The Perpetual Challenges of Electronics Cooling Technology for Computer Product Applications – from Laptop to Supercomputer

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Abstract

This presentation is intended to provide an overview and survey of the recent development of thermal packaging technology and thermal systems for cooling of current computer products. Examples of the latest product cooling techniques and applications will be used to articulate the need for the development of advanced cooling technology and innovative thermal systems to meet the ever-increasing chip level heat flux and the ensuing increase in heat load at the product level. This presentation draws input from the 2002 thermal management roadmap, which was published by the National Electronic Manufacturing Initiative - NEMI. It will conclude with a list of recommended research topics based on the consensus of the NEMI Thermal Management Technical Work Group-TWG that I have chaired since 2000.

Thermal Management
Technical Working Group (TWG)

Richard C. Chu, IBM (Chair)	Jogenda Joshi (Co-chair)
Avi Bar-Cohen, U. of Maryland	Gregory M. Chrysler, Intel
Darvin Edwards, TI	Suresh Garimella, Purdue U.
Magnus Herrlin, Telcordia	Larry Mok, IBM
Donald Price, Raytheon	Bahgat Sammakia, SUNY-Binghamton
Roger Schmidt, IBM	Lian-Tuu Yeh, Boeing

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
- Data Center Cooling

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.

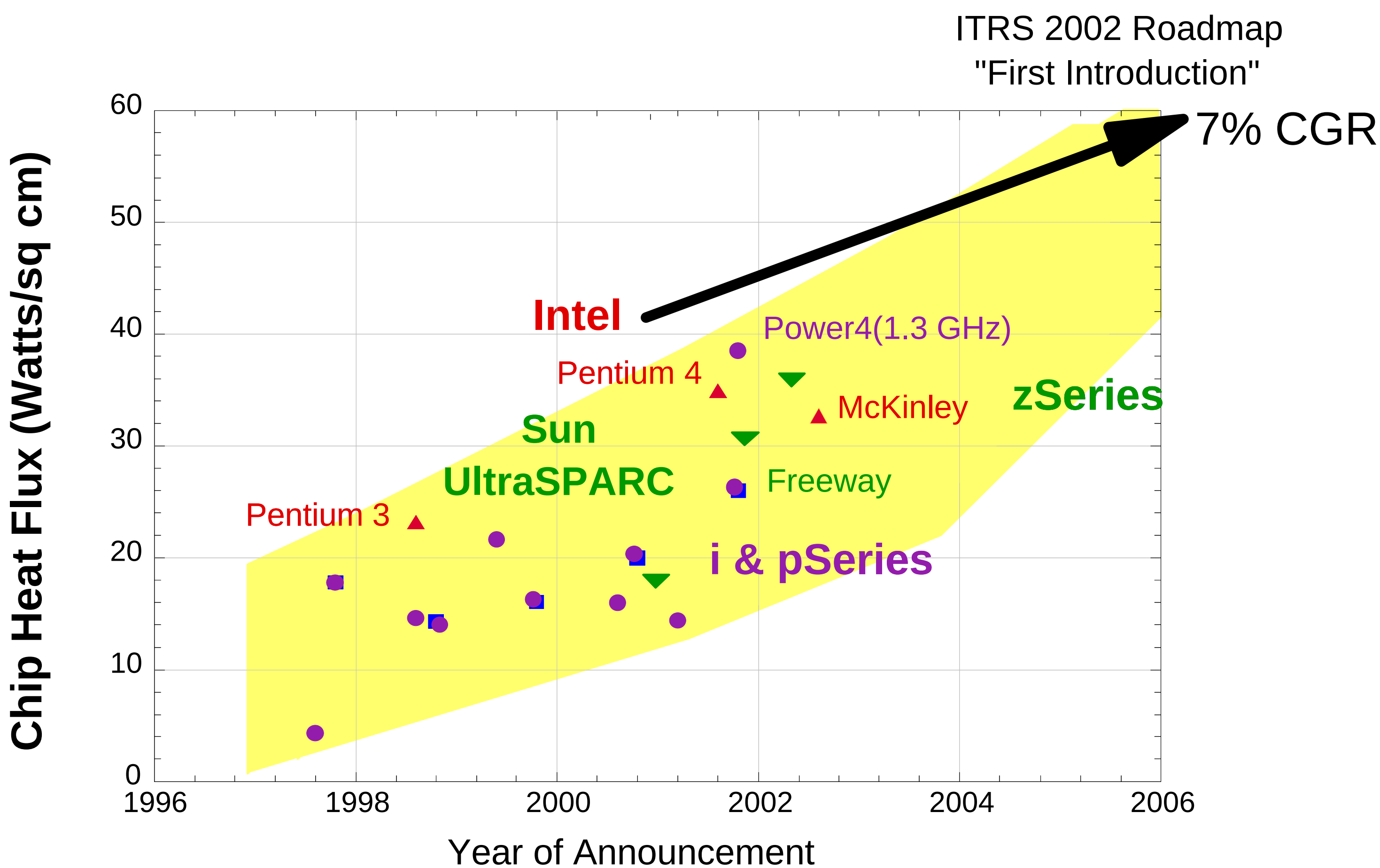
Thermal Management Requirements Matrix

● - State-of-Art

✓ - Likely

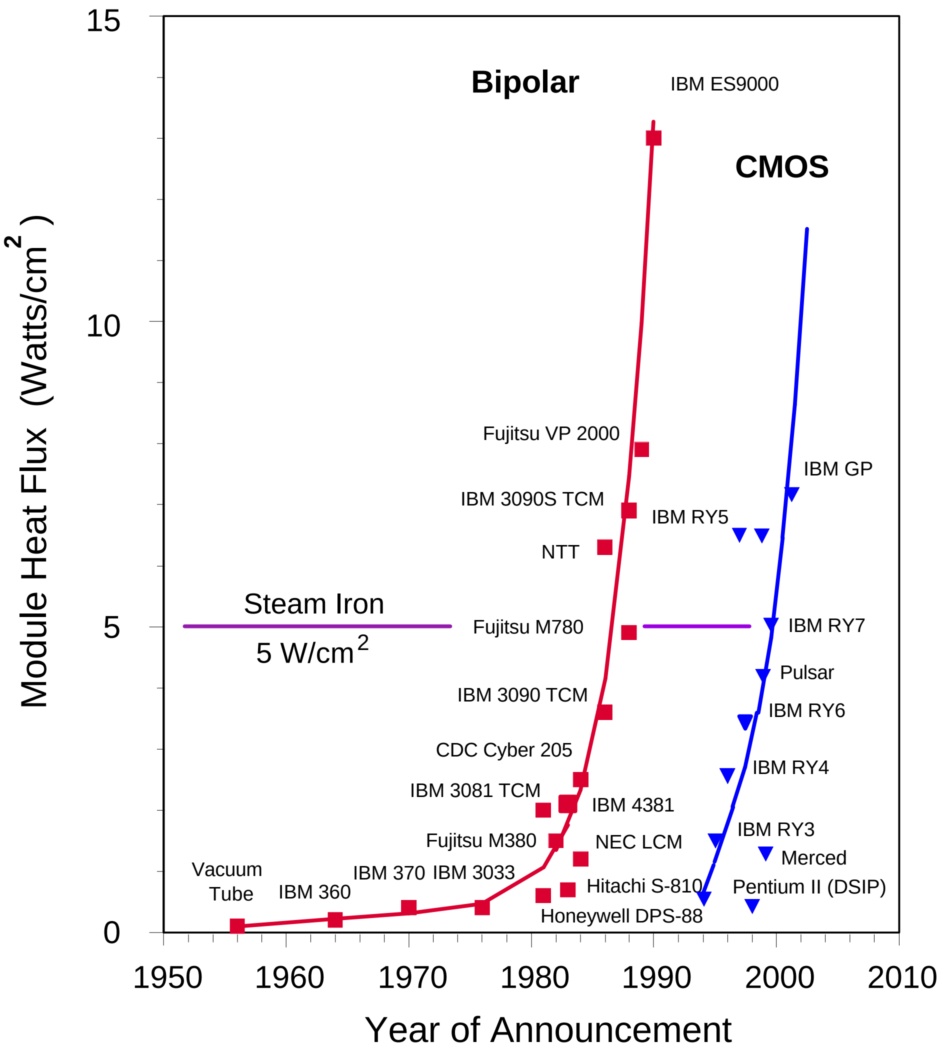
	Air Cooling	Conduction (Indirect Liquid)	Direct Liquid	Heat Pipe	Thermo -Electrics	Low Temperature	New Cooling Technology Needed (see list)
PC/Handheld/Wearable	●			●	✓		✓
Workstations	●	✓		✓	✓	●	✓
Mid-Size Computers	●	✓		✓	✓	✓	✓
Storage Subsystems	●	✓			✓		✓
Large Scale Computers	●	●	✓	✓	✓	●	✓
Super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

