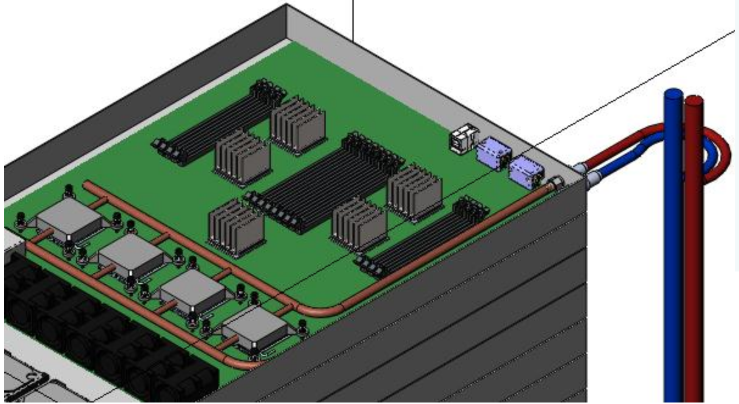
4: Rack level liquid flows directly to card level cooling system

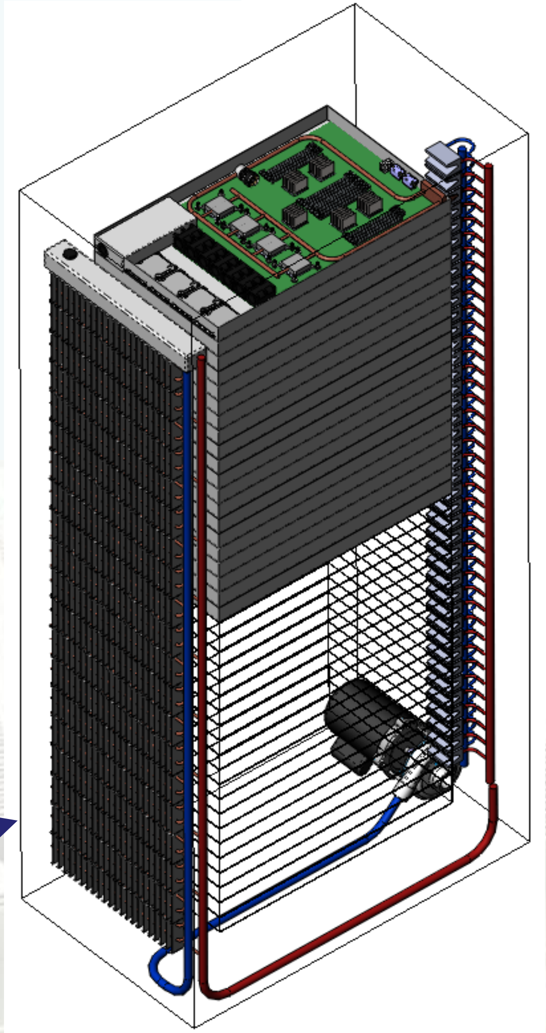


Rack level pumped liquid flows directly to cold plates mounted on CPU or ASIC modules.

3 & 4: Rack level liquid cooling system







Rack level liquid cooling system dissipates heat to (a) air flow through rack as shown or (b) facility level chilled liquid (not shown.)

Cooling Assessment Overview

- For any heat exchanger [1]

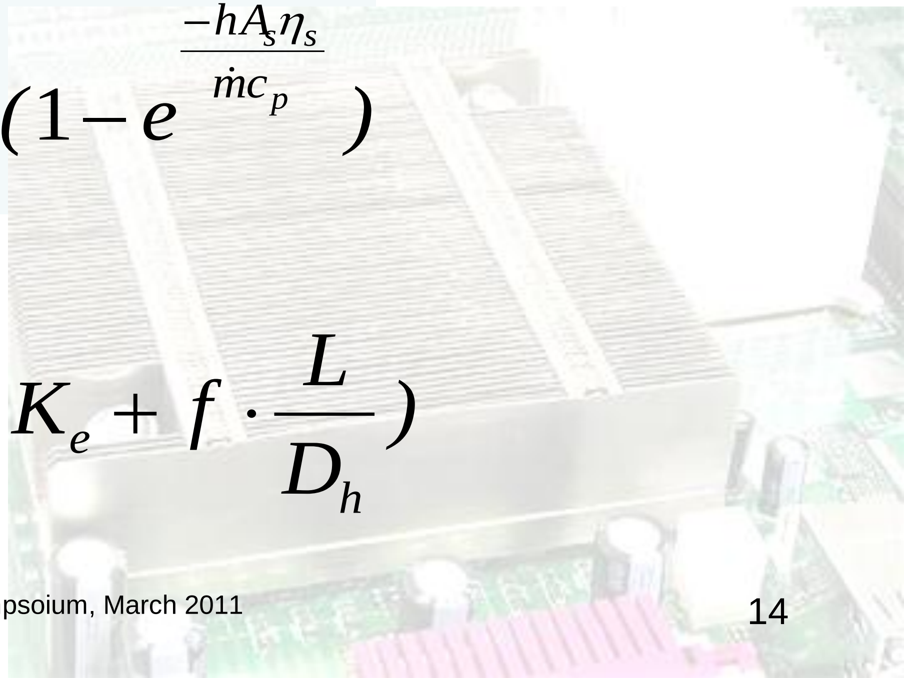
$$Q = \left(\dot{m}c_p\right)_{min} \cdot \left(\Delta T_{app}\right) \cdot \varepsilon$$

