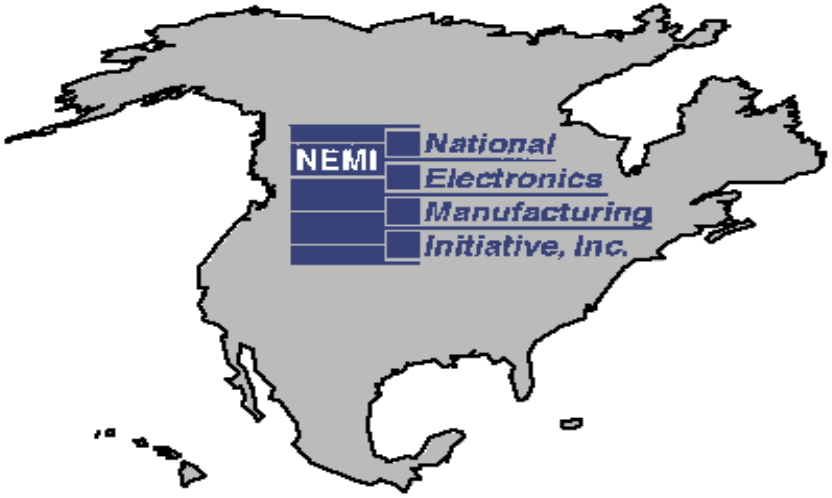


Thermal Management Roadmap
Cooling Electronic Products from Hand-HeldDevices to Supercomputers

Richard C. Chu - IBM

May 16, 2003, Rohsenow Symosium
Cambridge, MA

Thermal Management Technical Working Group (TWG)

Richard C. Chu, IBM (Chair)

Jogenda Joshi (Co-chair)

Avi Bar-Cohen, U. of Maryland

Darvin Edwards, TI

Magnus Herrlin, Telcordia

Donald Price, Raytheon

Roger Schmidt, IBM

Gregory M. Chrysler, Intel

Suresh Garimella, Purdue U.

Larry Mok, IBM

Bahgat Sammakia, SUNY-Binghamton

Lian-Tuu Yeh, Boeing

Thermal Management Roadmap - Scope

- **Introduction**
  - Overview
  - Review of thermal design requirements
  - Review of thermal design requirement matrix
  - Review of current product cooling designs
  - Review of cooling technologies
  - Review of advanced cooling technology development activities
- **Outline of Thermal Technology Needs**
  - High performance product sector
  - Cost performance product sector
  - Telecommunications product sector
  - Hand held product sector
  - Harsh environment (automotive) product sector
  - Harsh environment (military) product sector
- **Summary and Conclusions**
- **Future Cooling Technologies & Strategy**

Overview

Thermal management will play a pivotal role in the coming decade for all types of electronic products. Increased heat fluxes at all levels of packaging from chip to system to facility pose a major cooling challenge. To meet the challenge significant cooling technology enhancements will be needed in each of the following areas:

- Thermal interfaces
- Heat spreading
- Air cooling
- Indirect and direct water cooling
- Immersion cooling
- Refrigeration cooling
- Thermoelectric cooling
- Equipment-facility interface

Thermal Design Requirements (Traditional)

- Design for Performance
- Design for Reliability
- Design for Serviceability
- Design for Extensibility
- Design for Minimal Cost
- Design for Minimal Impact on User

Thermal Design Requirements (New)

- Design for improved coolability at the package level via optimized internal thermal conduction paths.
- Design for direct air cooling at the product level via enhanced convection process over the packages.
- Design for special cooling needs at the module level via spot cooling devices attached to the packages.
- Design for low temperature applications - subambient to cryogenic.
- Design for low cost via Computer Aided Thermal Engineering (CATE) and improved manufacturability.

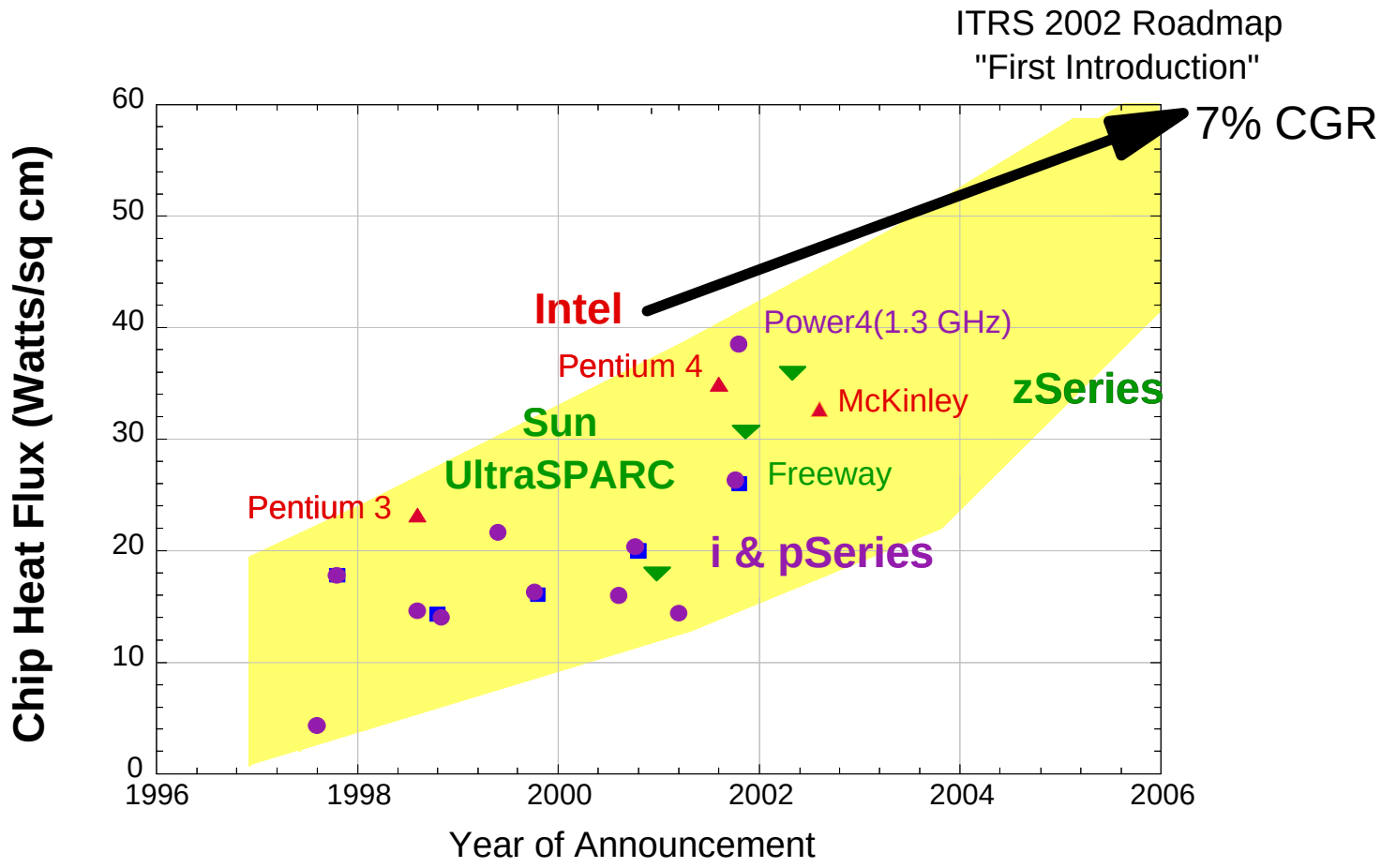
Thermal Management Requirements Matrix

● - State-of-Art

✓ - Likely

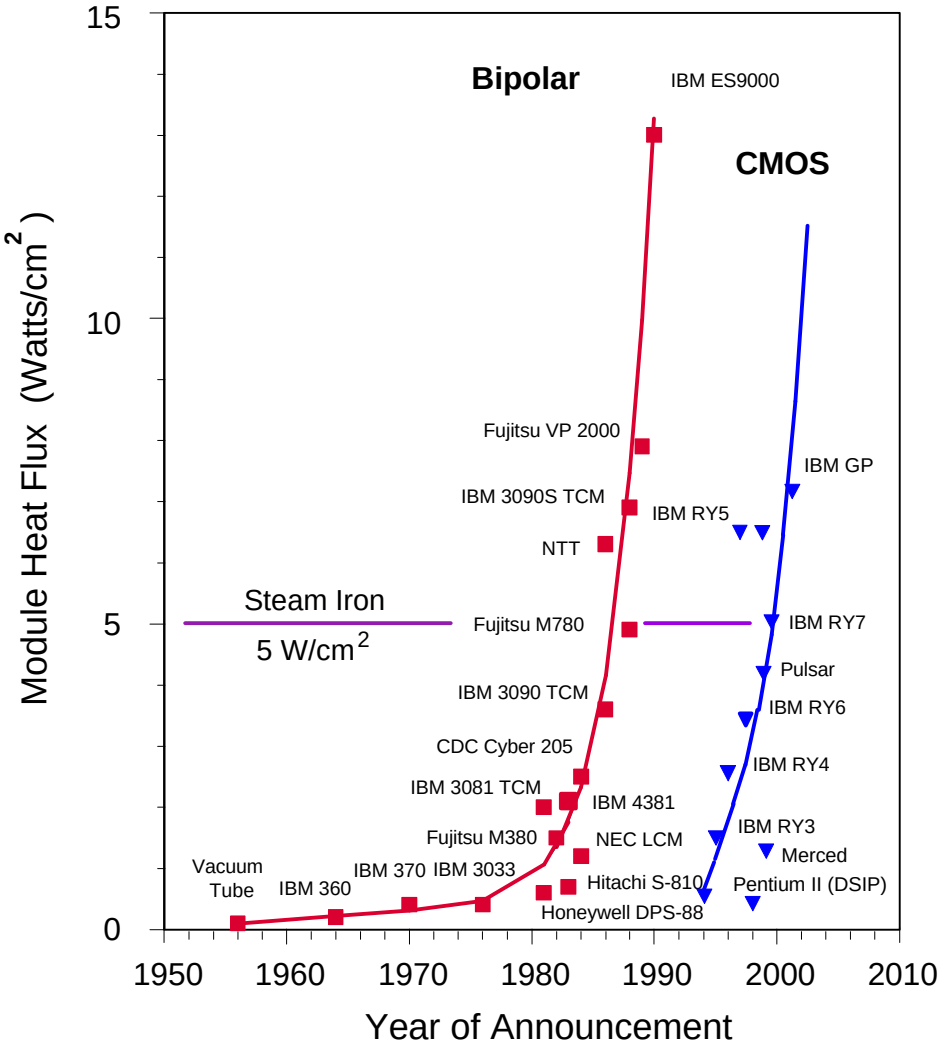
	Air Cooling	Conduction (Indirect Liquid)	Direct Liquid	Heat Pipe	Thermo -Electrics	Low Temperature	New Cooling Technology Needed (see list)
PC/Handheld/Wearable	●			✓	✓		✓
Workstations	●	✓		✓	✓	●	✓
Mid-Size Computers	●	✓		✓	✓	✓	✓
Storage Subsystems	●	✓			✓		✓
Large Scale Computers	●	●	✓	✓	✓	●	✓
Super Computers	●	✓	●	✓	✓	●	✓