Microprocessor Power Dissipation Trends

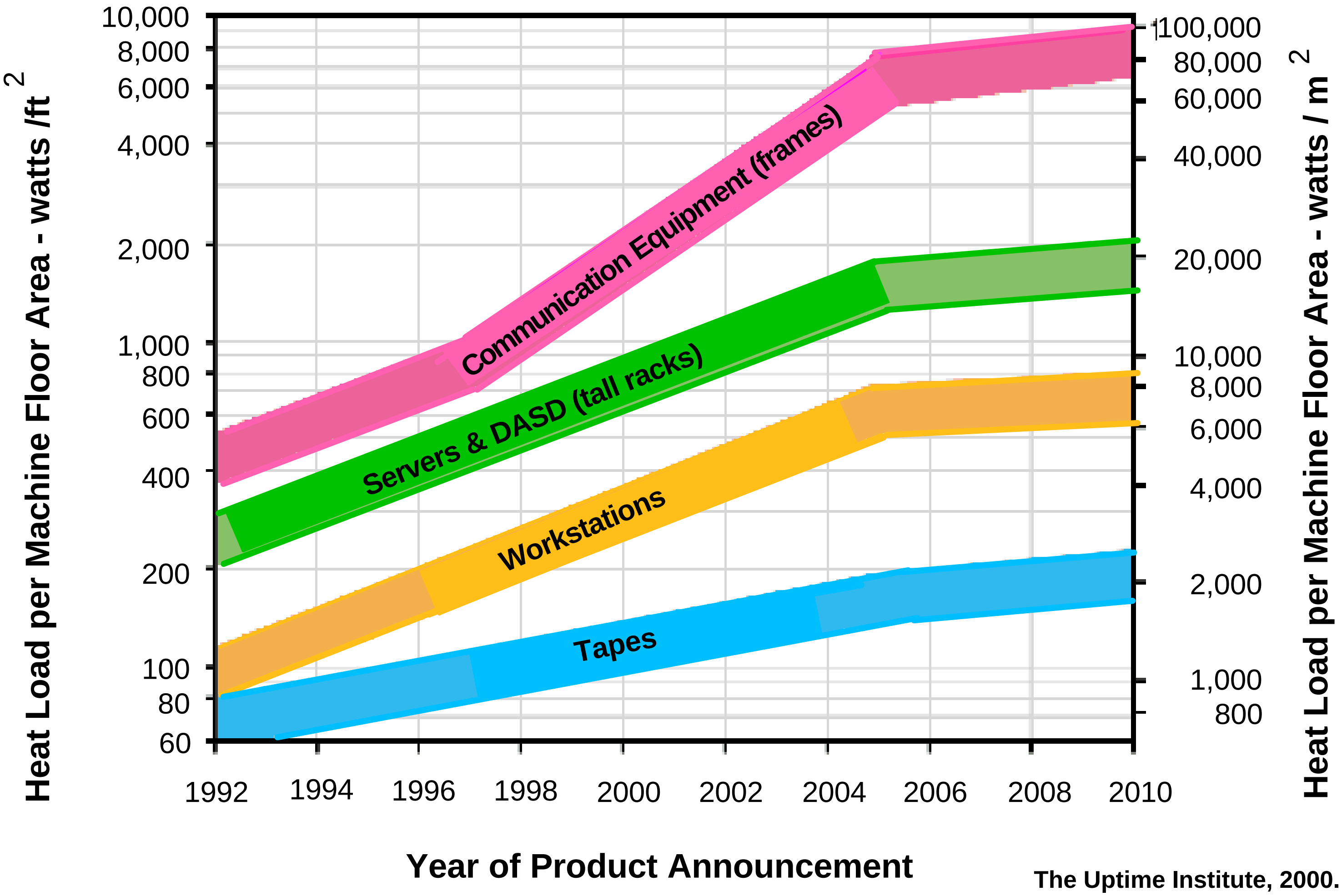


International Technology Roadmap for Semiconductors
2002 Update

Module Heat Flux Explosion

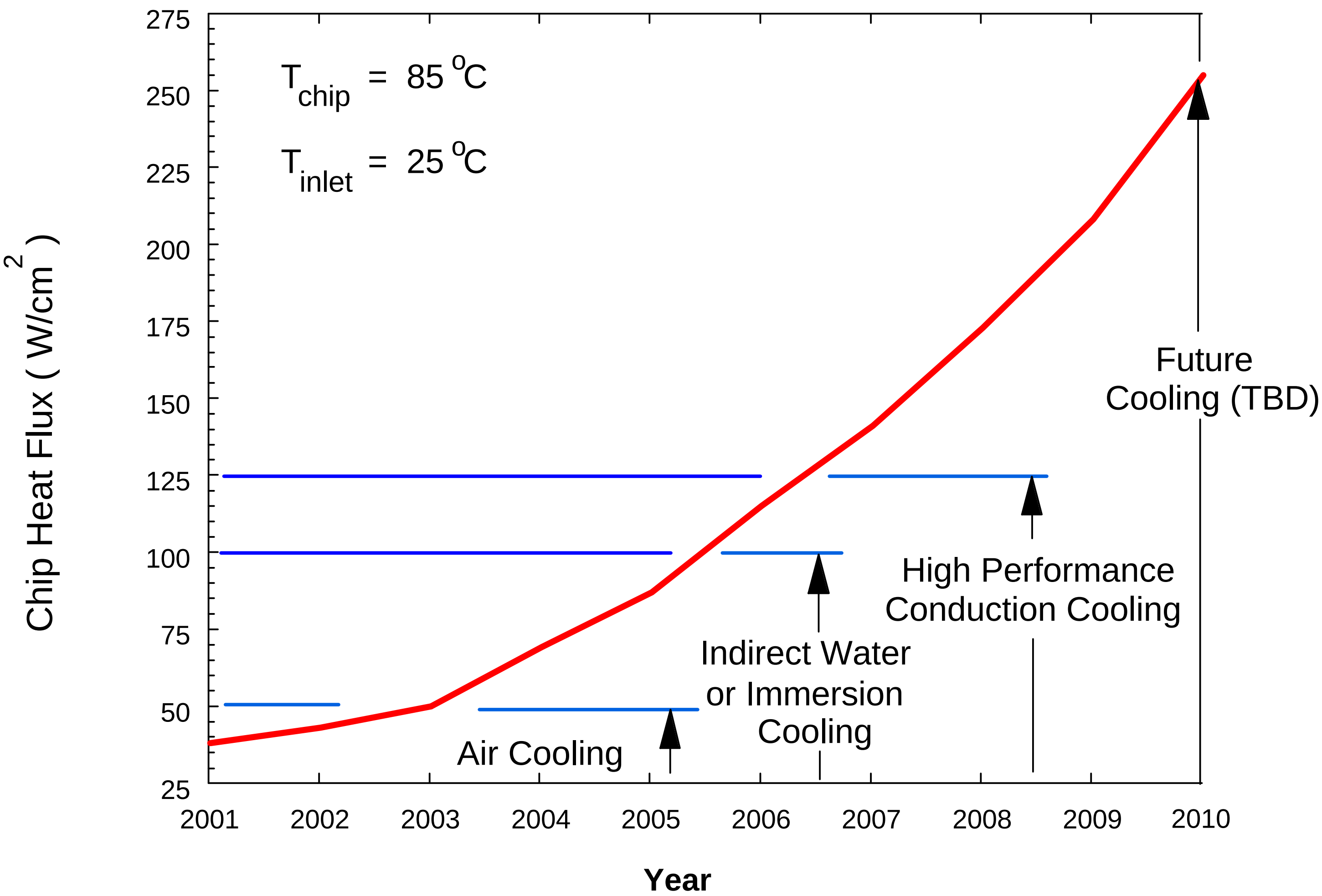


System Heat Density Trends



The Uptime Institute, 2000.

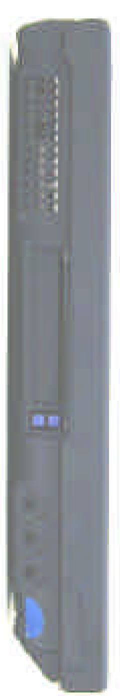
Projected Chip Heat Flux and Cooling Technology Limits