- Simplified version for heat sinks

$$Q = \dot{m}c_p \cdot \left(T_s - T_i\right) \cdot (1 - e^{\frac{-hA_s\eta_s}{\dot{m}c_p}})$$

- Pressure drop

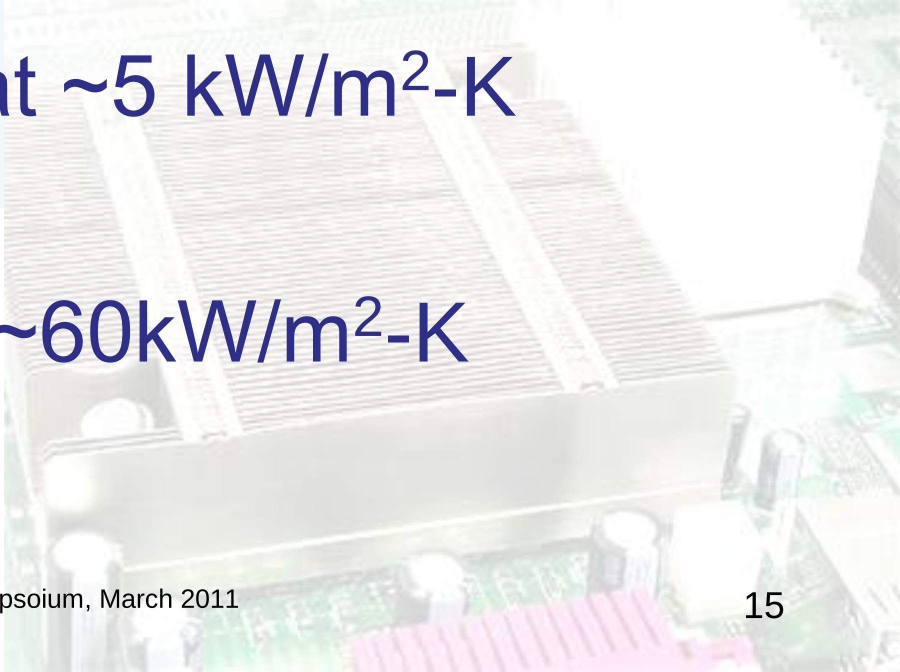
$$\Delta p = \frac{1}{2}\rho \cdot U_m^2 (K_c + K_e + f \cdot \frac{L}{D_h})$$



Methodology Simplifications

For Heat Exchangers with two fluid streams:

- Air and water “h” values are calculated using appropriate correlations [2]
- Condensation “h” set at ~5 kW/m^2-K
- Evaporation “h” set at ~60kW/m^2-K



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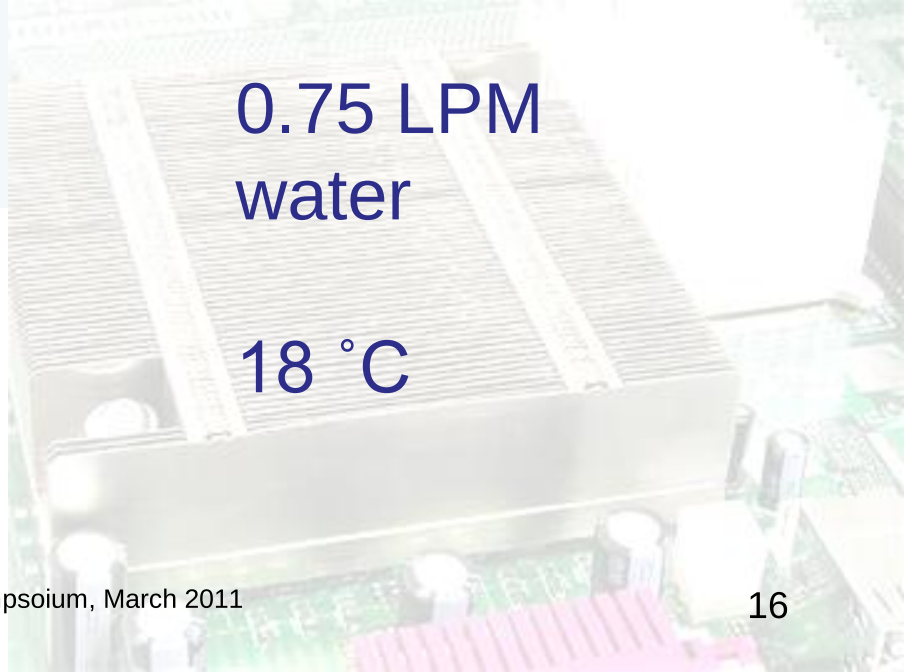
Design specs considered