Microprocessor Power Dissipation Trends

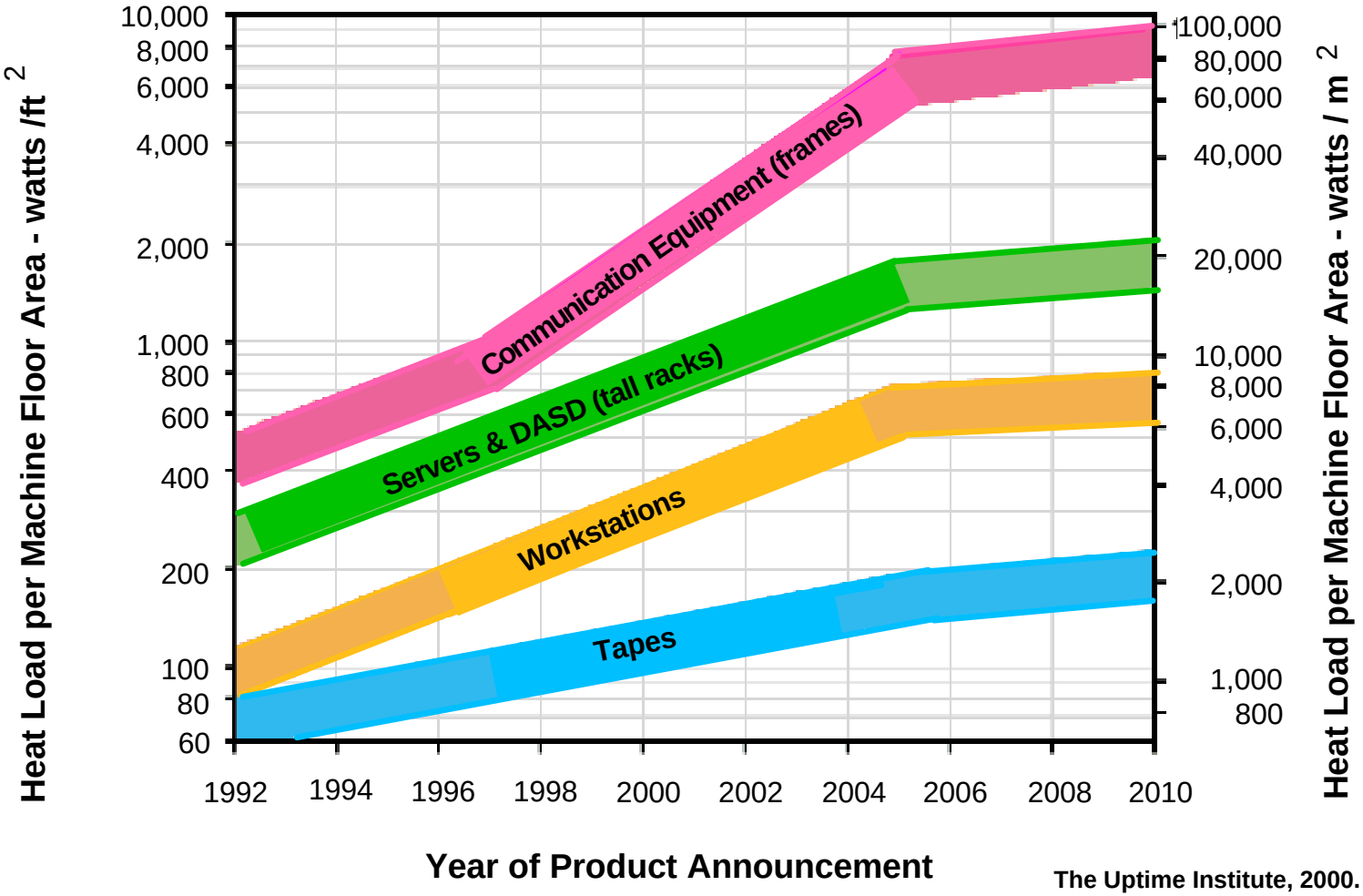


International Technology Roadmap for Semiconductors
2002 Update

Module Heat Flux Explosion

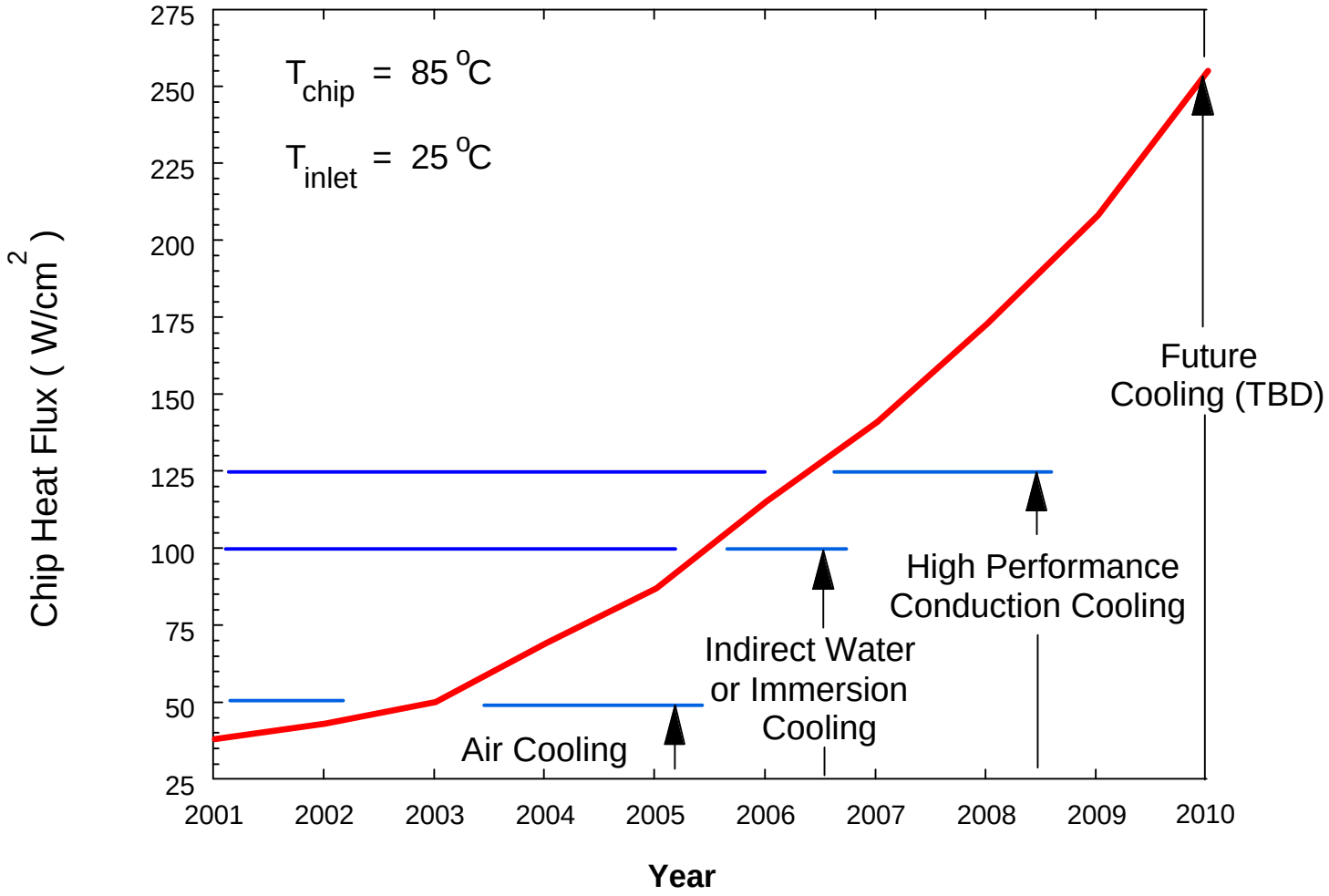


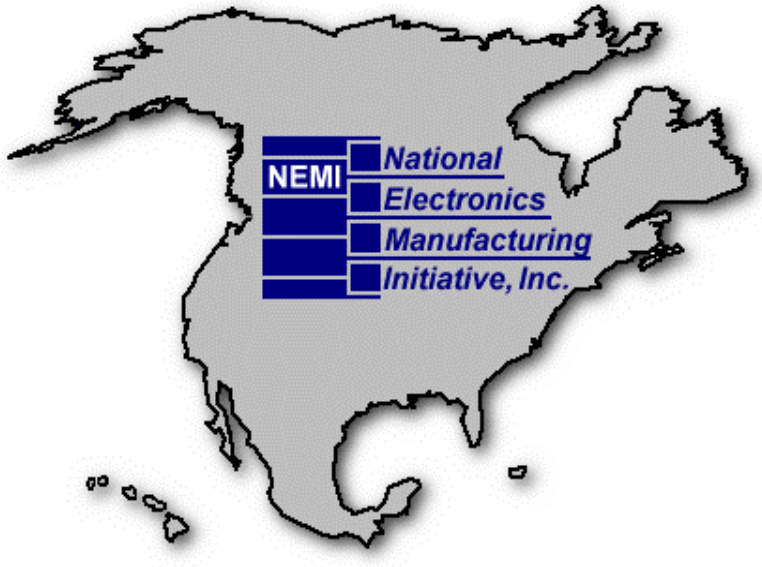
System Heat Density Trends



The Uptime Institute, 2000.

Projected Chip Heat Flux and Cooling Technology Limits



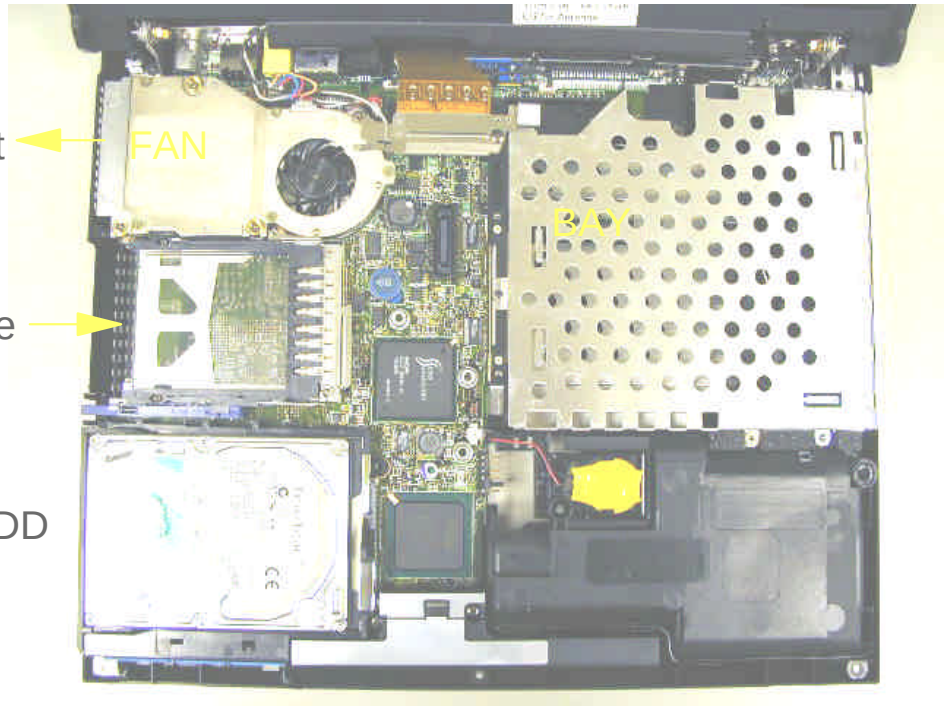


Current Product Cooling Designs

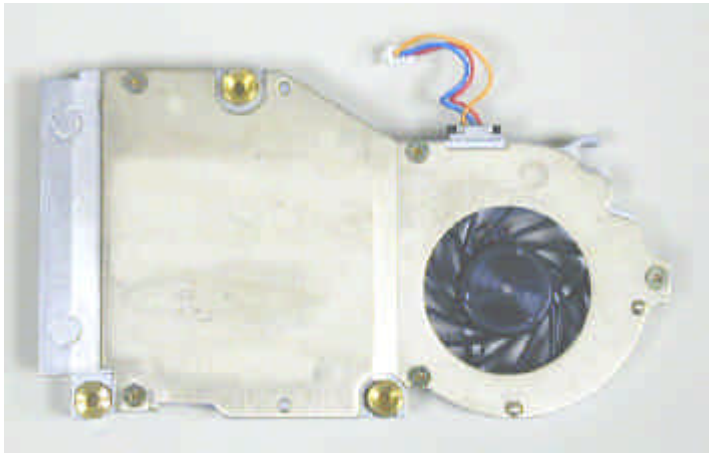
Dedicated to the Advancement of North American Electronics Manufacturing

IBM Thinkpad T23
Air Flow Layout

Inlet / Outlet zoom

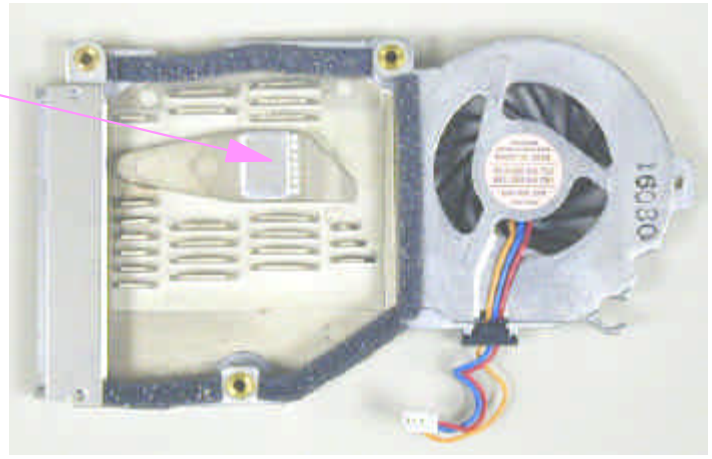


IBM Thinkpad T24
Push Fan



Top

CPU



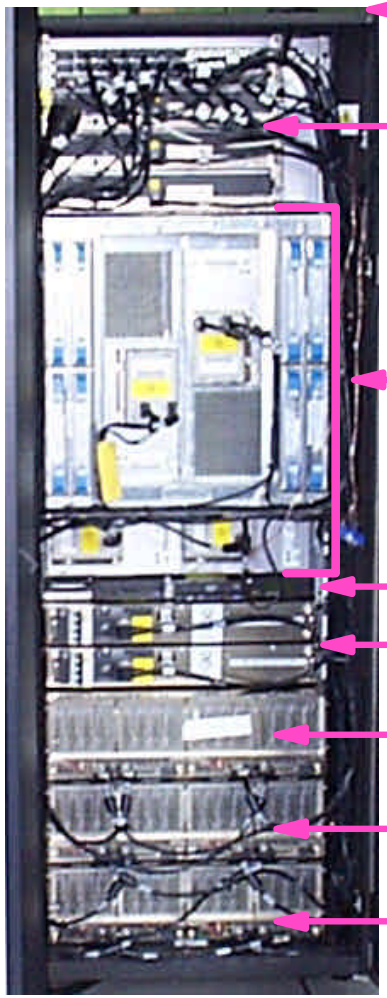
Bottom

Hitachi Water Cooling Laptop (Prototype Model)

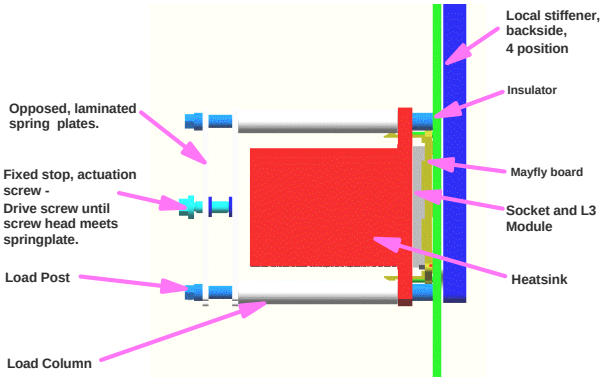
IBM pSeries 690 (with extra rack)

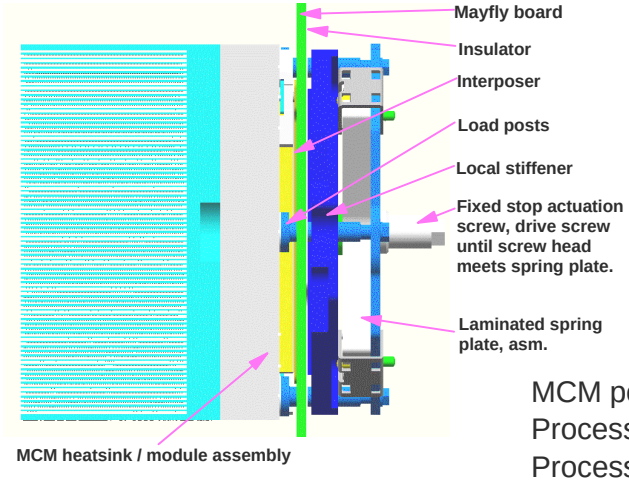
IBM pSeries 690 (continued)

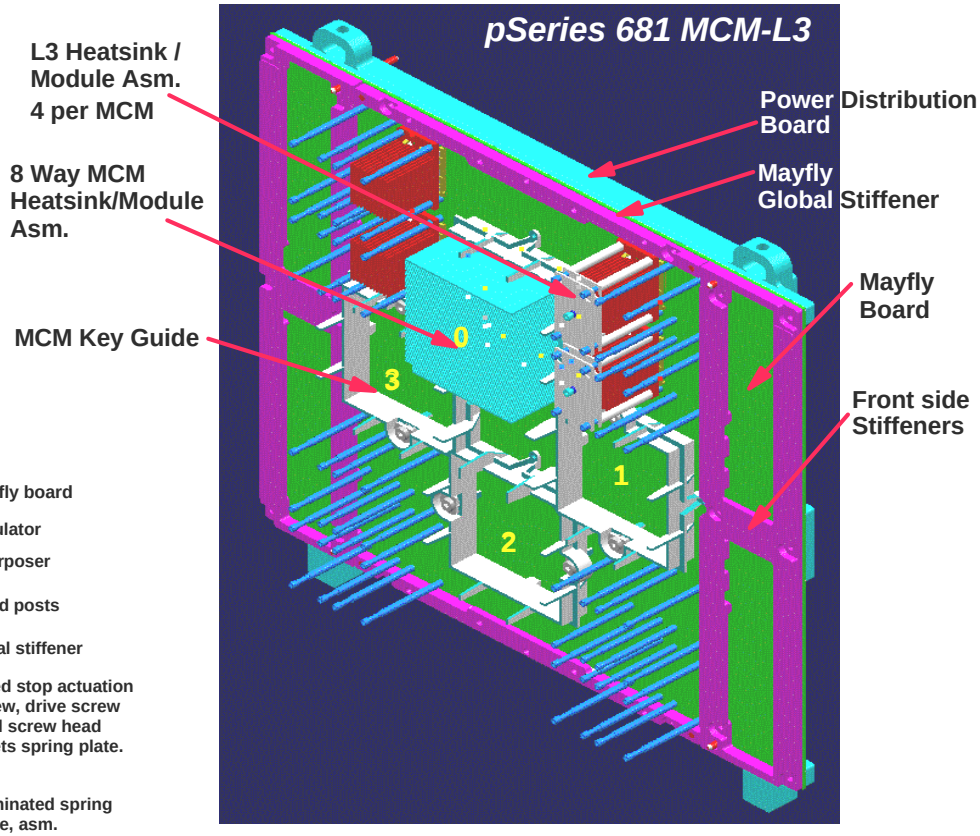
Processors	8-32 SMP's
Clock speed	64-bit 1.1 to 1.3 GHz
Main memory	8 GB to 256 GB
OS images	1-16
Memory bandwidth	205 GB/sec
I/O bandwidth	16 GB/sec
Internal storage	4.66 TB - 8 drawers (with extra rack)
PCI adaptors	up to 160
PCI hot-plug slots	yes
PCI bus recovery	yes
PCI bus deallocate	yes
Battery backup	yes