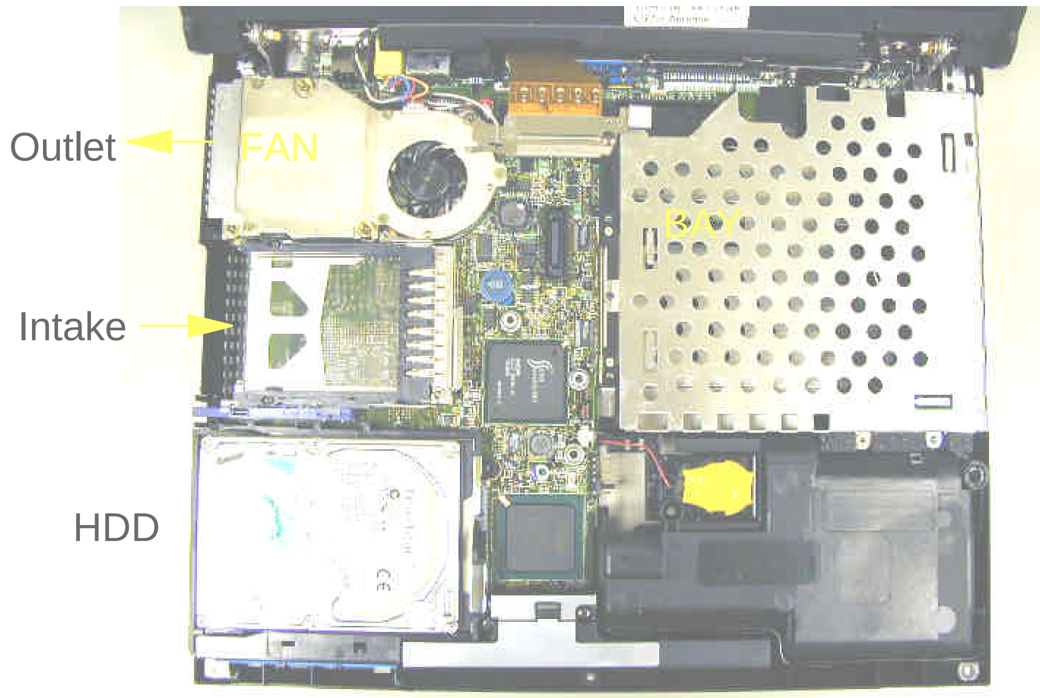


Current Product Cooling Designs

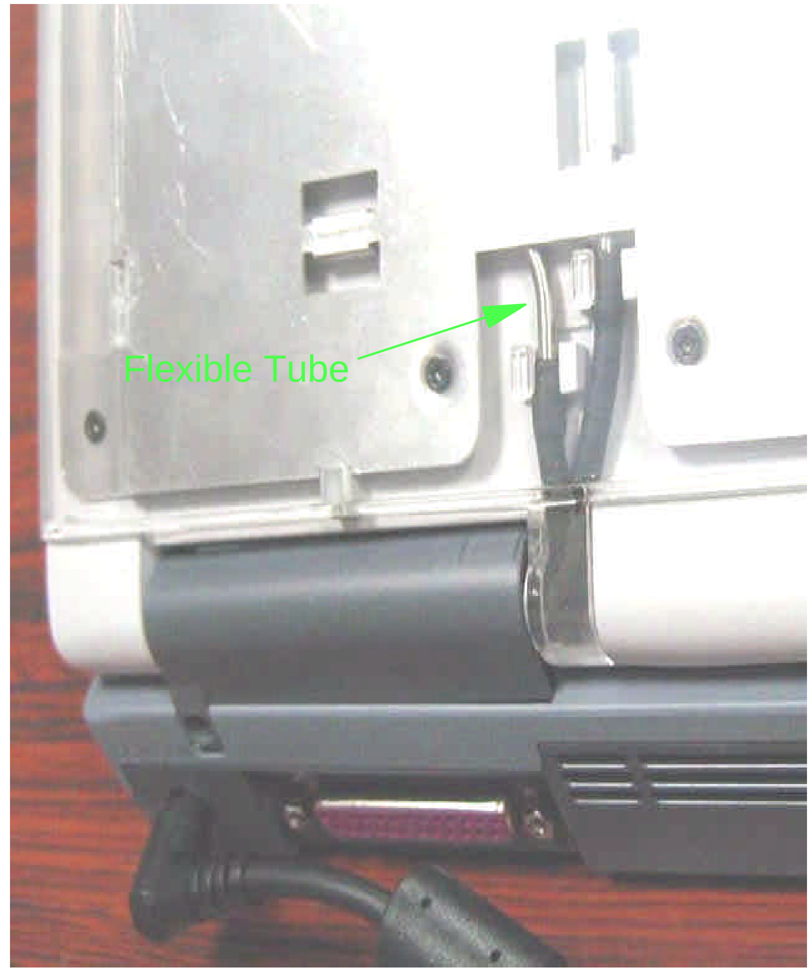
IBM Thinkpad T23 Air Flow Layout

Inlet / Outlet zoom





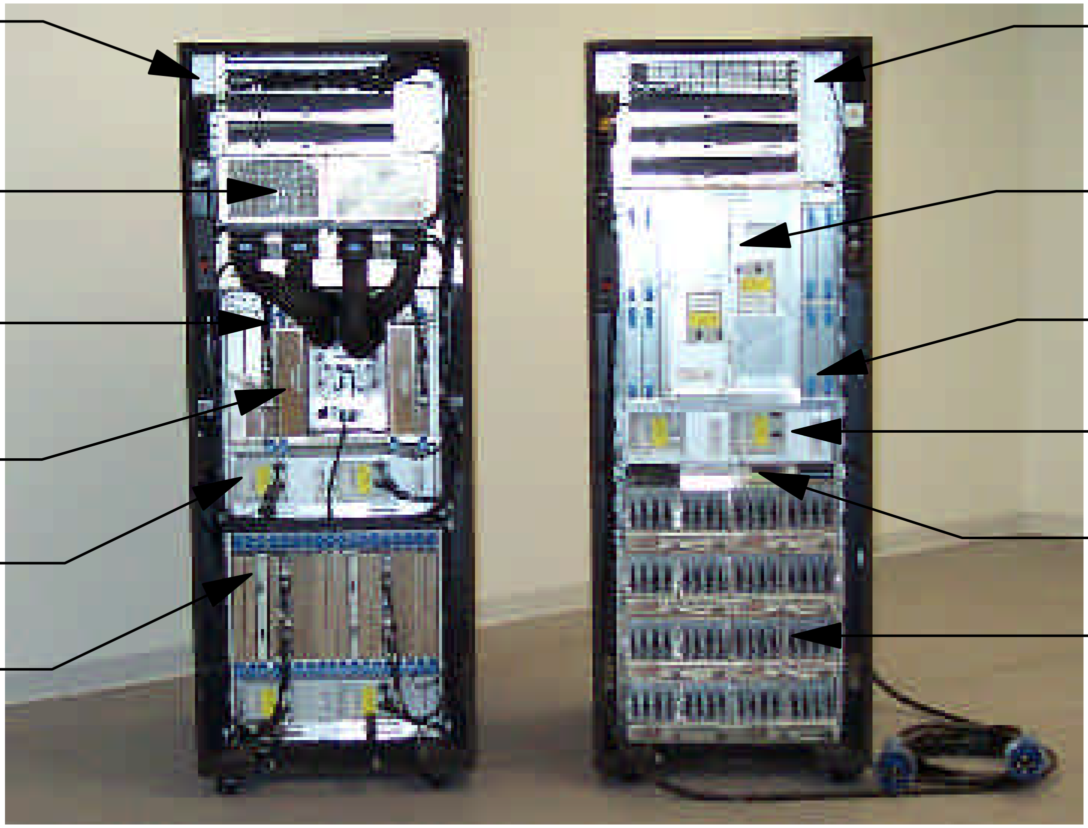
Hitachi Water Cooling Laptop (Prototype Model)



Large IBM Servers

IBM z900
S/390 Mainframe

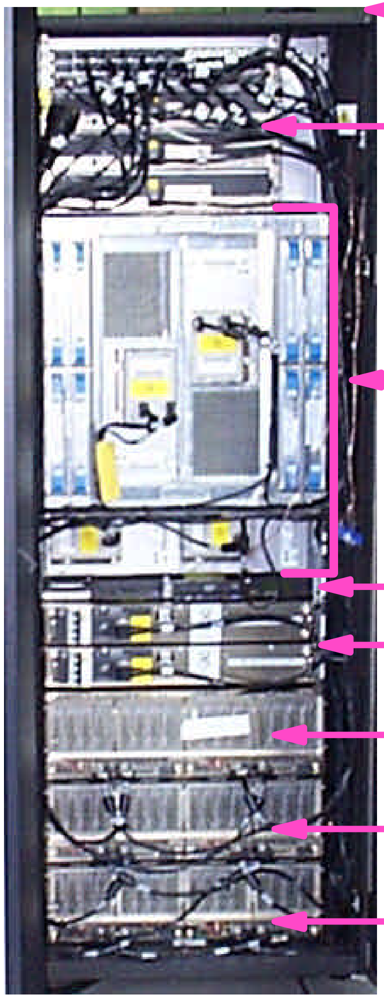
IBM pSeries
Regatta-H



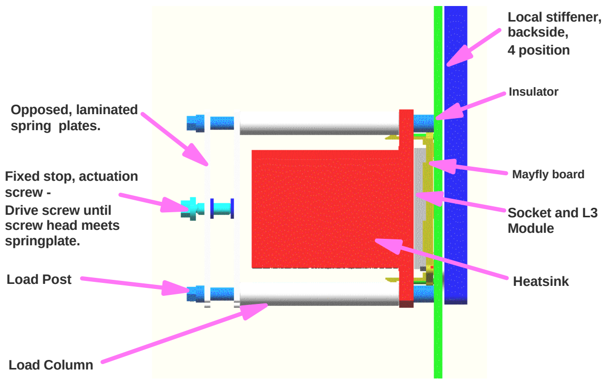
High Density Single Frame Systems

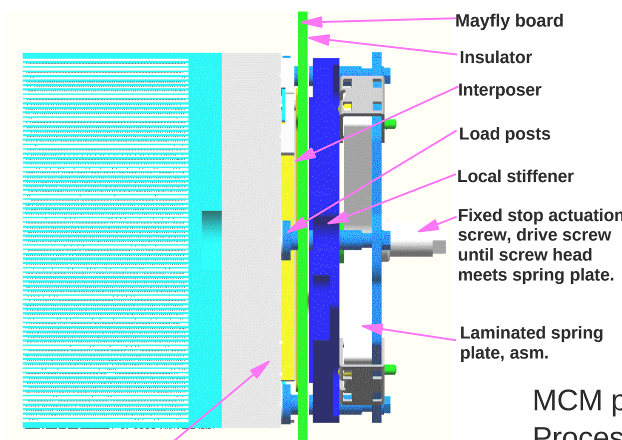
IBM pSeries 690 (continued)