- Input Power per CPU: 250 Watts
- CPU Heat Footprint: 25x25 mm2

- Air flow per CPU: 50 CFM
- Air Inlet Temp: 35 ˚C

- Liquid Flow per CPU: 0.75 LPM
- Liquid type: water

- Chilled Water Temp: 18 ˚C

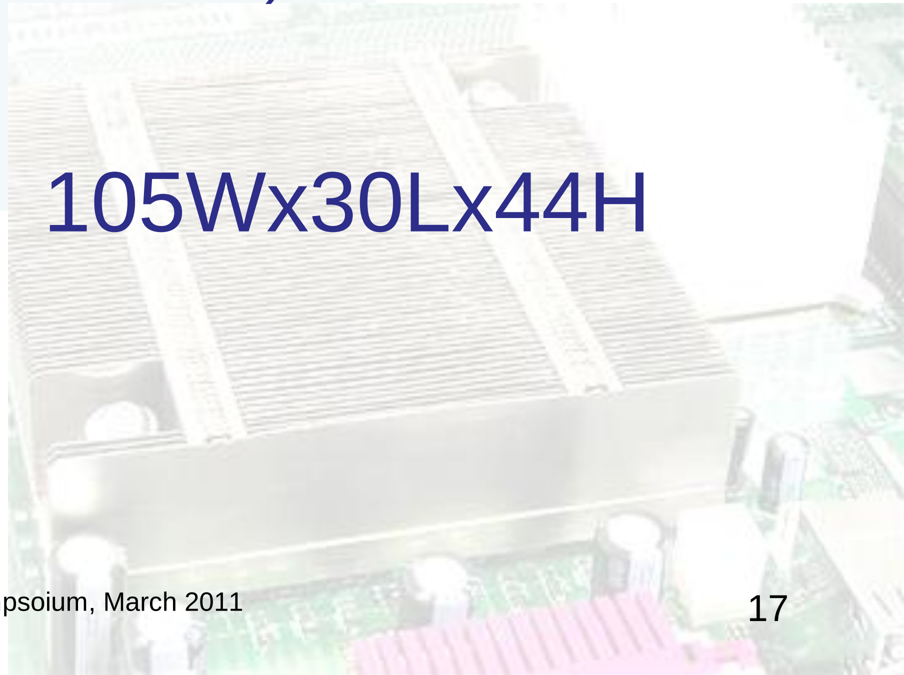


Design specs considered

- Local Heat Sink Size: 103Wx75Lx28H
- On Board HEX Size: 105Wx30Lx35H

  (Up to 300 mm forward of heat sources)
- Rack side HEX Size: 105Wx30Lx44H

  (At air inlet side of rack)



Performance Comparison

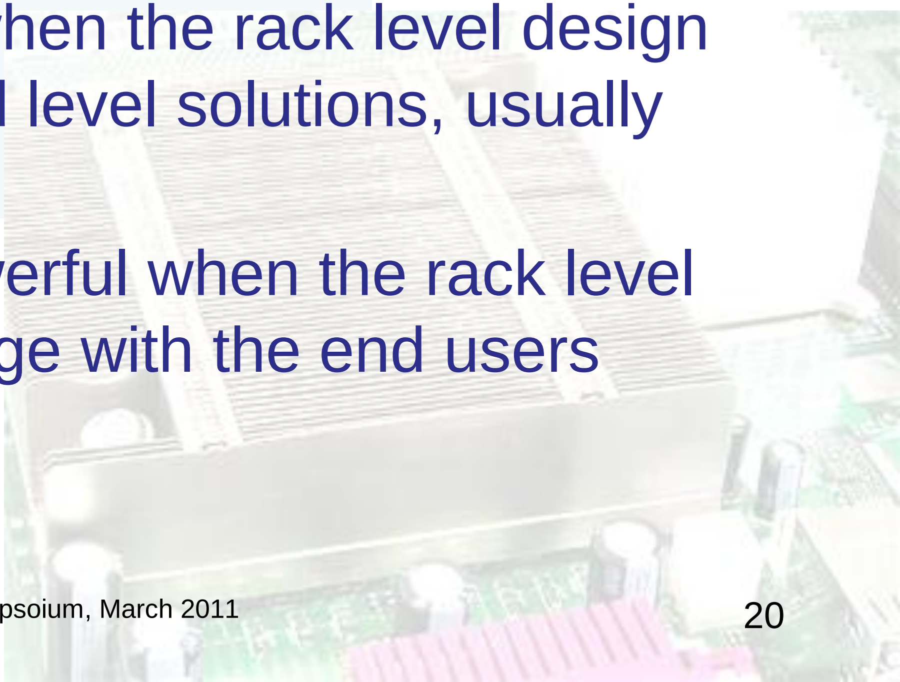
Thermal Architecture	**1**		**2a**	**2b**	**3a**	**3b**	**4a**	**4b**
	Local Heat Sinks on high power modules		**Heat transport loop with remote condenser in server**		**Server two-phase cooling loop with conduction connection to rack cooling system**		**Server liquid loop with liquid couplings to rack liquid cooling system**	
Version	**4 modules**	**2 modules**	**two phase passive loop**	**single phase pumped loop**	**rack liquid to rack air HEX**	**rack liquid to water HEX**	**rack liquid to rack air HEX**	**rack liquid to water HEX**
Ta	35	35	35	35	35	18	35	18
Design Constraint								
HX width	105	210	105	105	105		105	
HX length	75	75	30	30	30		30	
HX height	28	28	35	35	44		44	
Resistances								
Rfa			0.127	0.127	0.084	0.054	0.084	0.054
Rff					0.005	0.005		
Rsf	0.2	0.16	0.033	0.023	0.033	0.033	0.023	0.023
Rtim	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total Rc-a	0.22	0.18	0.18	0.17	0.142	0.112	0.127	0.097
Pressure Drops								
DP air (Pa)	100	50	100	100	100		100	
DP liq				15000	30000	30000	30000	30000
Performance Summary								
Case Temp (˚C)	90	80	80	77.5	70.5	46	66.8	42.3
Fan Power (W)	9.4	4.7	9.4	9.4	9.4	0.0	9.4	0.0
Pump Power (W)	0.0	0.0	0.0	0.4	0.8	0.8	0.8	0.8