IBM pSeries 690 (continued)

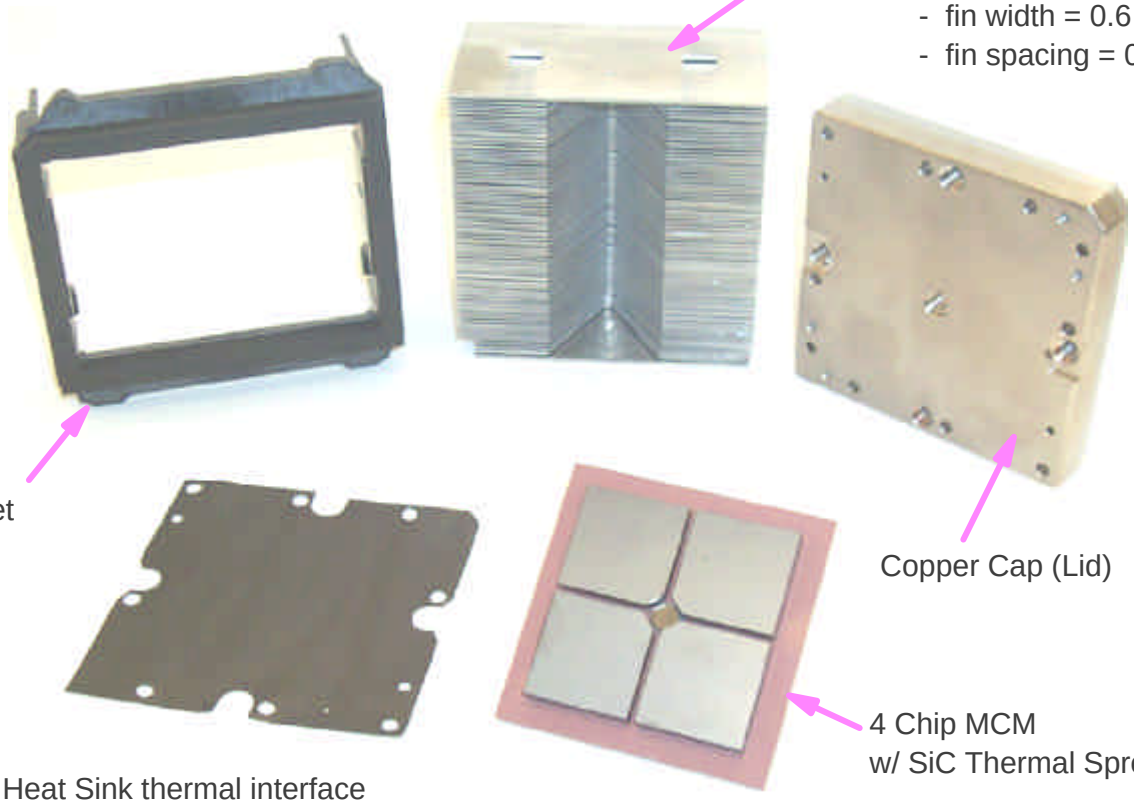






MCM power ~ 624 watts
Processor - 2 cores - 156 watts max
Processor 415 sq mm
Tj ~ 105C

IBM pSeries 690 MCM



Aluminum Air Cooled Heat Sink
- 68 fins
- fin width = 0.6 mm
- fin spacing = 0.73 mm

Shroud with gasket

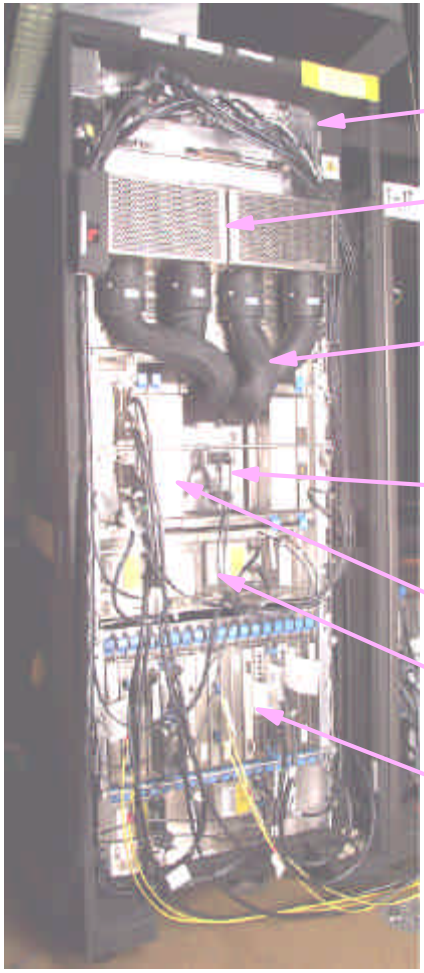
Copper Cap (Lid)

4 Chip MCM
w/ SiC Thermal Spreaders

Cap / Heat Sink thermal interface
- Powerstrate 60
- Al foil with phase change material on both sides

IBM zSeries 900 Server (with extra rack)

IBM zSeries 900 Server (continued)



Front Side

Power

Modular Cooling Units
(MRUs)

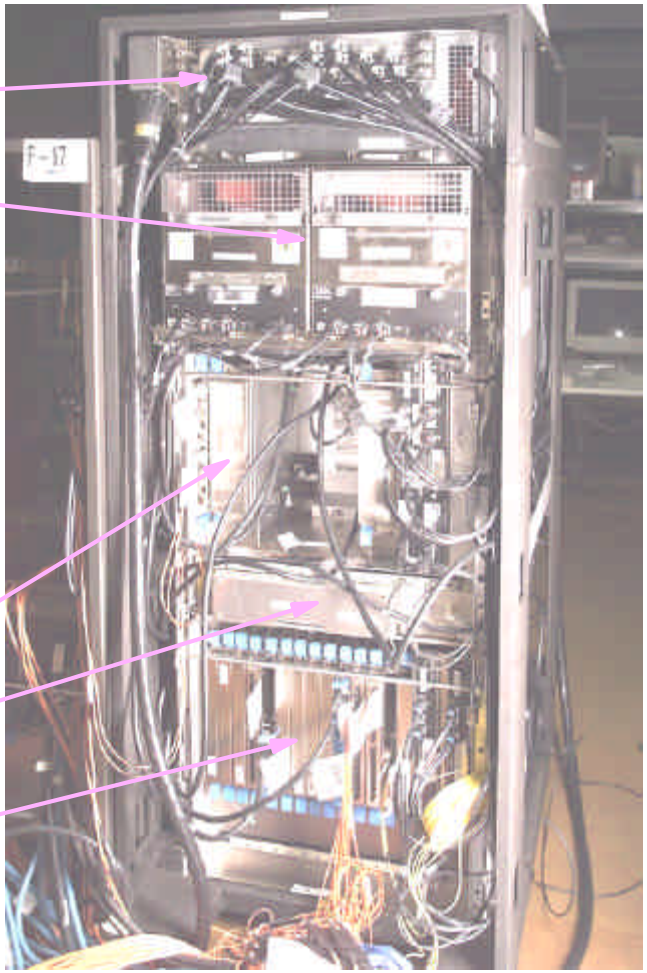
Refrigerant
(R134A)
Lines

Evaporator
(MCM behind)

Memory Cards

Blowers

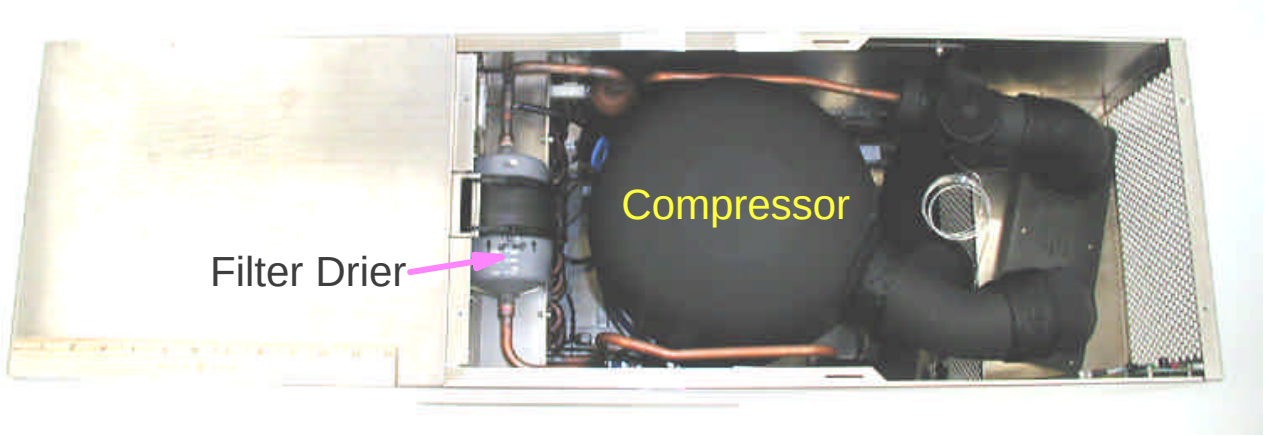
I/O Cage



Back Side

IBM zSeries 900 Server Evaporator

IBM zSeries 900 Modular Refrigeration Unit



Large IBM Servers

IBM z900
S/390 Mainframe

IBM pSeries
Regatta-H

13KW Dual Bulk Power:

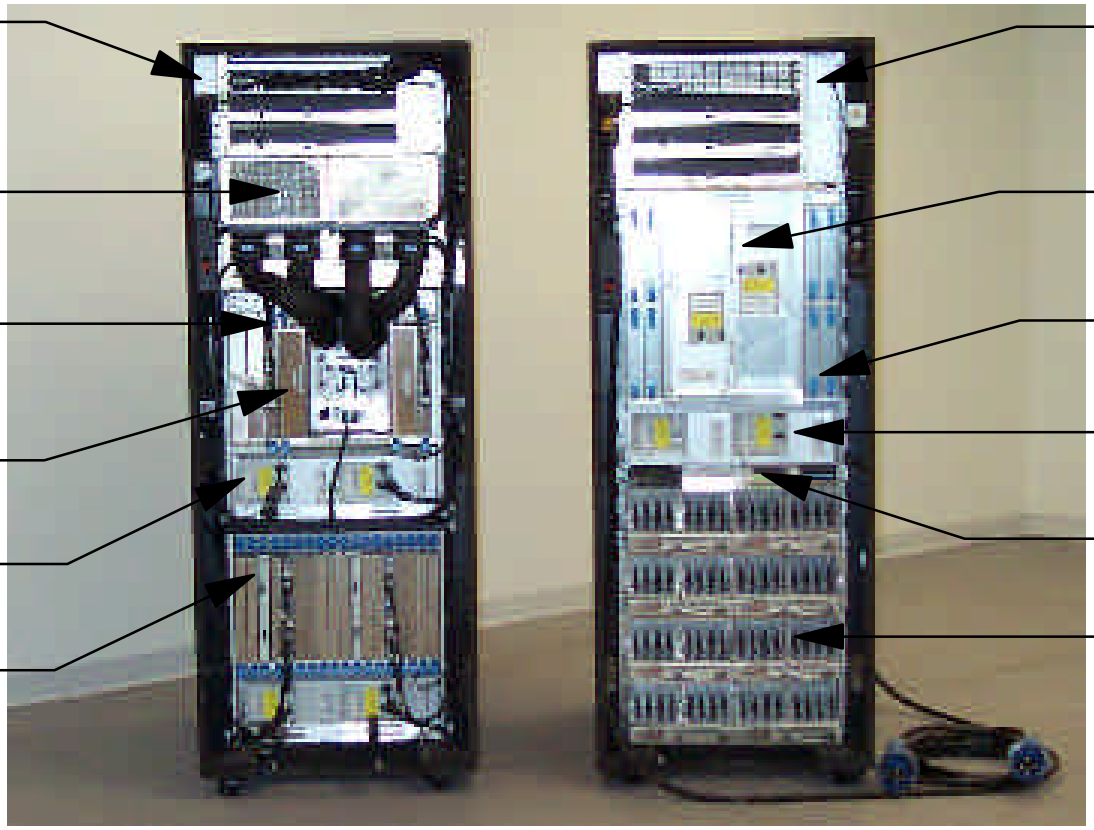
Modular CPU Cooling Units:
* Cools CPU Chips to 0C Tj
* Advanced Refrigeration
* Fully Redundant

CPU Cage:
* 20 way SMP @ 0.8GHz

4 Memory Books:
* 24GB / Memory Book

CPU Cage Cooling Blowers:
* High Pressure & Flow
* Intelligent Variable Speed

I/O Cage:
* 28 I/O Book Slots



20KW Dual Bulk Power:

CPU Cage:
* 32 way SMP @ 1.3GHz

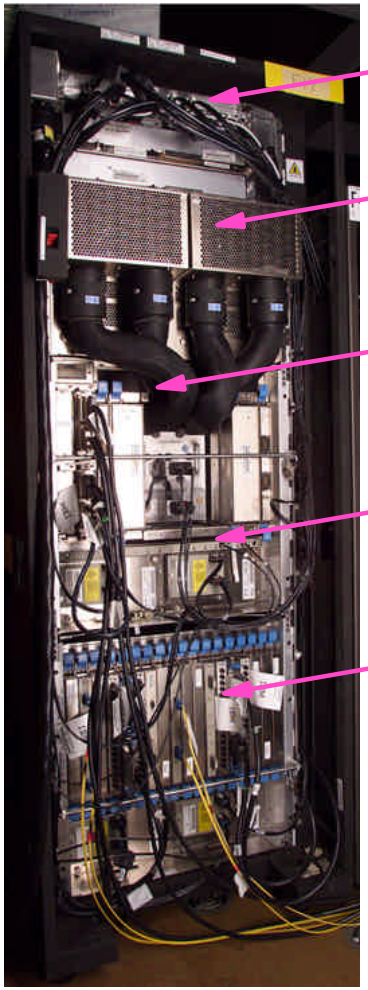
CPU Cage Cooling Blowers:
* High Pressure & Flow
* Intelligent Variable Speed

Removable Media Drawer:

I/O and Storage Drawer:

High Density Single Frame Systems

IBM zSeries Server Model z900



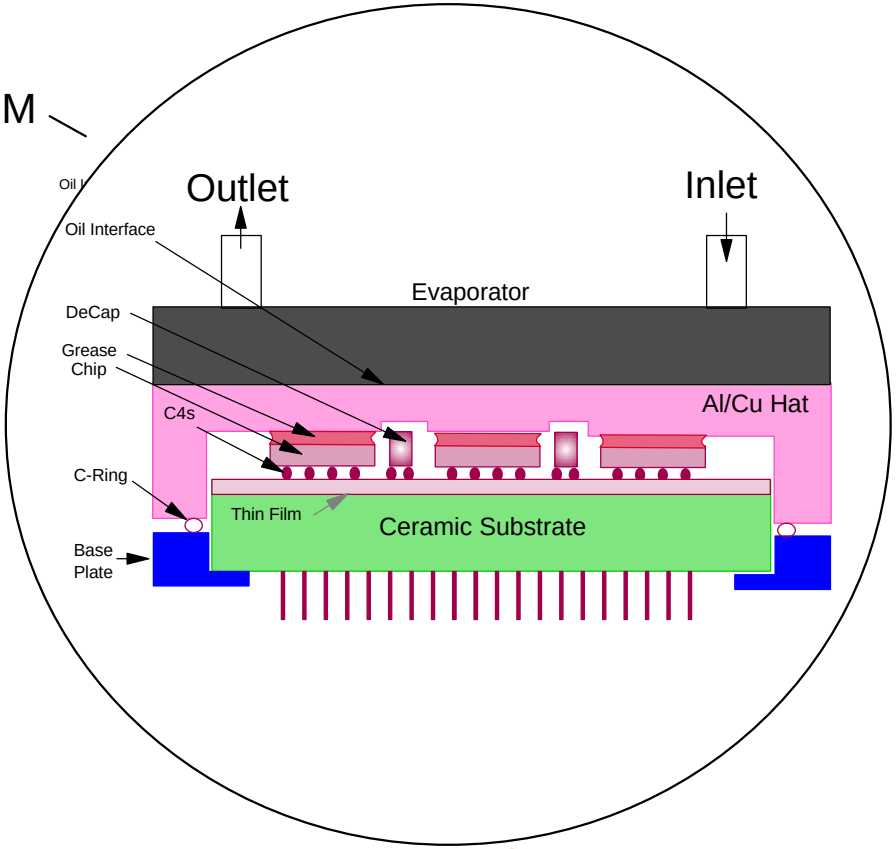
Bulk Power Supplies

Modular Refrigeration Units(MRU)