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

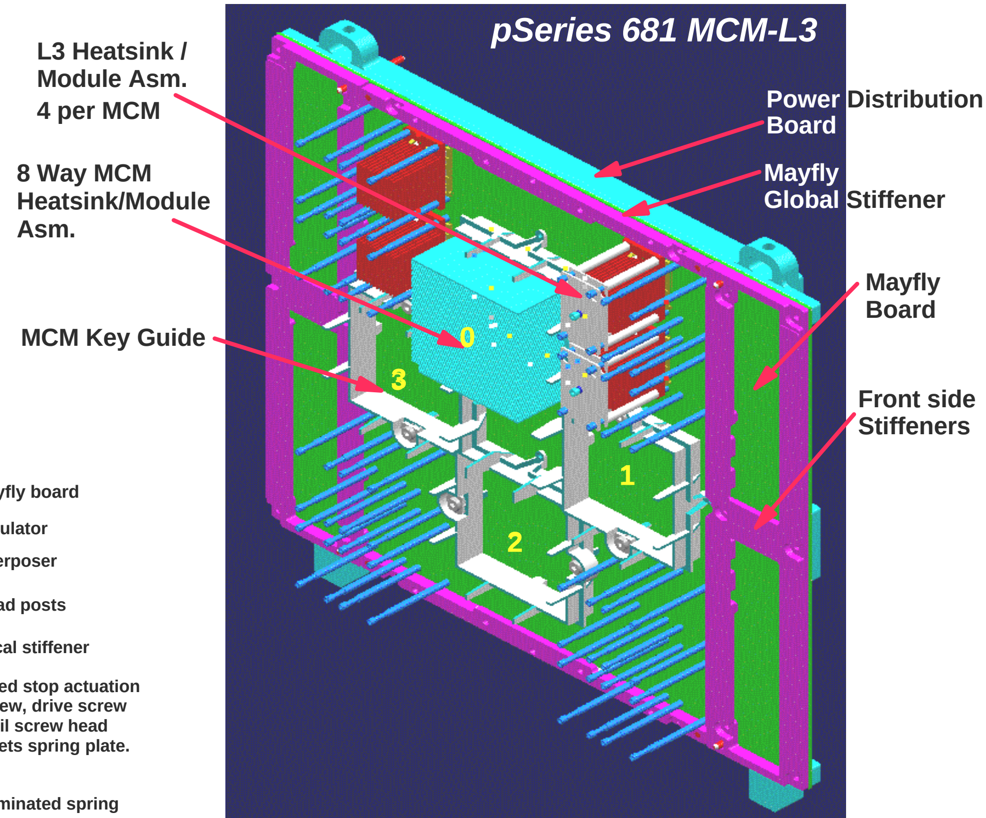


IBM pSeries 690 (continued)





MCM heatsink / module assembly

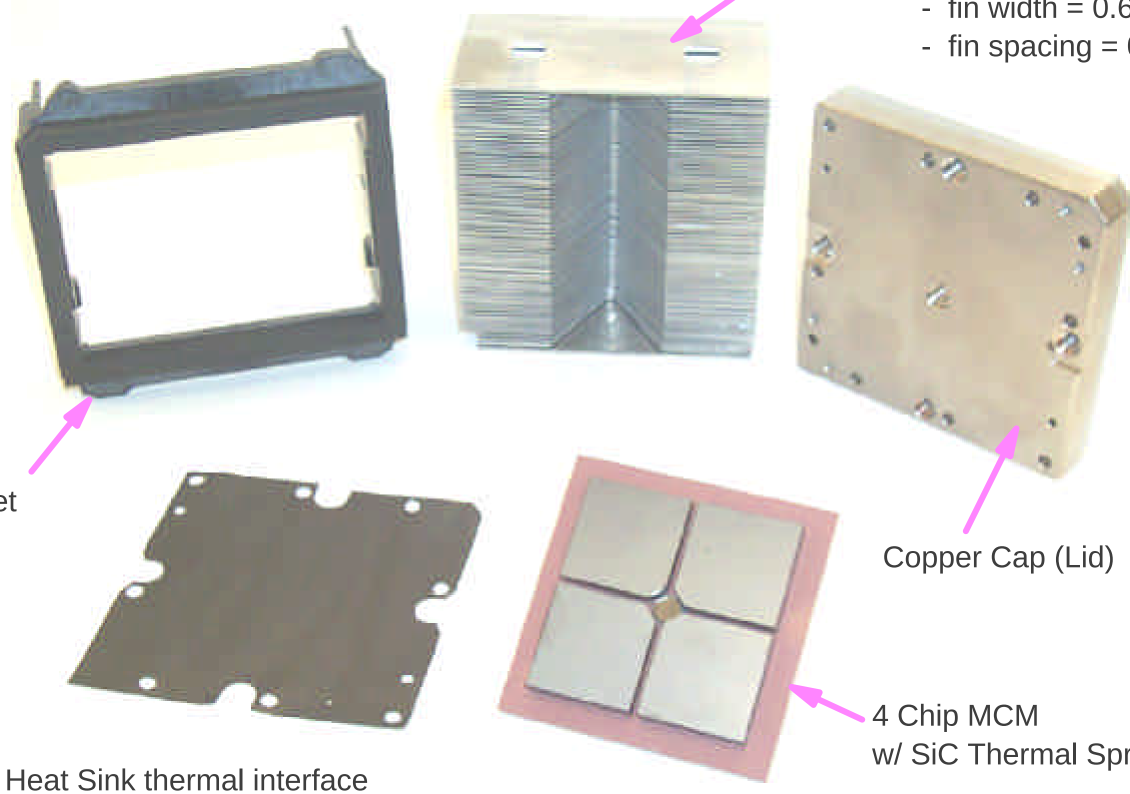


MCM power ~ 624 watts
Processor - 2 cores - 156 watts max
Processor 415 sq mm
Tj ~ 105C

IBM pSeries 690 MCM

IBM

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



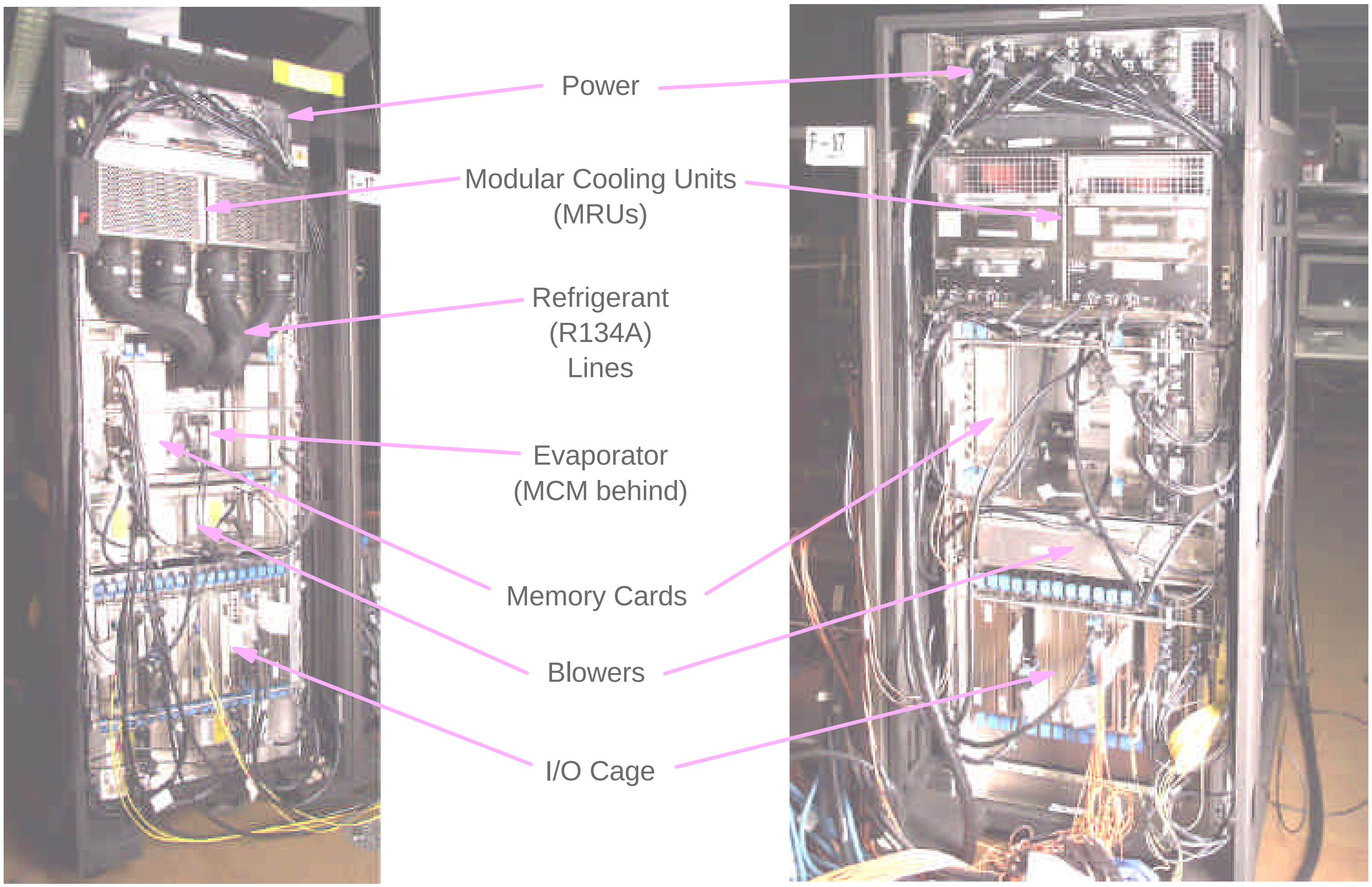
Shroud with gasket

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 (continued)