Selection Metrics

Thermal Architecture	**1**		**2a**	**2b**	**3a**	**3b**	**4a**	**4b**
	Local Heat Sinks on high power modules		**Heat transport loop with remote condenser in server**		**Server two-phase cooling loop with conduction connection to rack cooling system**		**Server liquid loop with liquid couplings to rack liquid cooling system**	
Version	**4 modules**	**2 modules**	**passive**	**pumped**	**rack air HEX**	**rack water HEX**	**rack air HEX**	**rack water HEX**
Case Temperature (˚C)	90	80	80	77.5	70.5	46	66.8	42.3
Pumping Power (W)	10	5	10	10	11	1	11	1
Mass (kg)	0.4	0.8	0.36	0.42	0.46	0.4	0.46	0.4
Mass on CPU (kg)	0.4	0.8	0.2	0.2	0.2	0.2	0.2	0.2
Cost per CPU	0.5X	1X	1.1X	1.4X	2X	1.8X	2X	1.8X
Failure Modes	Micro-leaks, Freeze-Thaw	Micro-leaks, Freeze-Thaw	Micro-leaks	Pumps	Pumps, Thermal Connect	Pumps, Thermal Connect	Pumps, Liquid Coupling	Pumps, Liquid Coupling
L2 Life (years)	10	10	7	5	5	5	4	4

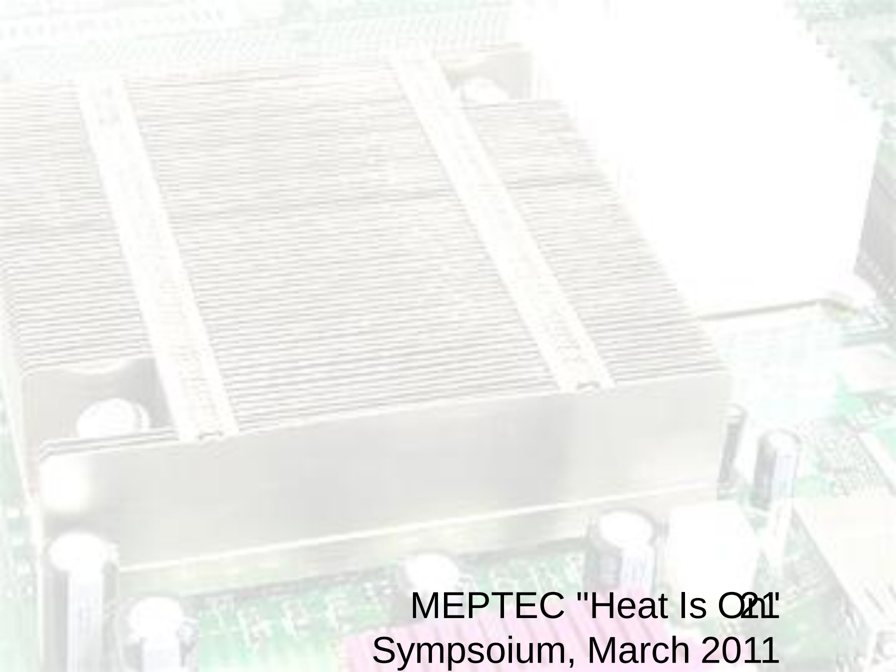
Concluding Remarks

- A number of cooling architectures are evaluated for rack based electronics systems. Cooling performance as well as cost and reliability estimates are made.
- Options 1 and 2 can be implemented even if the rack contains cards from multiple independent suppliers.
- Option 3 and 4 can be used when the rack level design is well integrated with the card level solutions, usually from a single supplier.
- Options 3 and 4 are most powerful when the rack level solution includes heat exchange with the end users facility level chilled water.