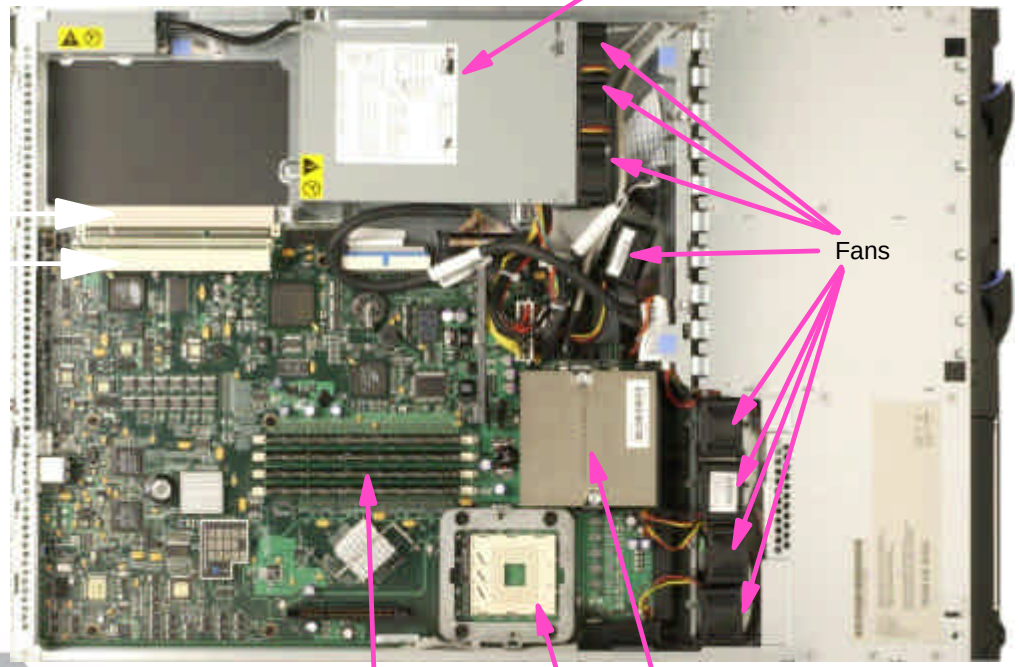
Evaporator/MCM

Blowers

Input/Output

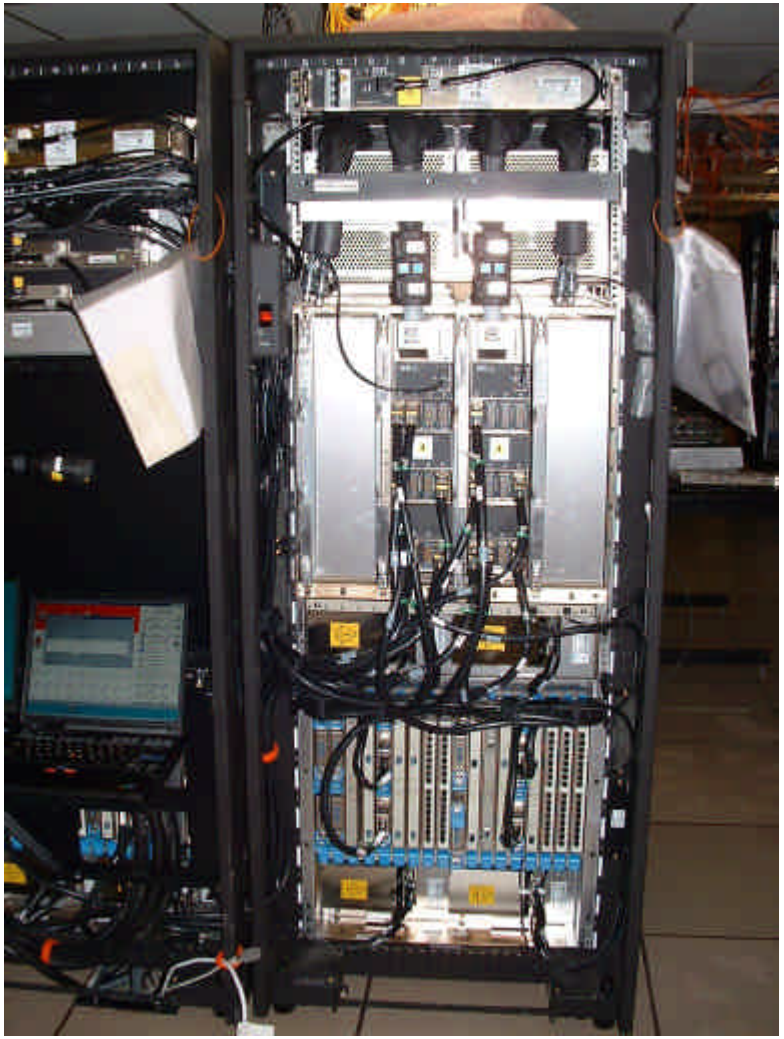


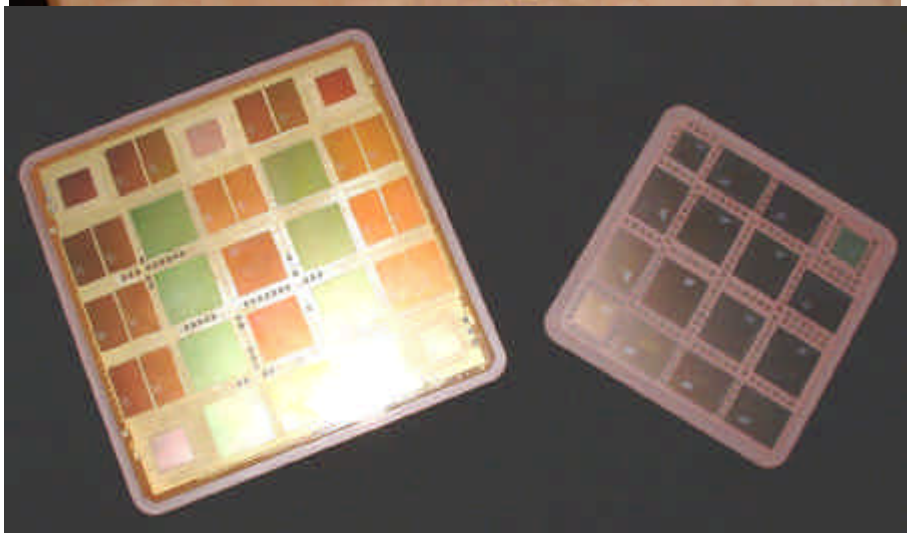
IBM's xSeries Model 335



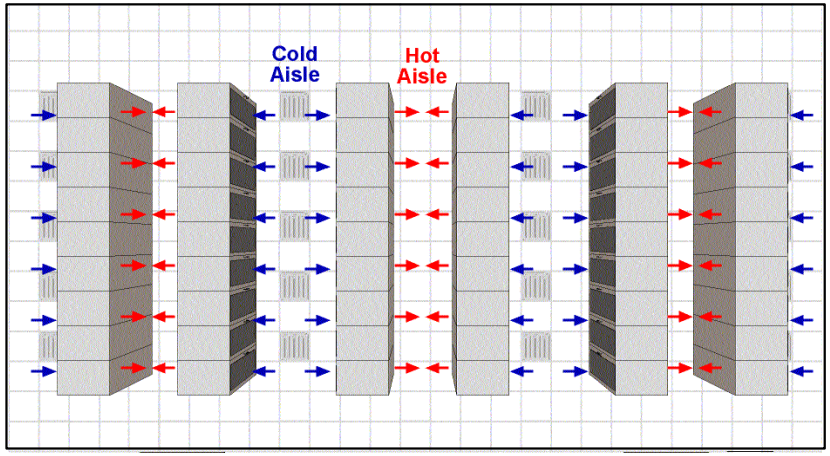
New IBM xSeries server

IBM's zSeries Model z990: T-Rex



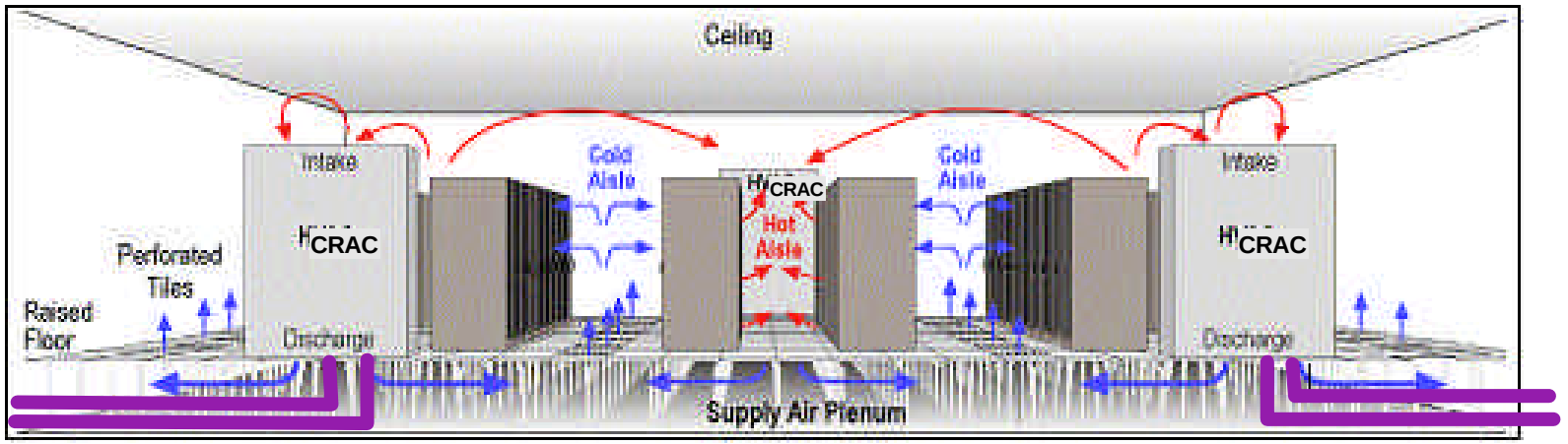


Data Center Cooling



Top View

CRAC - Computer Room Air Conditioner



Facilities Chilled Water

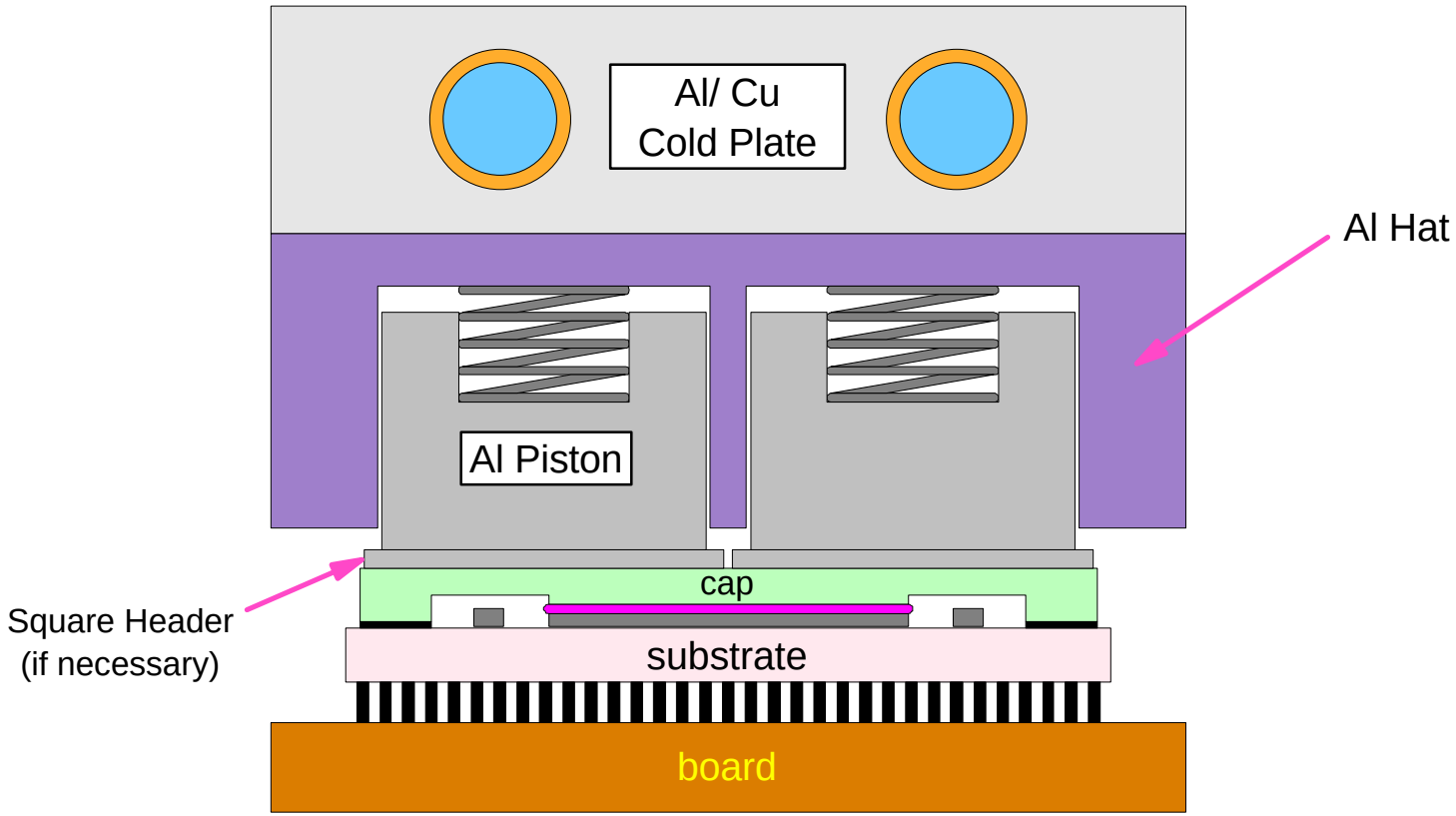
Side View

Super Computer System Summary (studied)