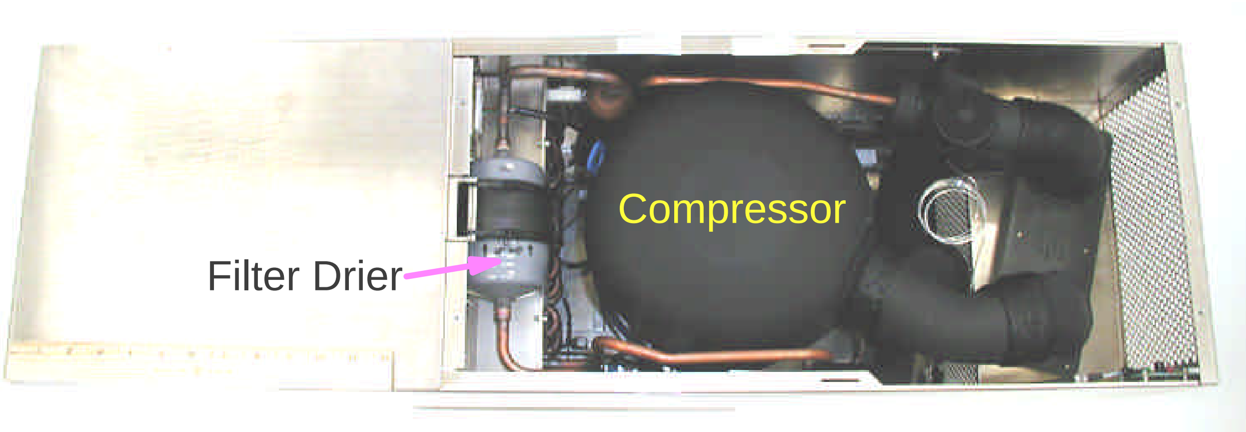


Front Side

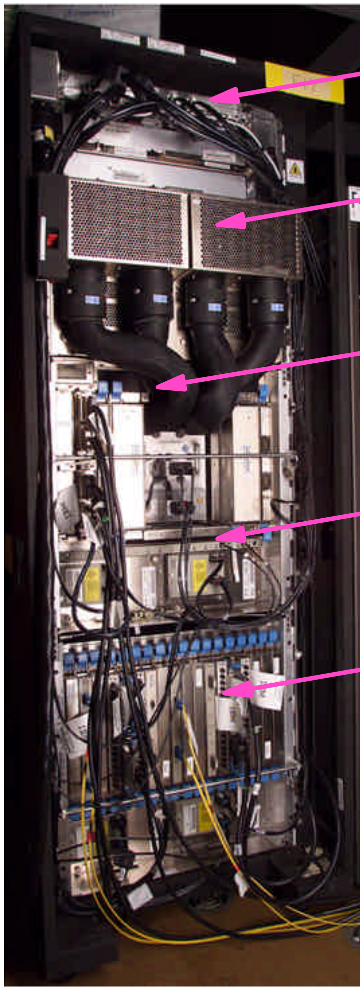
Back Side

IBM zSeries 900 Server Evaporator

IBM zSeries 900 Modular Refrigeration Unit



IBM zSeries Server Model z900



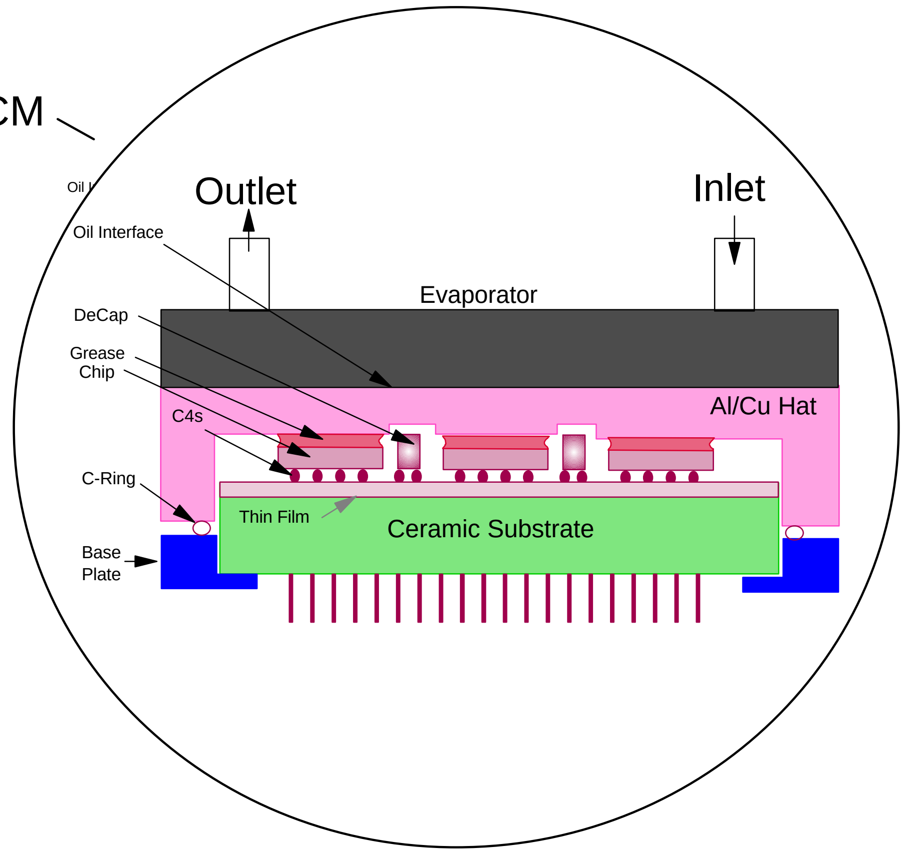
Bulk Power Supplies

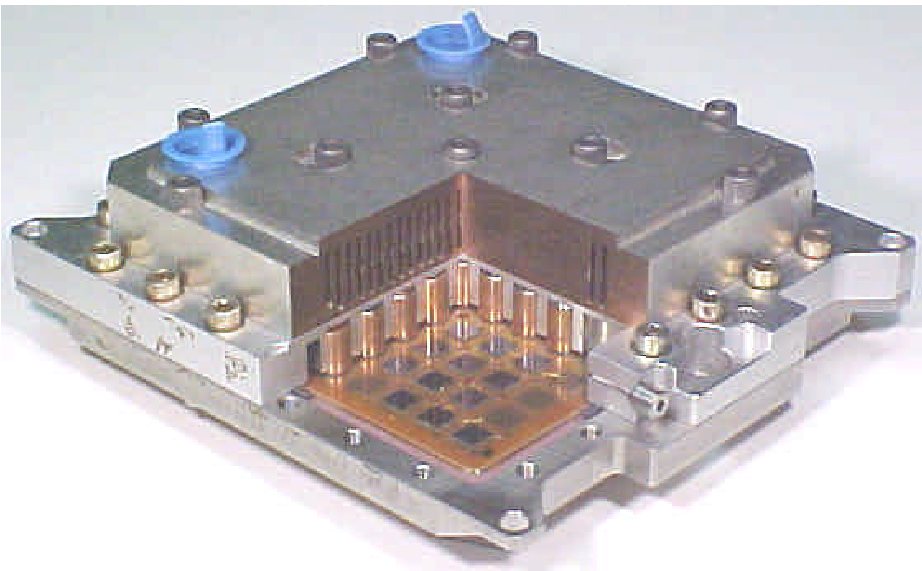
Modular Refrigeration Units(MRU)