References

1. Kays, W.M. and London, A.L., Compact Heat Exchangers, 3rd Ed., McGraw Hill, NY, 1984
2. Handbook of Single-Phase Convective Heat Transfer, S. Kakac, R.K. Shah and W. Aung, eds., Wiley, New York, 1987



Nomenclature

A_s	heat transfer surface area
c_p	specific heat
D_h	hydraulic diameter
f	friction factor
K	inertial pressure loss factor
L	length of flow path
h	heat transfer coefficient
m	mass flow rate
p	pressure
Q	heat transfer rate
T_i	inlet temperature
T_s	surface temperature
U_m	velocity through minimum flow cross sectional area

Greek Symbols

ρ	density
η_s	heat transfer surface efficiency

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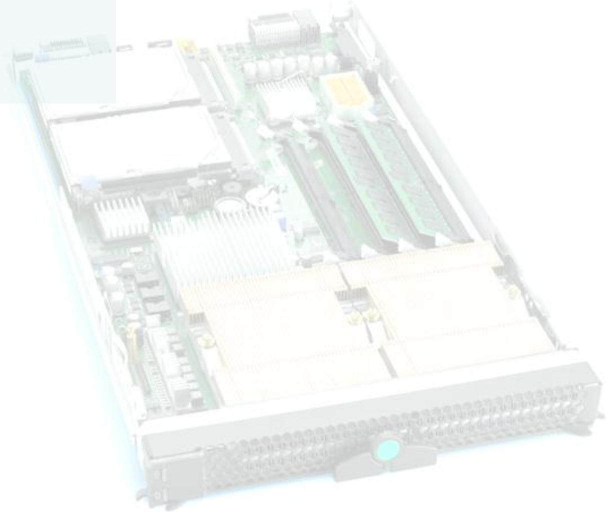
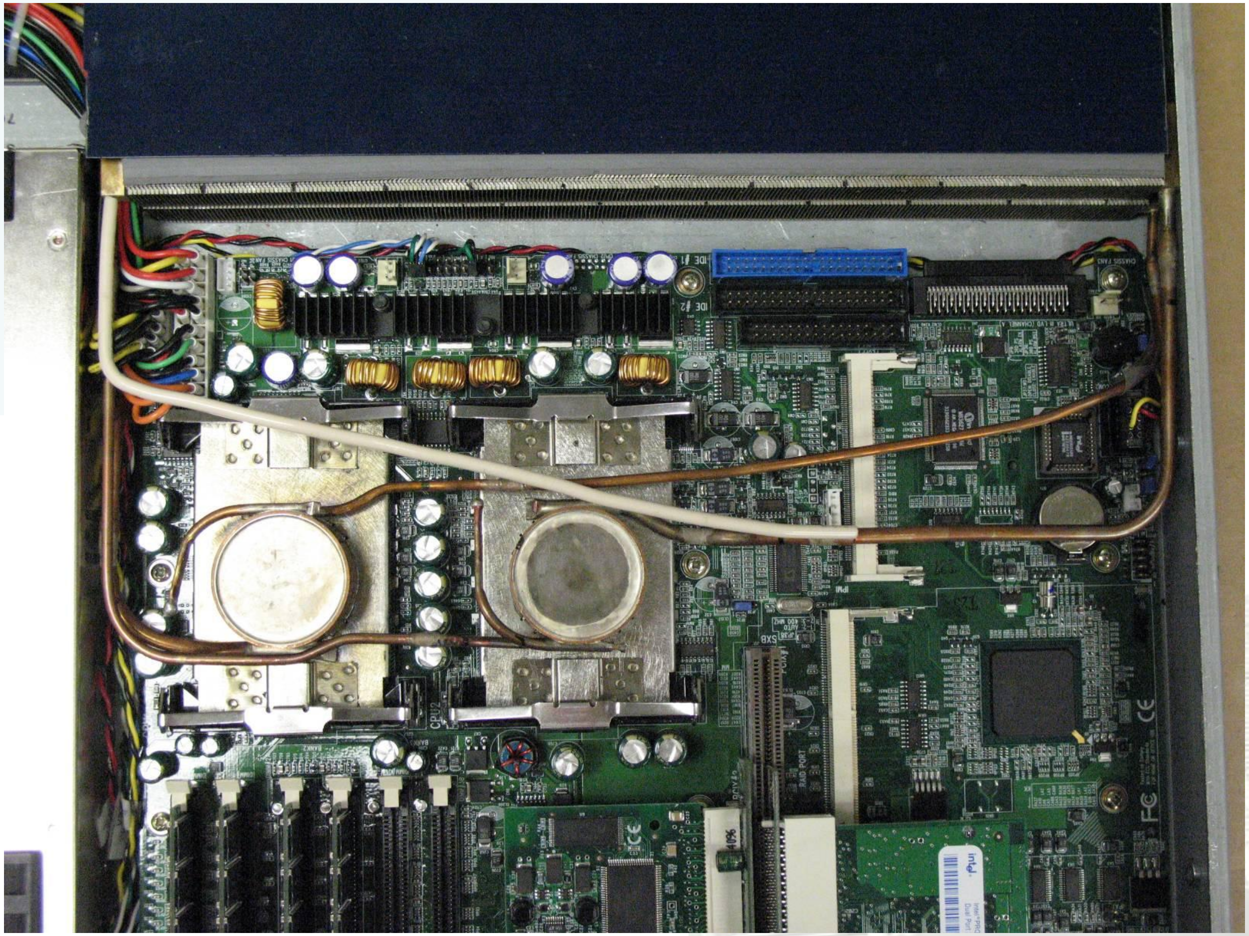
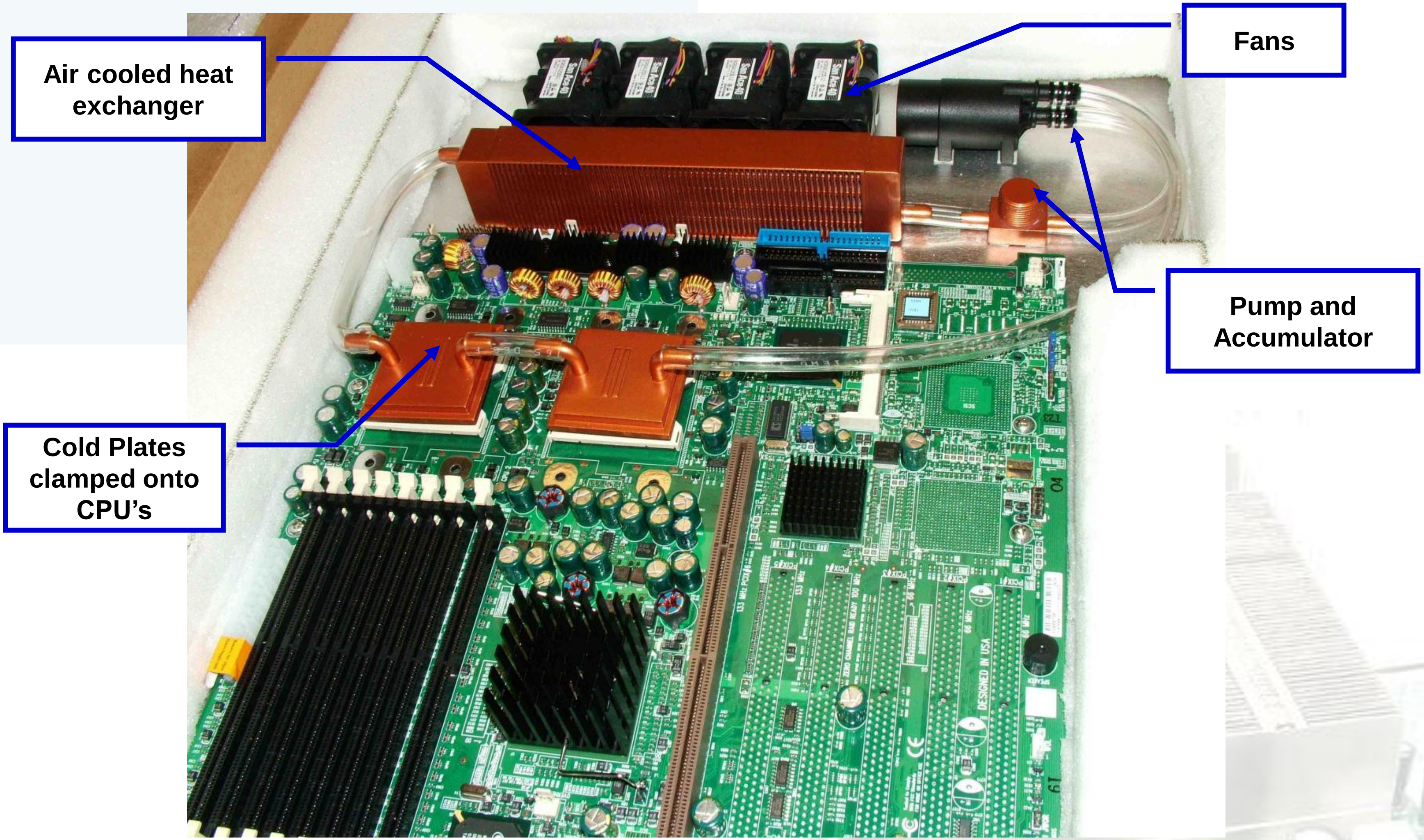
Illustrative Pictures