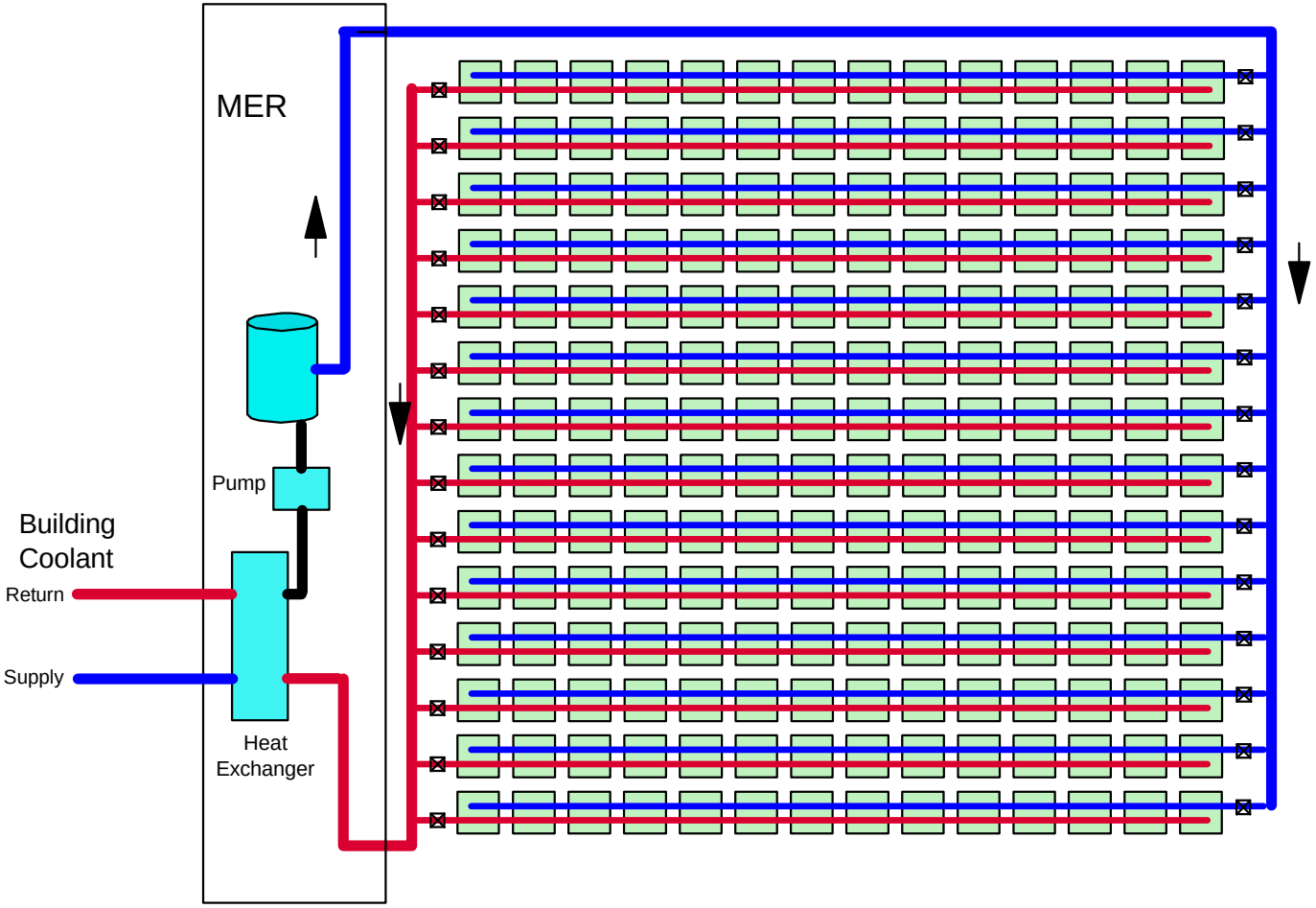
	Number of Modules	Number of Processors	Power (1) (W)	Water Flow Rate (1) (gpm)	Air Flow Rate (1) (cfm)
Module	n/a	28	40	n/a	6
Board	36	1,008	1,440 (2,000)	1 (1.5)	216 (300)
Cabinet	144	4,032	5,760 (8,000)	4 (6)	864 (1,200)
System	36,864	1,032,192	1,474,560 (2,048,000)	1,024 (1,536)	221,184 (307,200)

Note: 1) Top number pertains to the processors;
bottom numbers (in parentheses) pertain to the total package

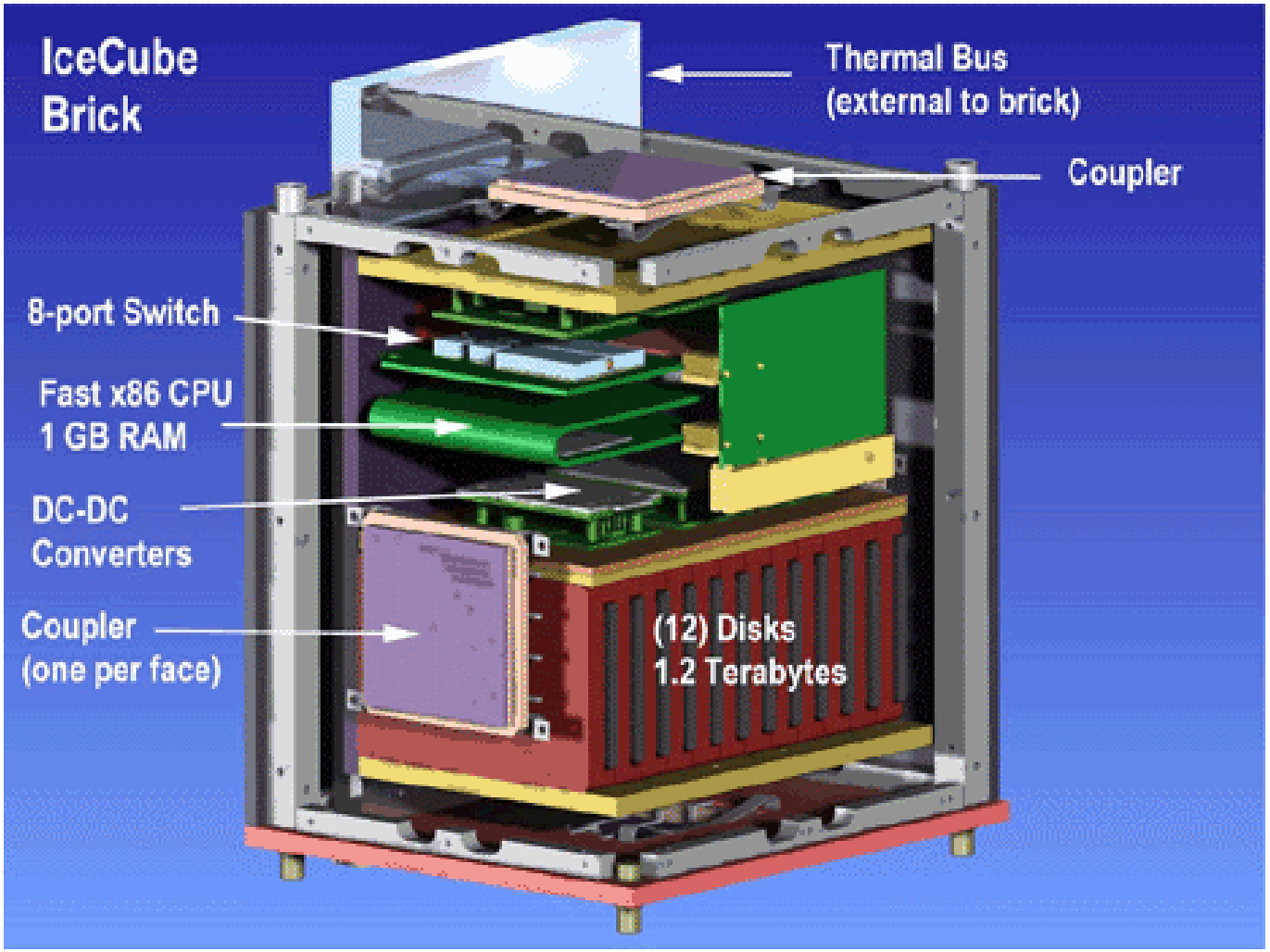
Super Computer System Cooling Module (studied)

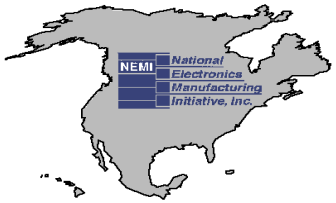


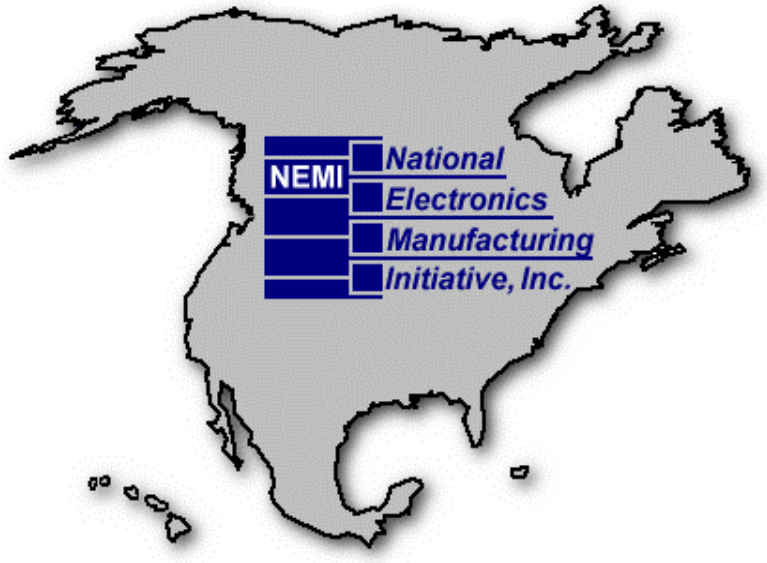
Super Computer Cooling System (studied)



IBM Prototype Data-Storage System: Storage-Array Brick







Cooling Technologies

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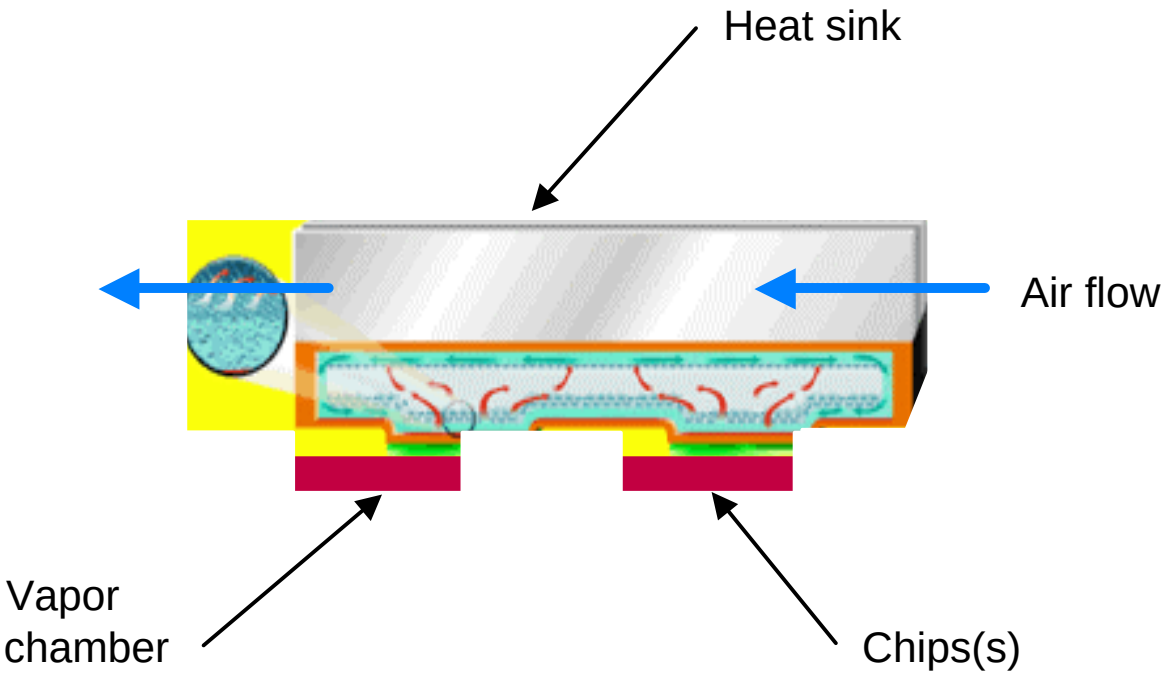
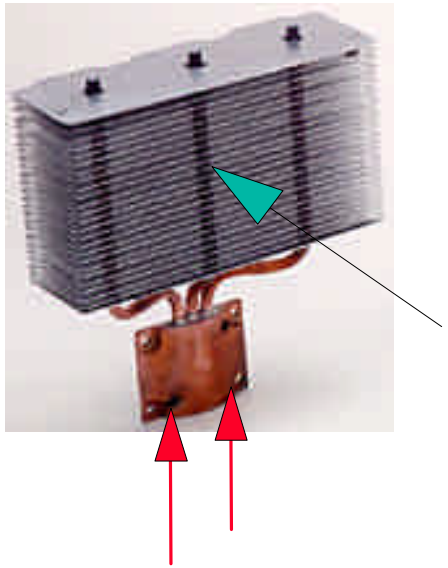
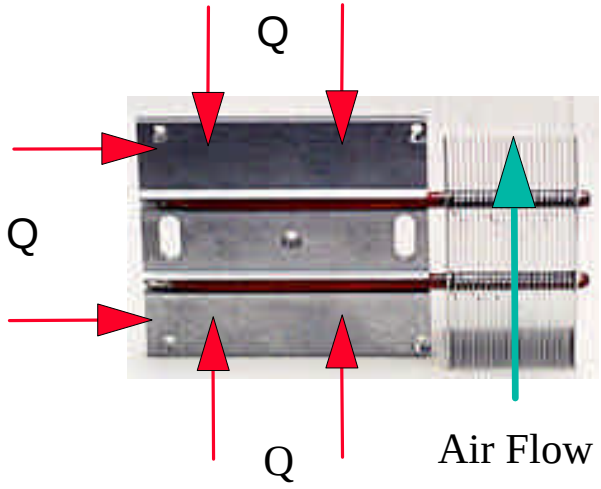
Vapor Chamber Heat Spreader