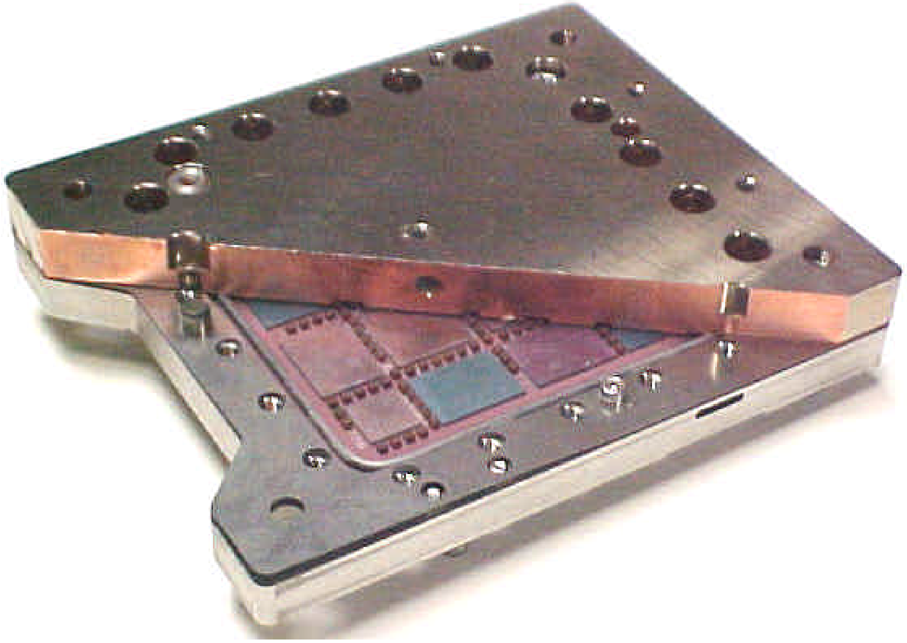
Evaporator/MCM

Blowers

Input/Output



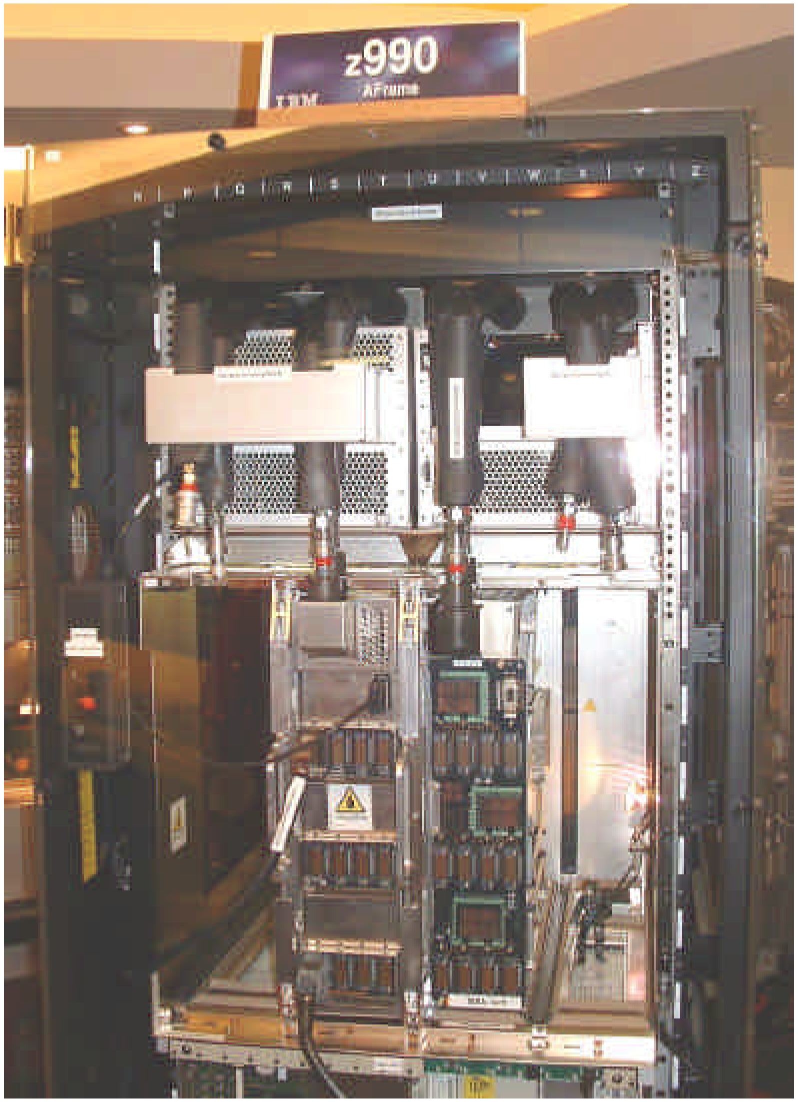




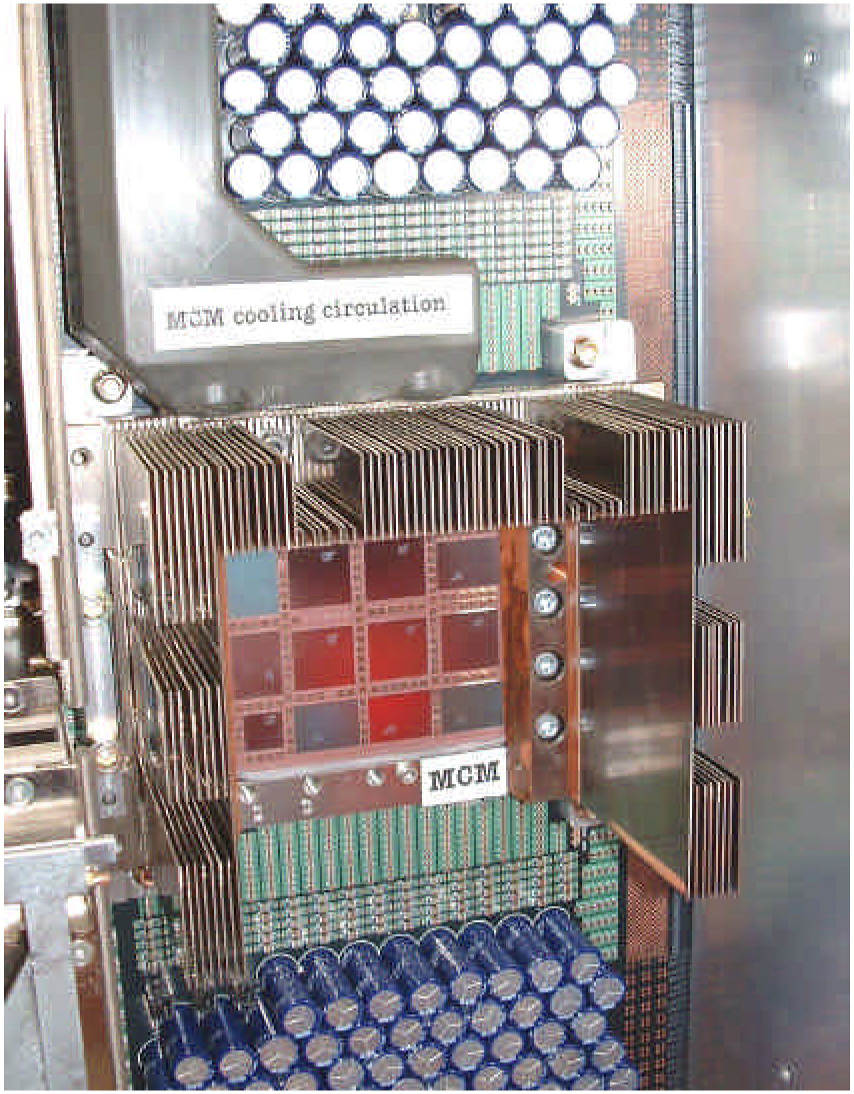
TCM

MCM - FPC

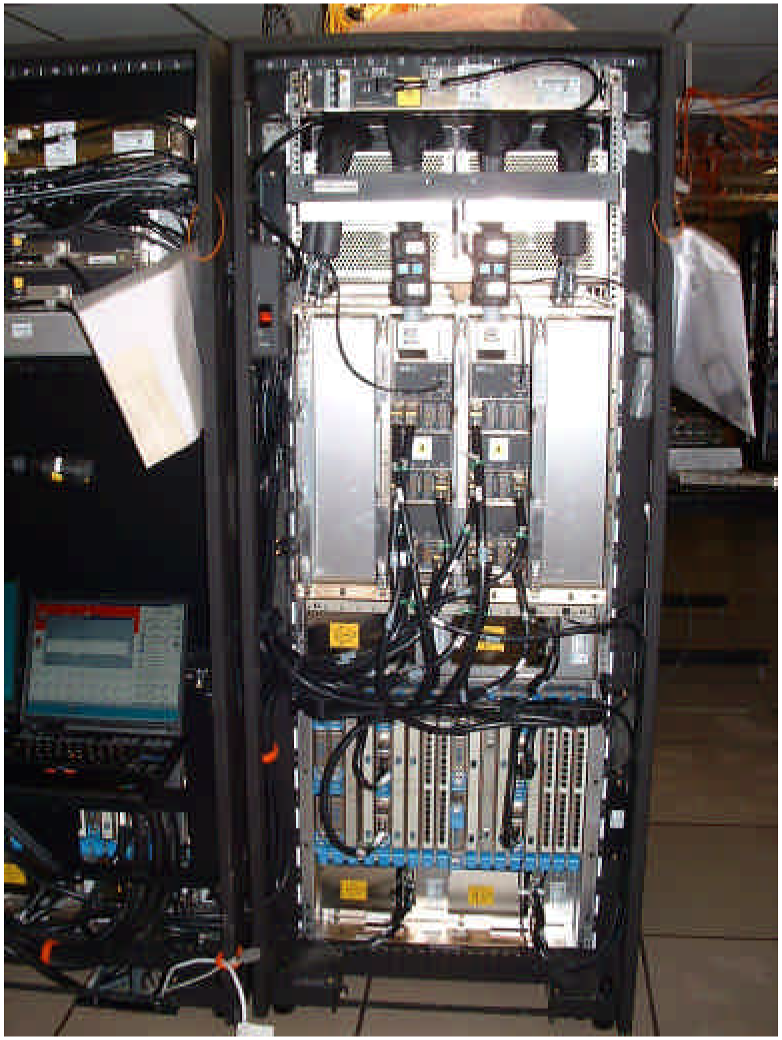
IBM zSeries 990 Server



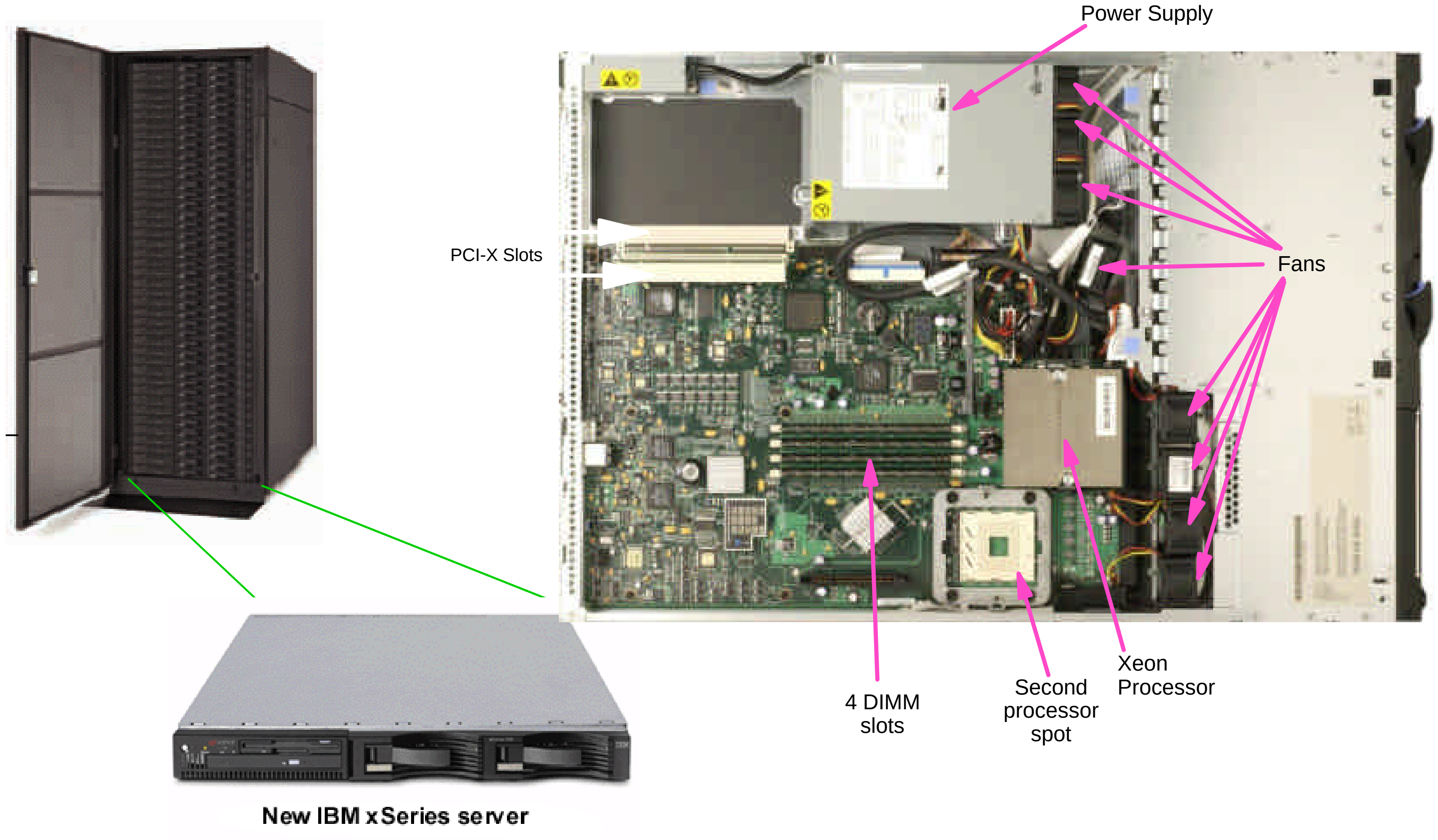
IBM zSeries 990 Server (continued)