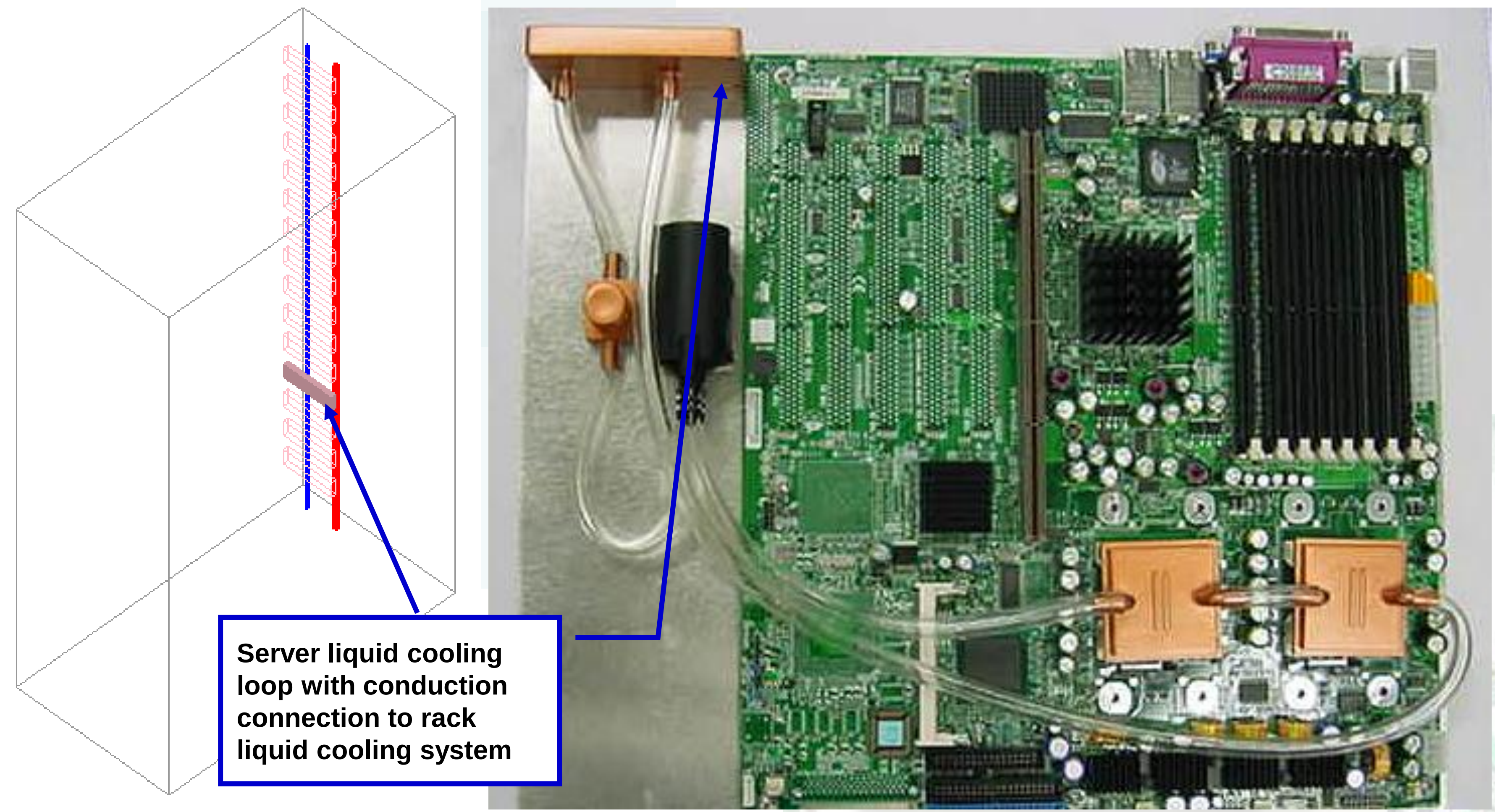
2A: LHP passive two-phase, HX in server volume