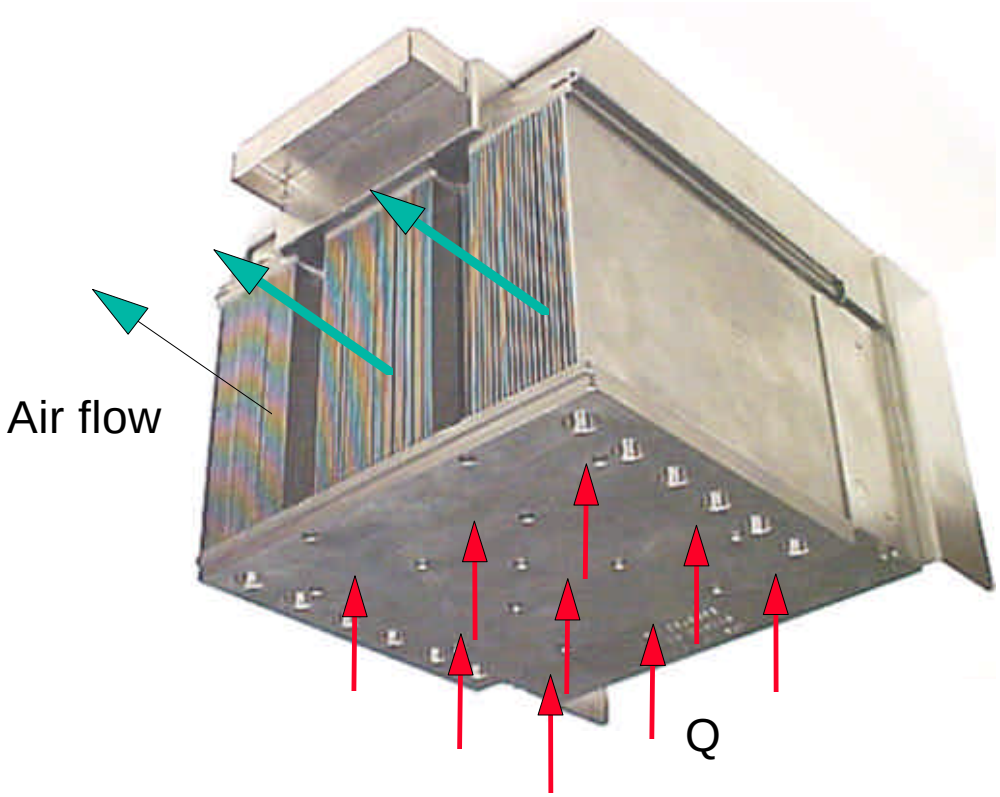


Examples of Heat Pipes Used in Electronics Cooling

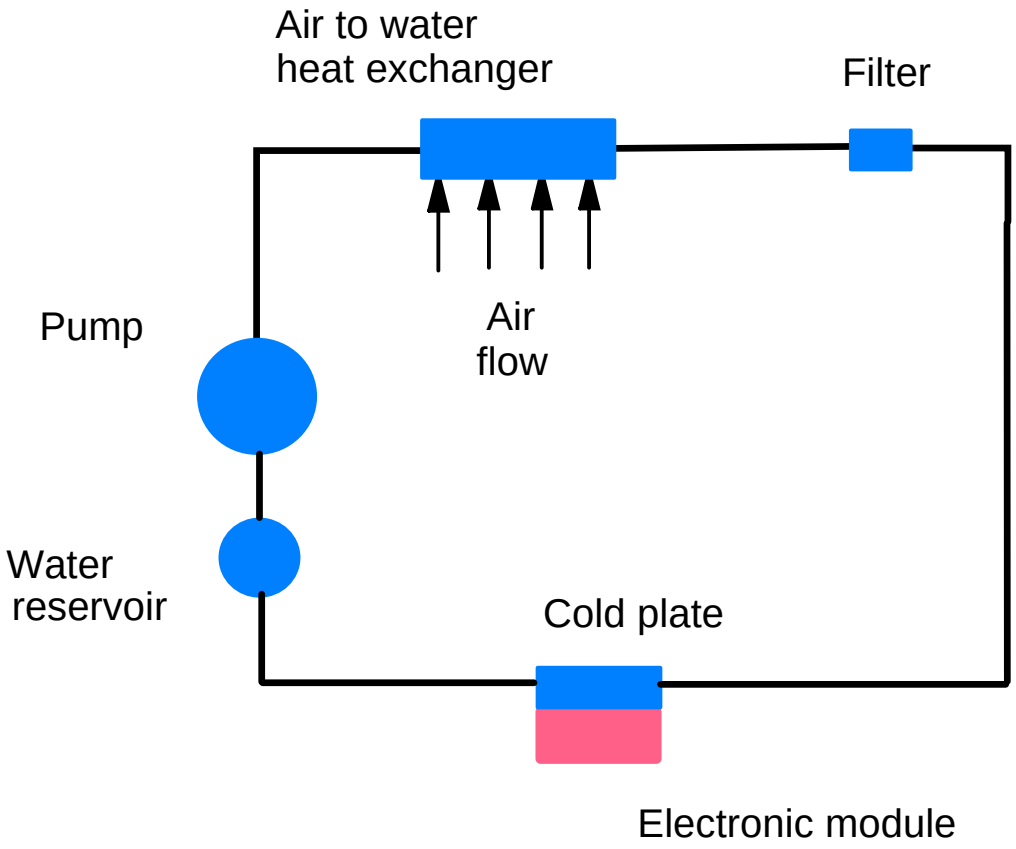




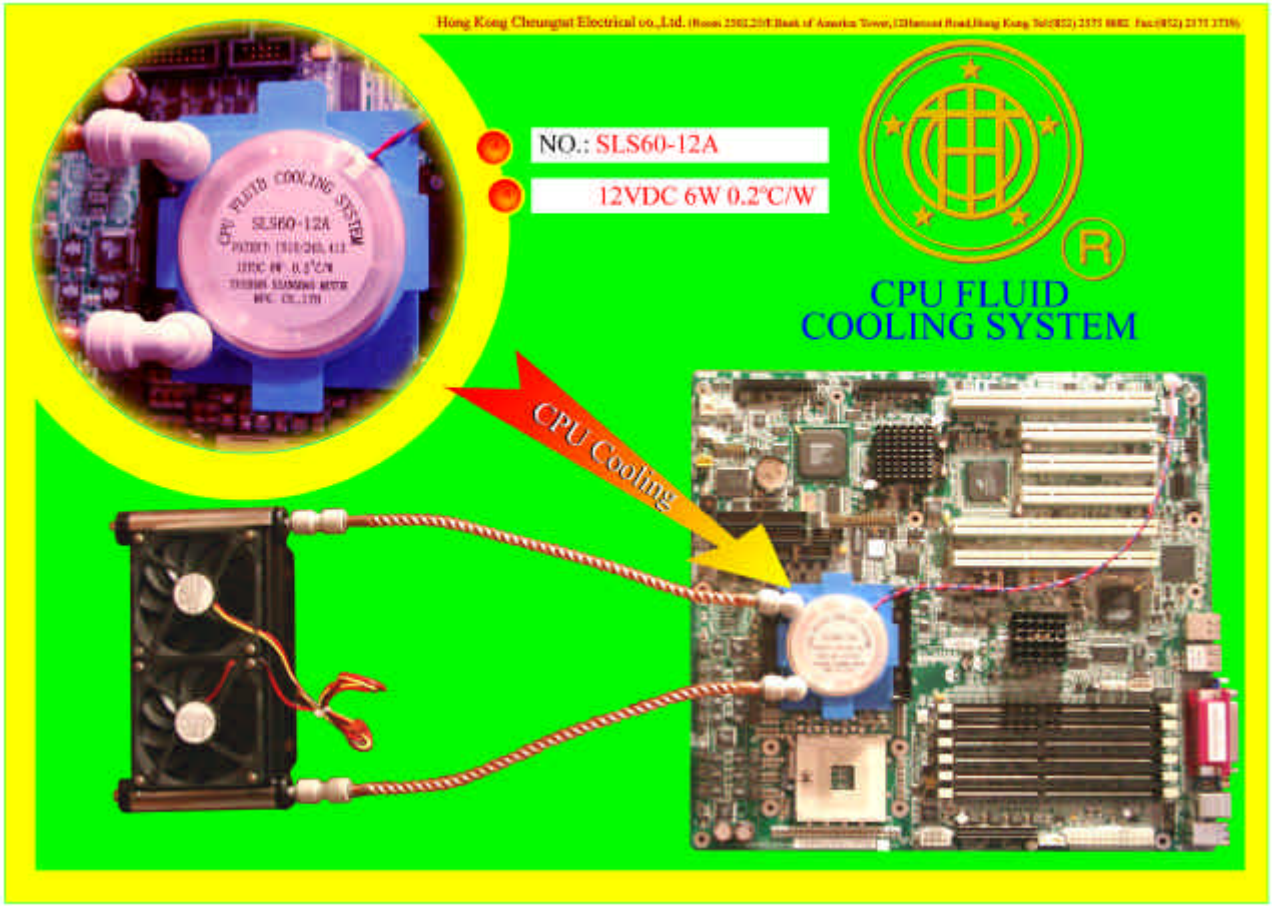
Example of a Large Air-Cooled Heat Sink for A High Performance Processor Module



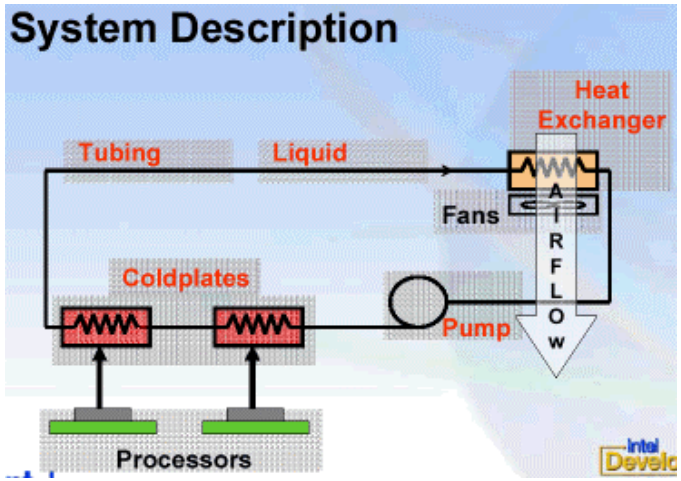
Closed Loop Water Cooling System With Heat Rejection to Air

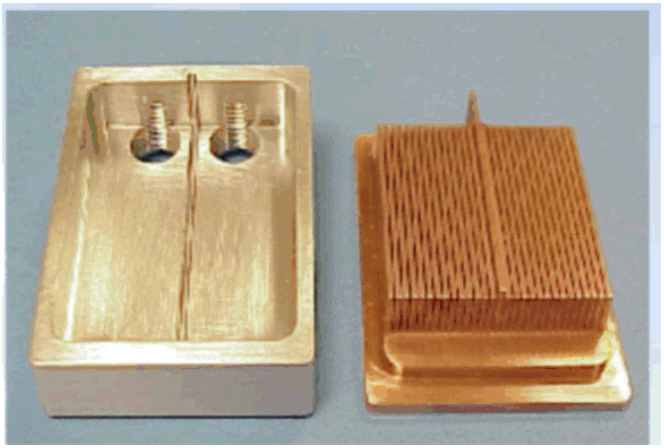


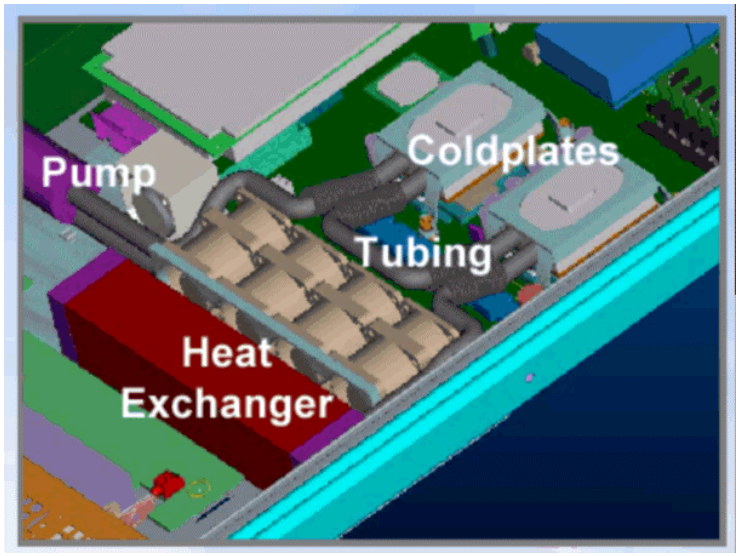
Closed Loop Water Cooling System With Heat Rejection to Air



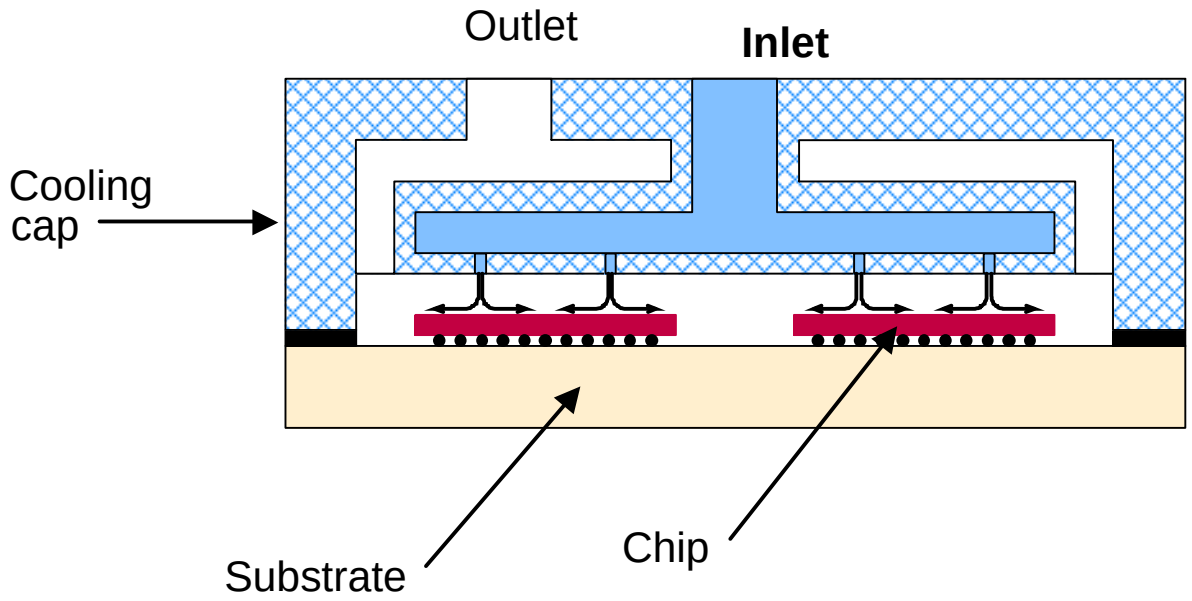
Closed Loop Water Cooling System With Heat Rejection to Air