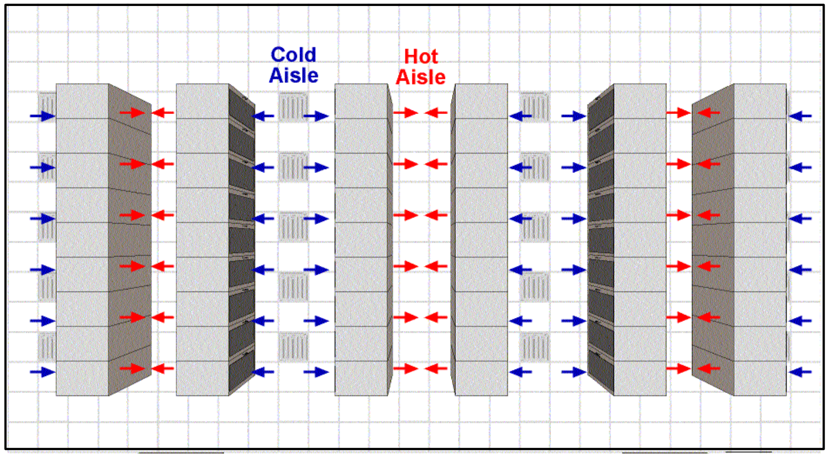
IBM's zSeries Model z990: T-Rex



IBM's xSeries Model 335

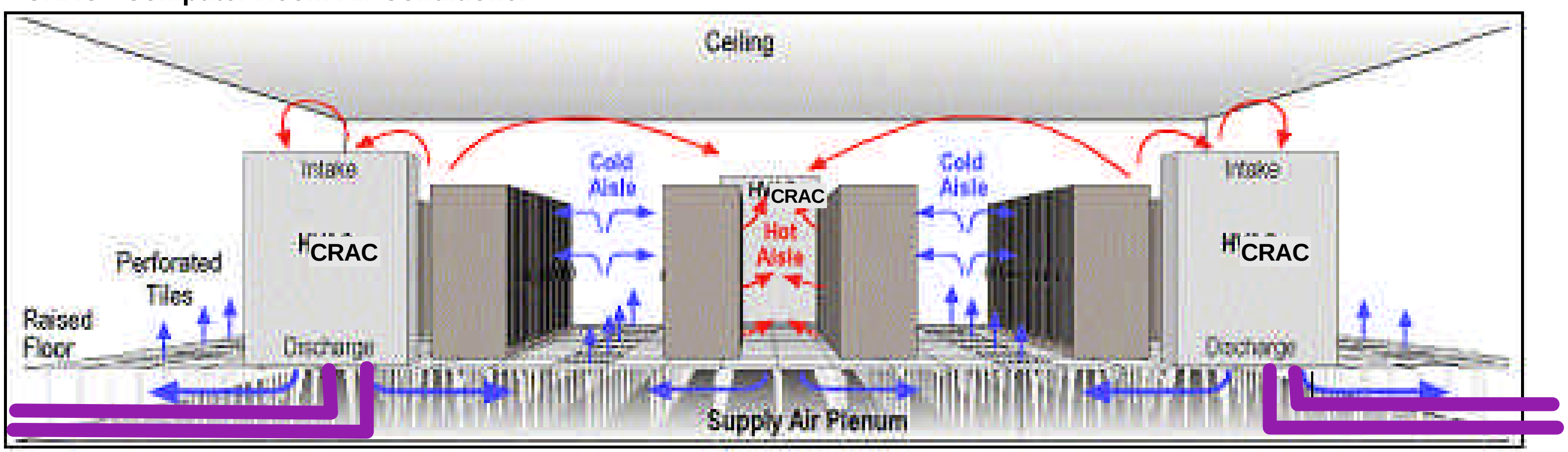


Data Center Cooling



Top View

CRAC - Computer Room Air Conditioner



Facilities Chilled Water

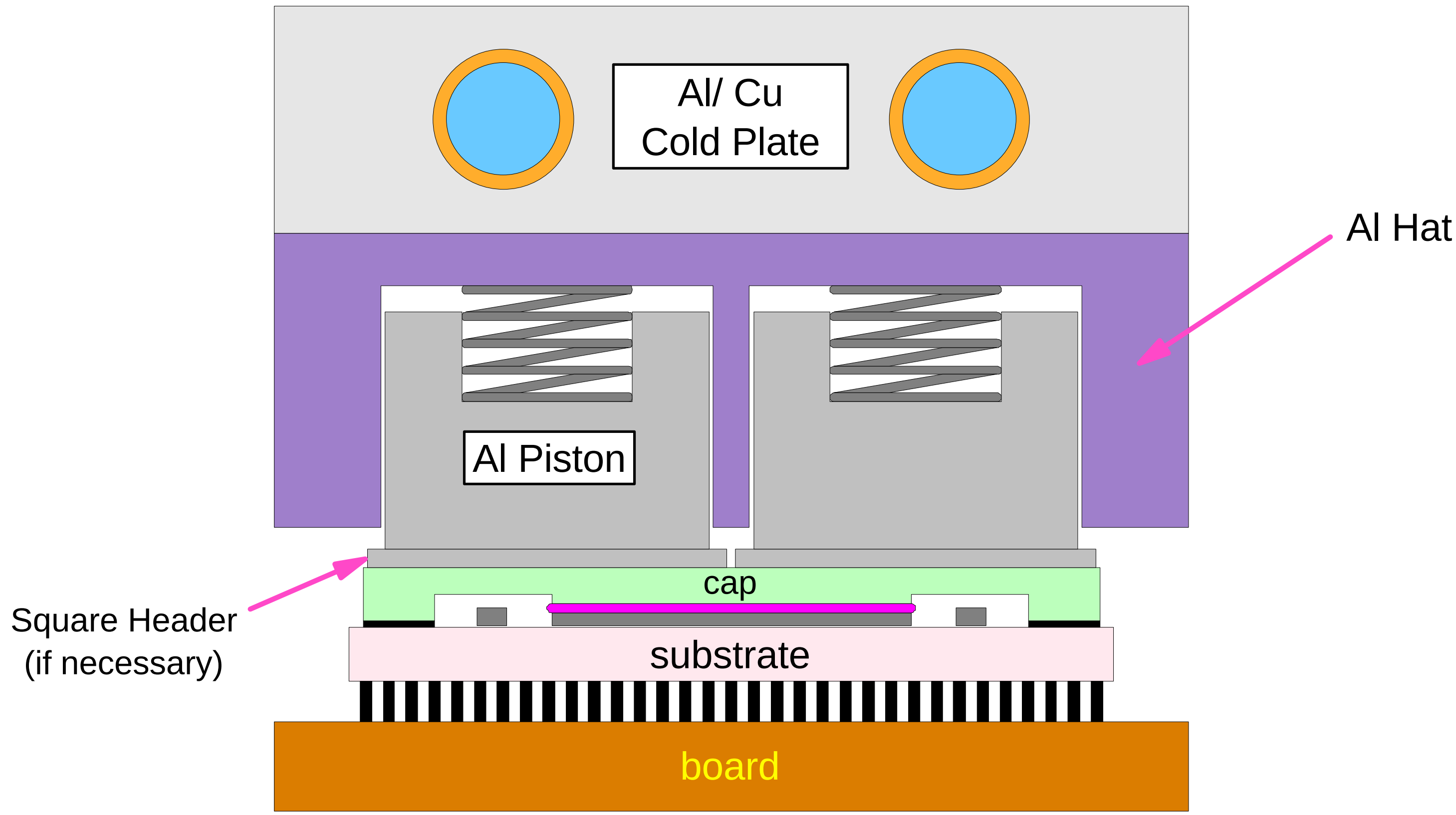
Side View

Super Computer System Summary (studied)