2B: Pumped liquid cooling, HX in server volume

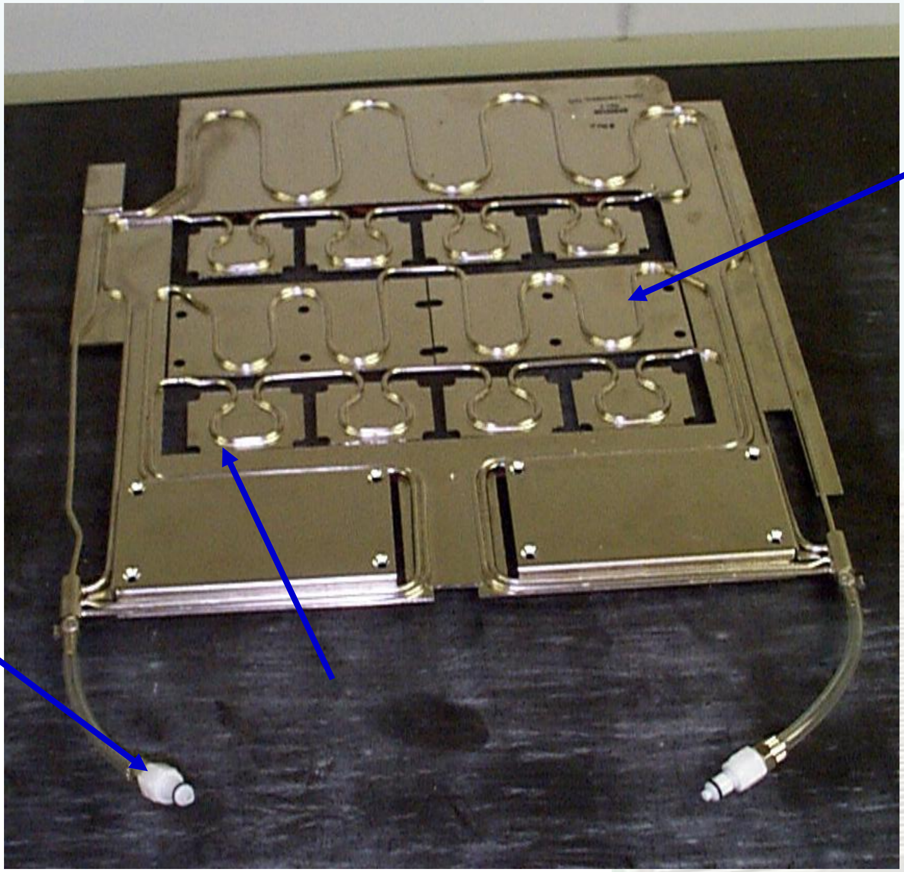


3: Server loop conduction connected to rack loop



Server liquid cooling loop with conduction connection to rack liquid cooling system