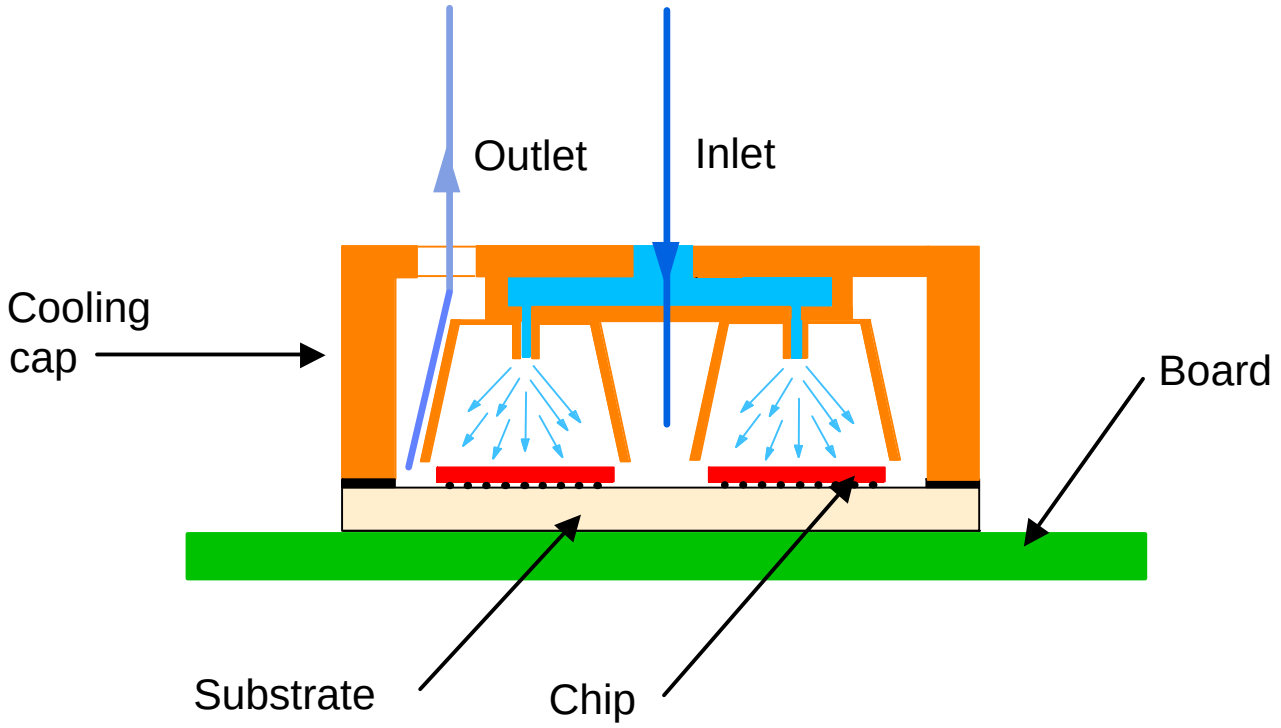




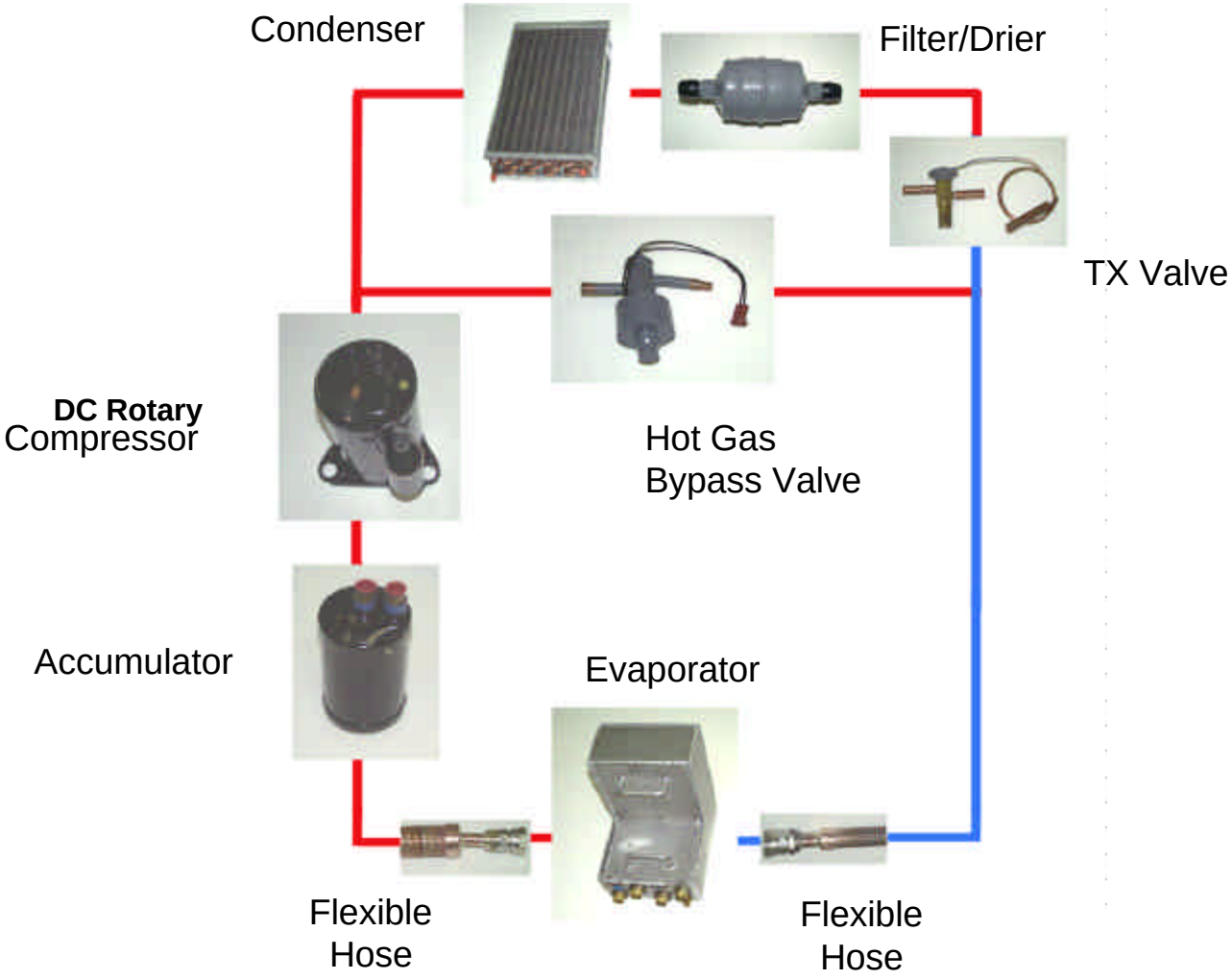
Liquid Jet Impingement Cooling



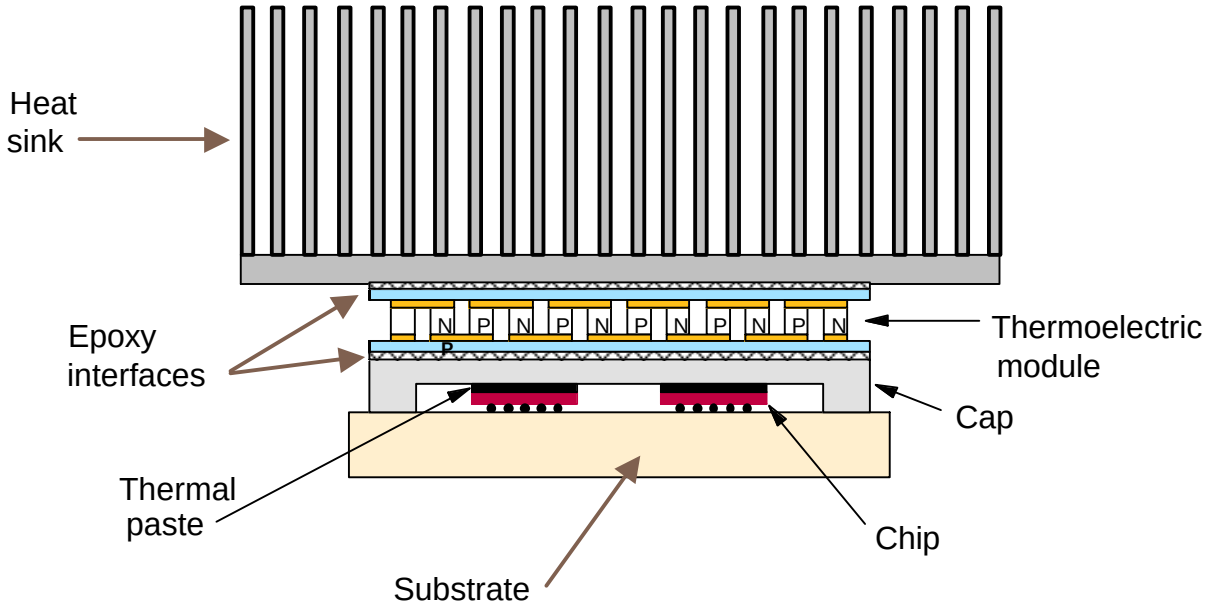
Liquid Spray Cooling

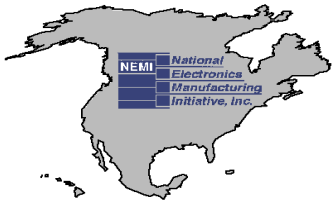


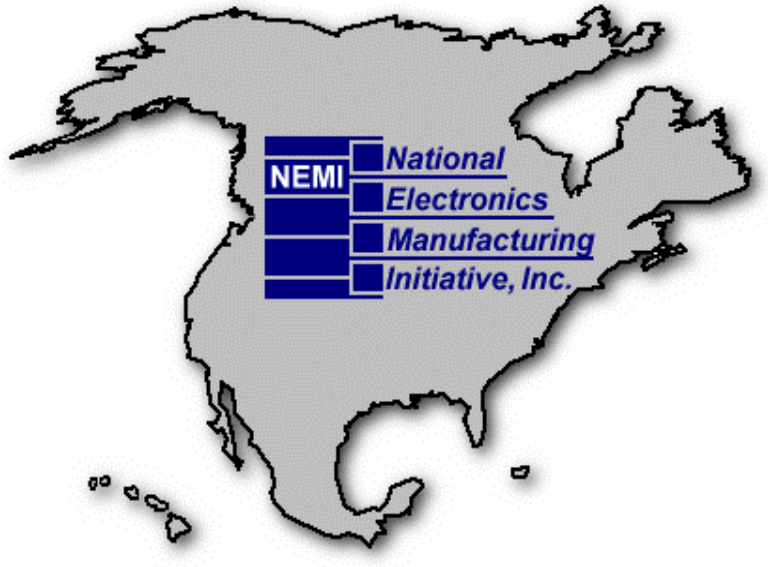
Refrigeration Loop and Components for Cooling a High Performance Processor



Cooling Enhancement of an Electronic Module With a Thermoelectric Cooler







Advanced Cooling Technology Development Activities

Dedicated to the Advancement of North American Electronics Manufacturing
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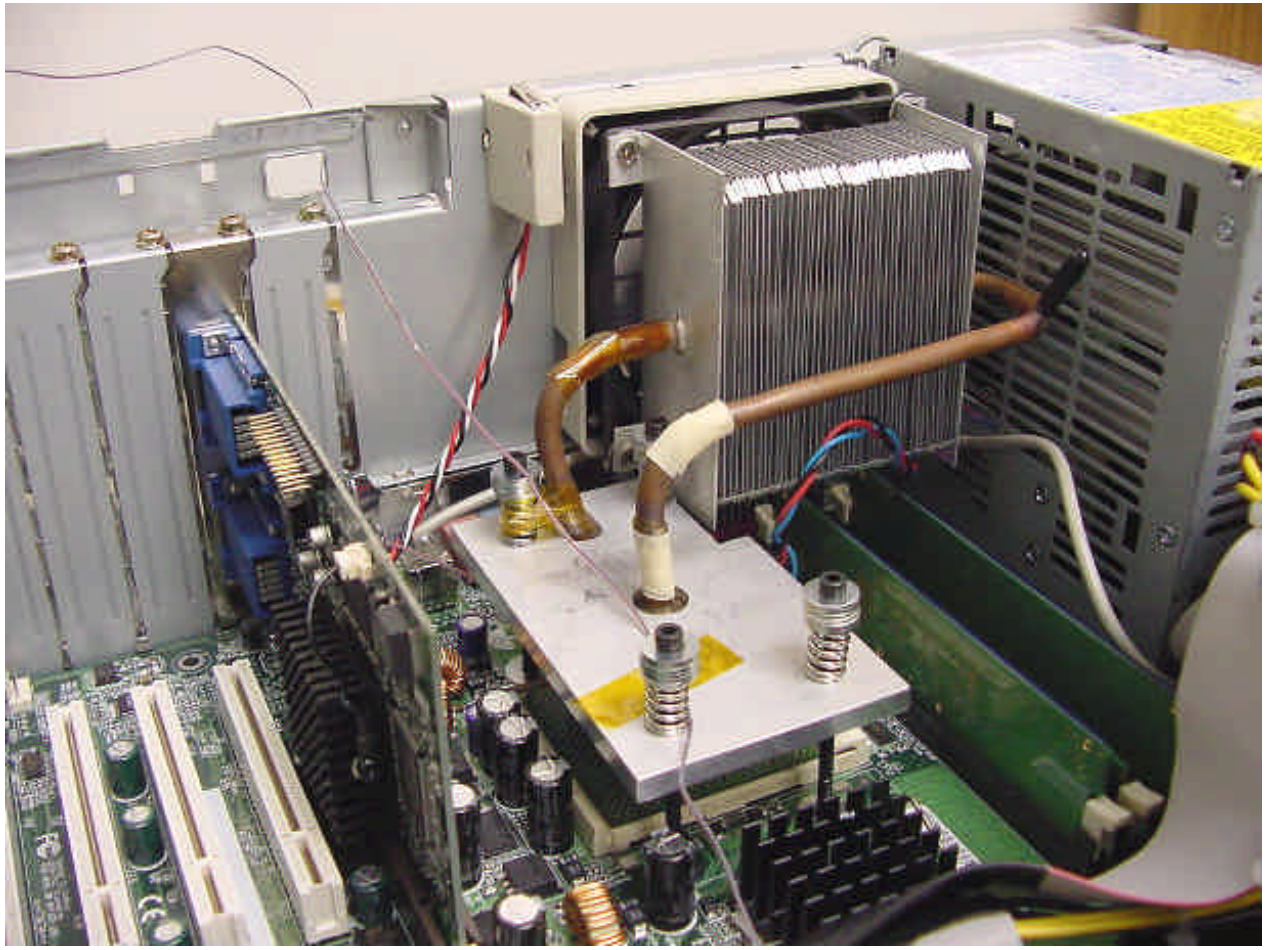
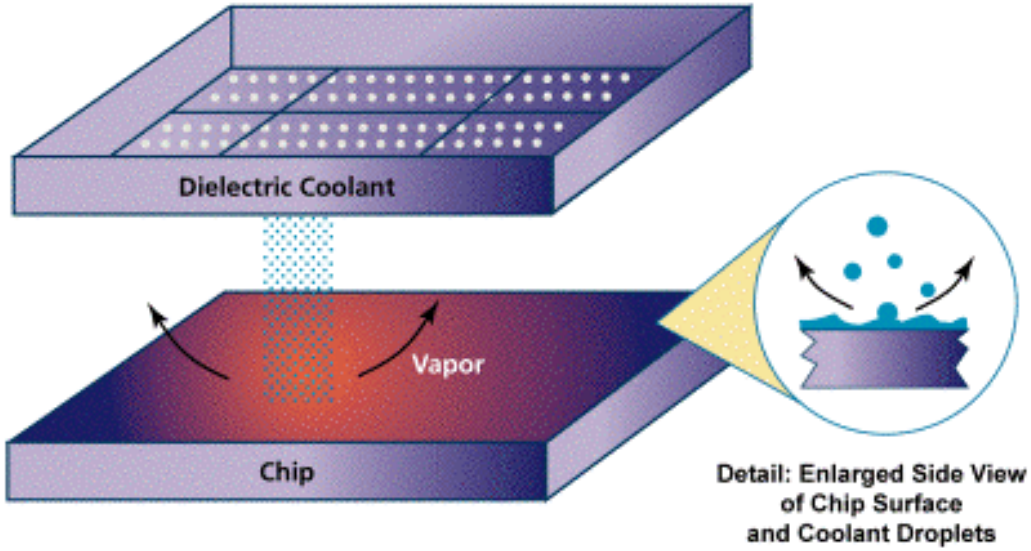
Two-Phase Thermosyphon Test Vehicle



Demonstrated for 85 W Intel Pentium 4 Processor in 2001.

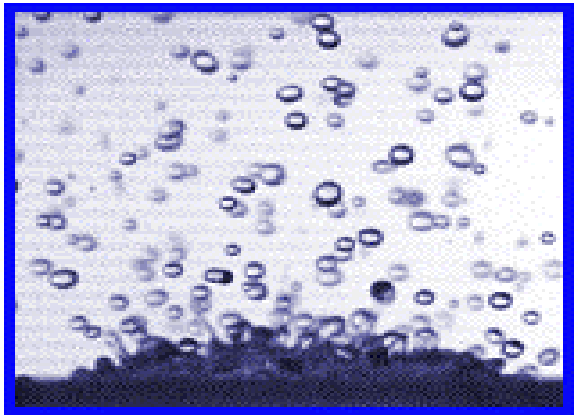
"Heat Out of Small Packages", Y. Joshi, *Mechanical Engineering*, Vol. 123, pp. 56-58, Dec. 2001.