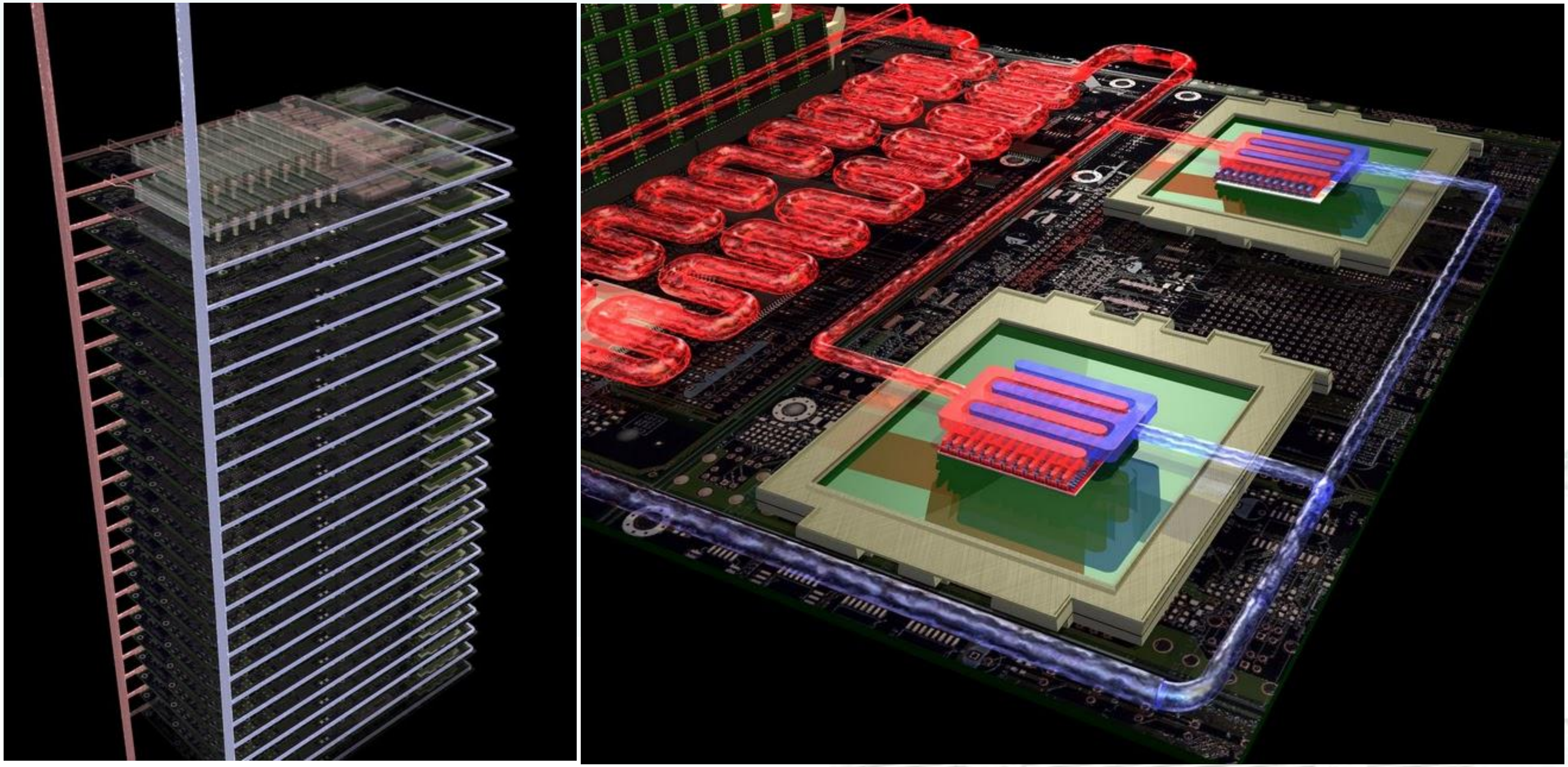
4: Card level loop with liquid couplings to rack loop



Fluid path on cold plate to manage non-uniform heat loads on card

Zero-Leak fluid couplings plug into liquid manifolds in rack

4: Water cooled rack



IBM Research's Water Cooled Chips: Scientists at IBM's Zurich Research Lab are working on the future of water cooling, bringing cold water to the hottest part, directly on the chip itself, and then capturing the water at its hottest and piping it off the chip for re-use. Shown here is an array of the chips in a rack, with the cold water going in, capturing the heat, and then the hot water is pumped out.

Source: http://picasaweb.google.com/ibmphoto/IBMSystems#5187345288745090450