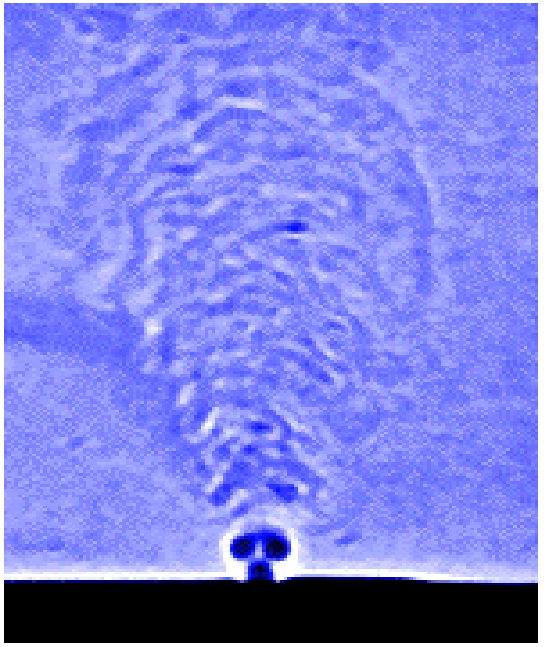
Recent Research (DARPA HERETIC)
Spray Cooling (Carnegie Mellon University)



http://www.darpa.mil/MTO/HERETIC/projects/2.html

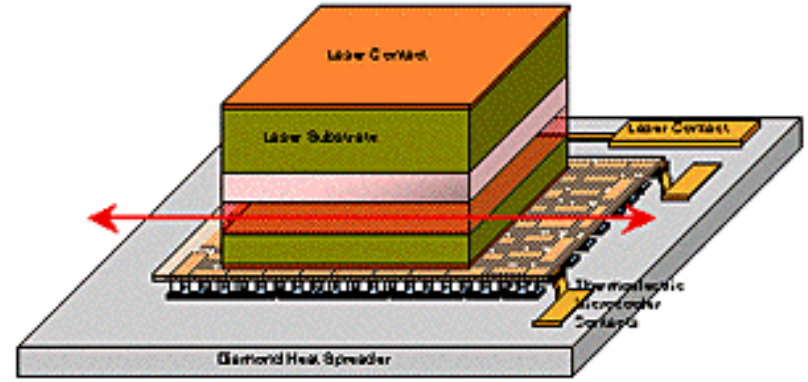
Recent Research (DARPA HERETIC)
Droplet Atomization and Microjets (Georgia Tech)

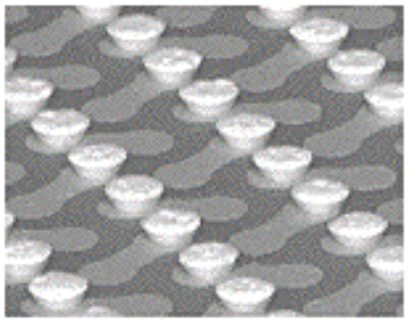




http://www.darpa.mil/MTO/HERETIC/projects/4.html

Recent Research (DARPA HERETIC)
Thermoelectric Coolers for Lasers (JPL)





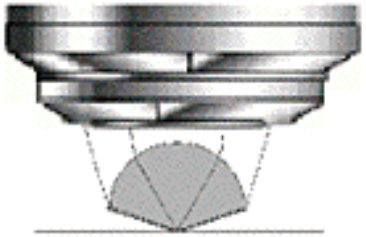
Advanced Thermal Modeling

Ultra-High Resolution Thermal Imaging

Thermoelectric Microcooler

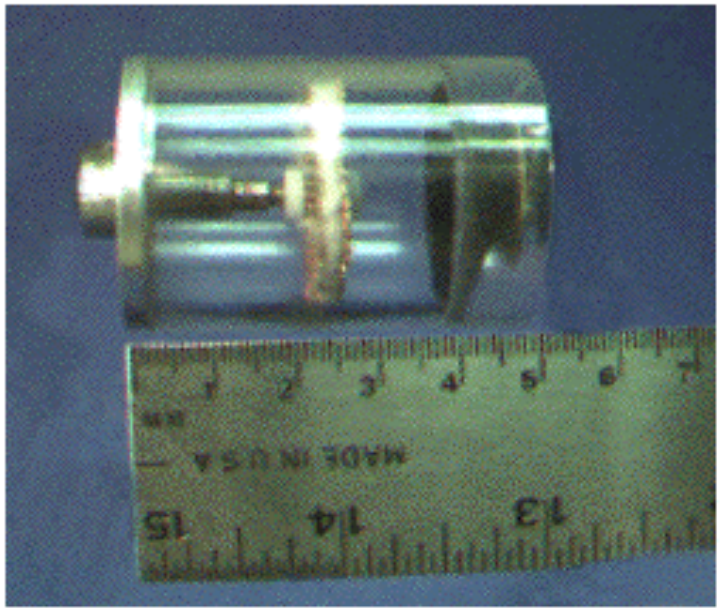
Integrated Mid-IR Laser

Super Solid Immersion Lens



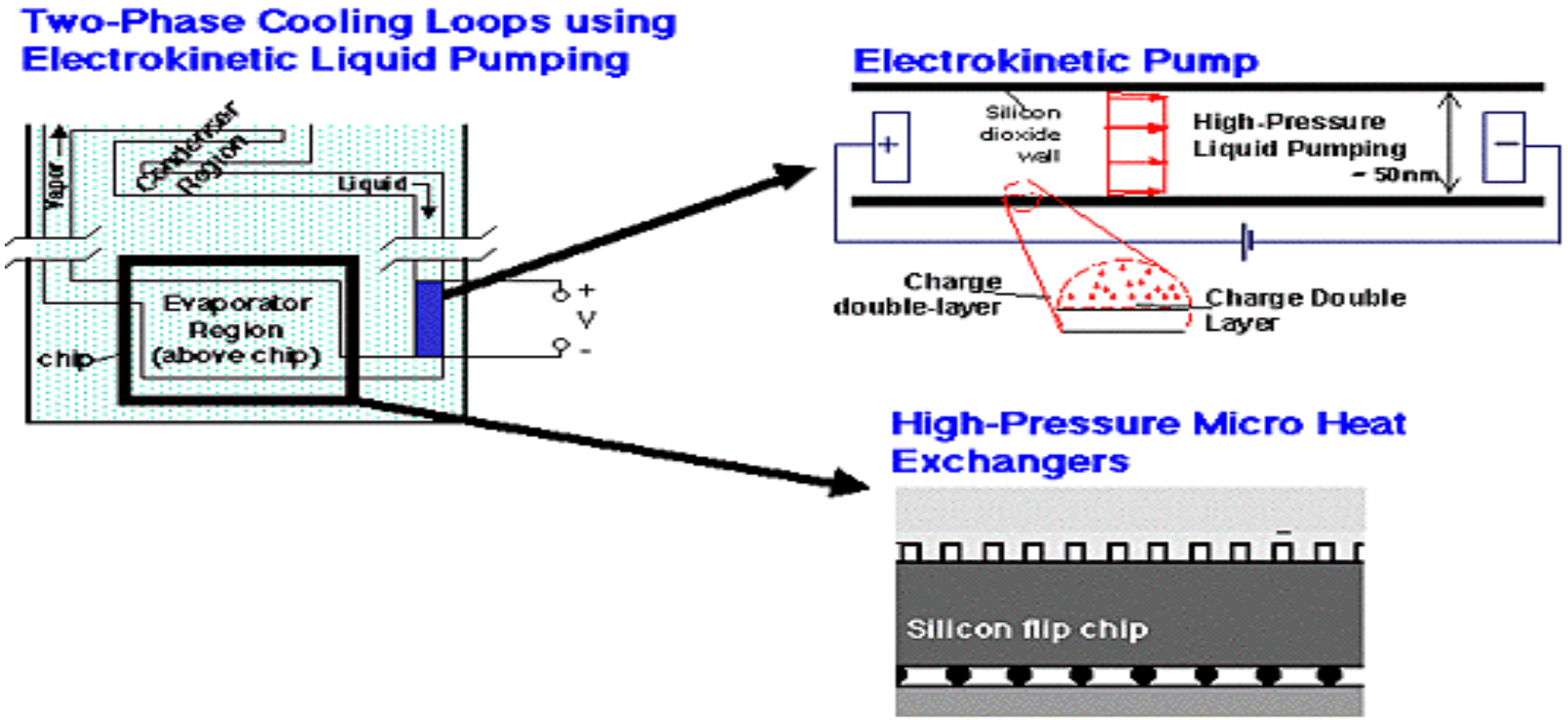
http://www.darpa.mil/MTO/HERETIC/projects/5.html

Recent Research (DARPA HERETIC)
Thermoacoustic Refrigerators (Rockwell)



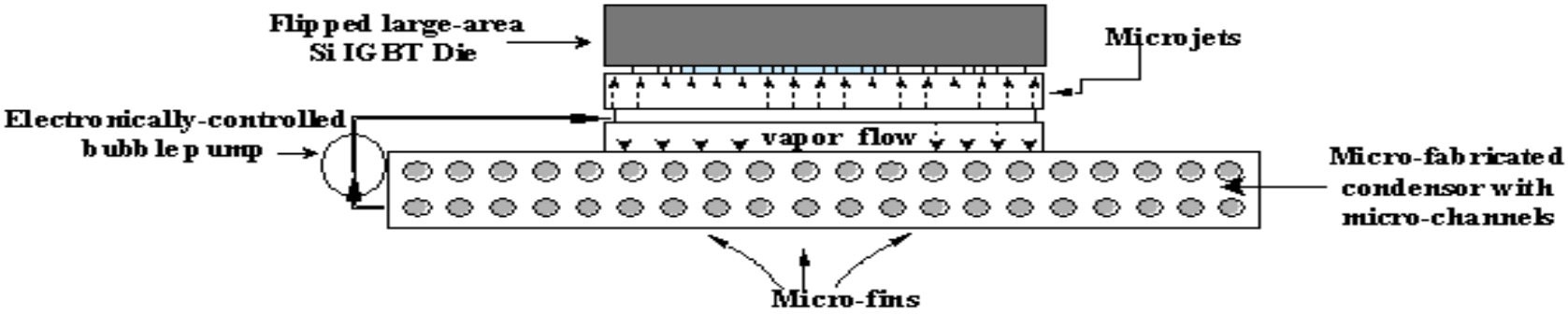
http://www.darpa.mil/MTO/HERETIC/projects/6.html

Recent Research (DARPA HERETIC)
Electrokinetic Pumped Loops (Stanford)



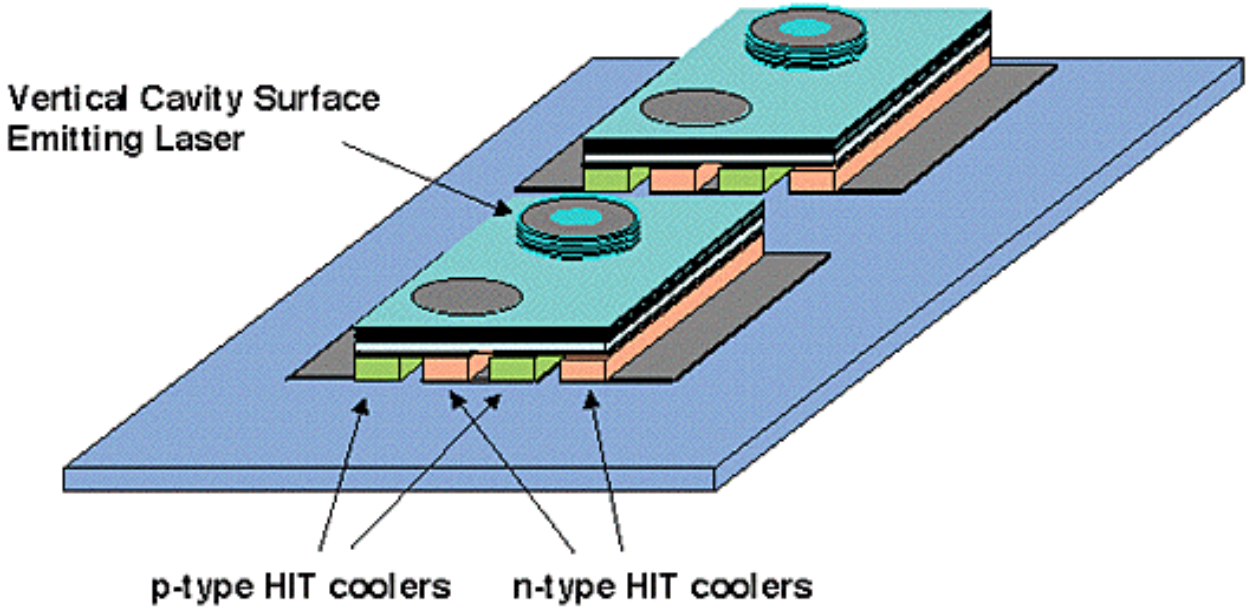
http://www.darpa.mil/MTO/HERETIC/projects/7.html

Recent Research (DARPA HERETIC)
Microjets With Liquid/Vapor Phase Change (UCLA)



http://www.darpa.mil/MTO/HERETIC/projects/10.html

Recent Research (DARPA HERETIC)
Soild State Thermionic Coolers (UCSB)



http://www.darpa.mil/MTO/HERETIC/projects/11.html

Summary and Conclusions

- CMOS will continue to be the pervasive semiconductor technology for both memory and logic.
- Chip sizes will increase but with a higher corresponding increase in circuit density resulting in higher heat flux.
- All new electronic products will most likely be air-cooled, including most computers, for the next few years.
- Portable (laptop) computers will need enhanced cooling technology in the near future despite the emphasis on low power dissipation.
- Power of hand held devices is not increasing with time. Battery life poses major restrictions on power dissipation and most applications do not require any thermal management.
- High heat flux cooling capability is required for all high performance electronics.
- High thermal conductivity interface material is needed for heat sink applications.
- Low temperature cooling may get “hot” in the near future.
- Supercomputers with highly parallel scalable design may require new cooling systems when node power exceeds current levels, or the number of nodes continues to increase significantly, resulting in a large system load “explosion”.
- Cost will be a significant challenge for all future thermal designs and the speed to accomplish new designs will be vital to their success.

Future Cooling Technologies and Strategy

- Enhanced Air Cooling Technology and System
  - High performance heat sink
  - Mini air movers for local enhancement
  - Higher pressure air movers and higher volume air flow systems
  - Highly parallel flow distribution system
  - Active redundancy with control
- Other Candidate Cooling Technologies
  - Direct liquid cooling technology - for high performance applications
  - Heat pipe and vapor chamber cooling technology - for special situations
  - Thermoelectric cooling technology - for special situations
  - Thermal interface enhancement technology
  - Self-contained, low cost liquid cooling technology
  - Low temperature cooling technology - for performance enhancement
- Strategy for the Future
  - Explore all options
  - Establish a closer working relationship with vendors
  - Pool resources to fund cooling technology development
  - Get university/research labs involved

Grand Challenges for Electronic Cooling Technology in the Coming Decade

- Low cost, high performance, direct immersion cooling technology
- Low cost, high performance thermal interface (10X) technology
- Low cost, high performance cold plate (5X) technology
- Low cost, high performance heat sink (5X) technology
- Low cost and low noise (2X), high performance (2X) air/liquid moving device technology
- Low cost, high performance, scalable cooling system
- Low cost, high performance, future data center cooling concept