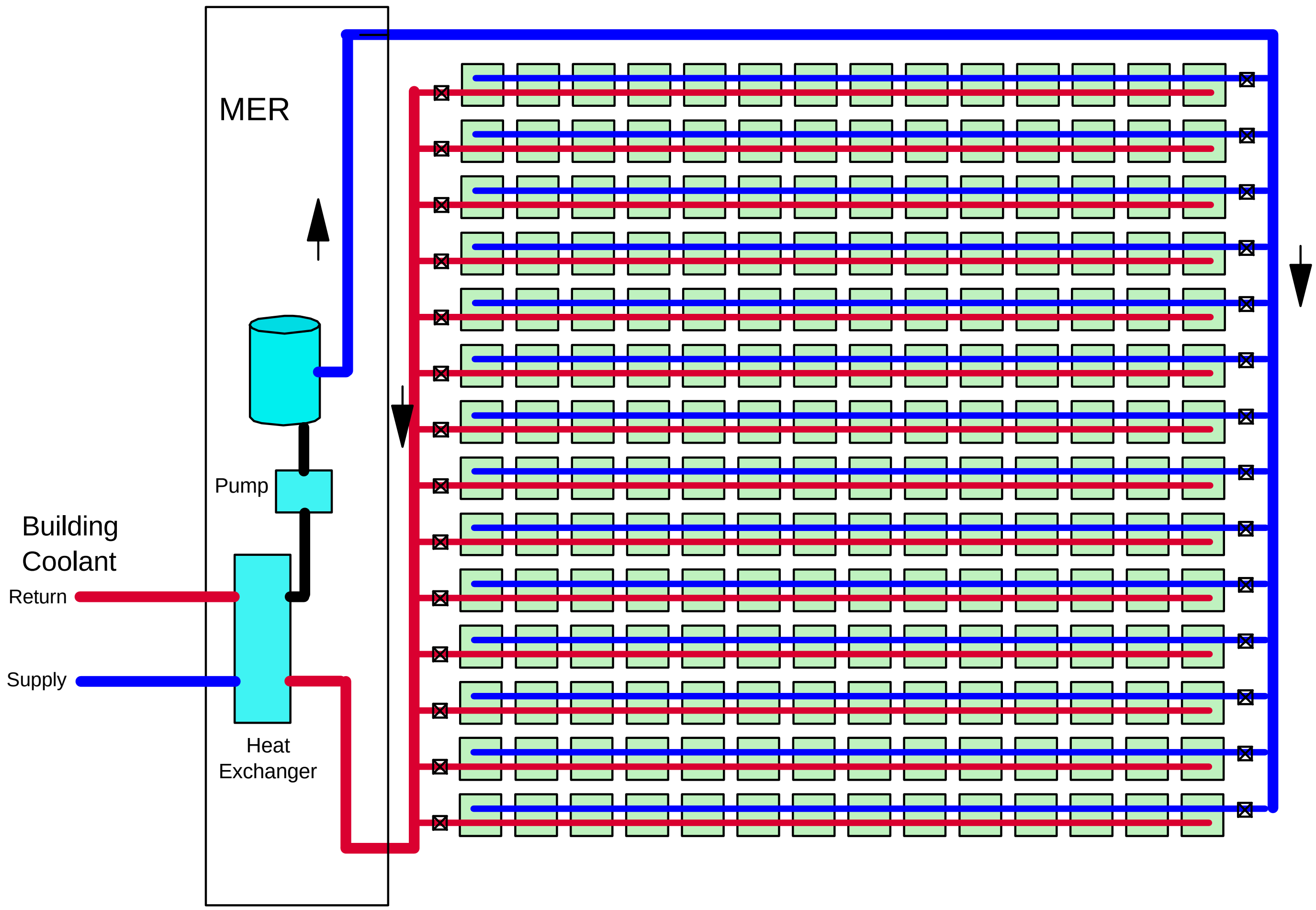
	Number of Modules	Number of Processors	Power (1) (W)	Water Flow Rate (1) (gpm)	Air Flow Rate (1) (cfm)
Module	n/a	28	40	n/a	6
Board	36	1,008	1,440 (2,000)	1 (1.5)	216 (300)
Cabinet	144	4,032	5,760 (8,000)	4 (6)	864 (1,200)
System	36,864	1,032,192	1,474,560 (2,048,000)	1,024 (1,536)	221,184 (307,200)

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

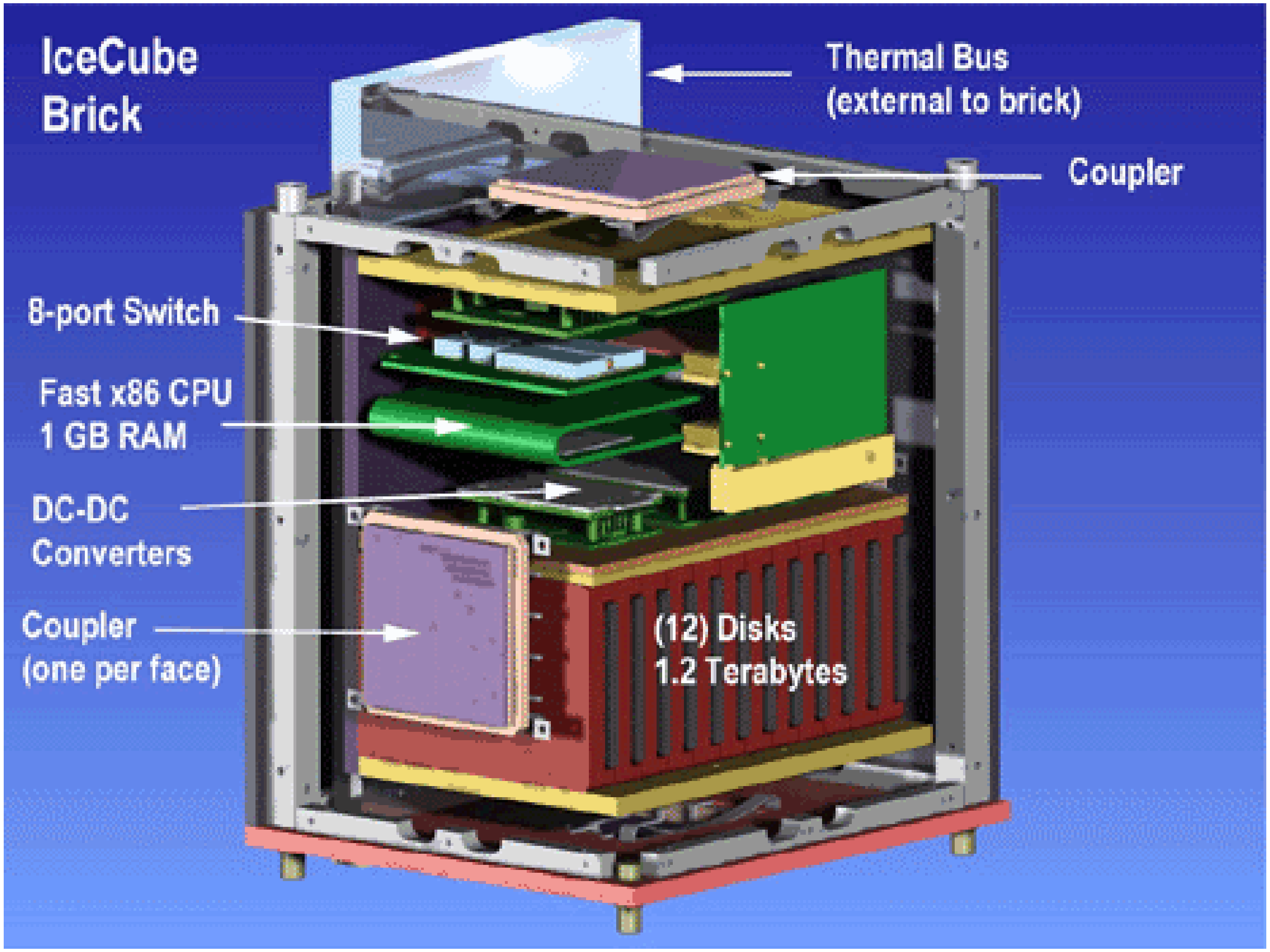
Super Computer System Cooling Module (studied)



Super Computer Cooling System (studied)

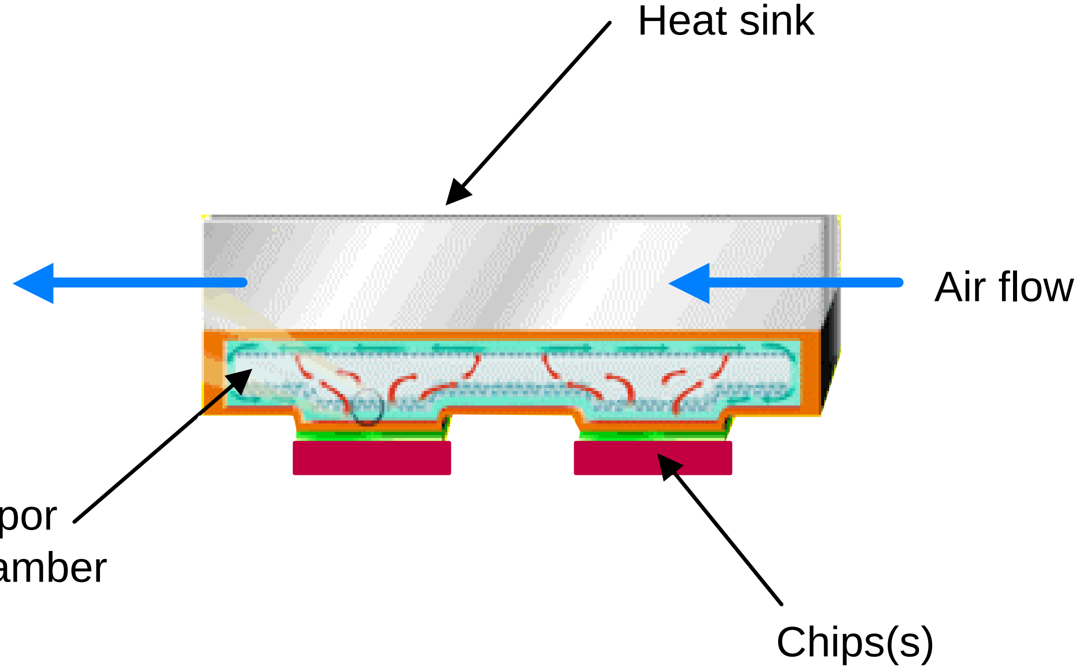


IBM Prototype Data-Storage System: Storage-Array Brick

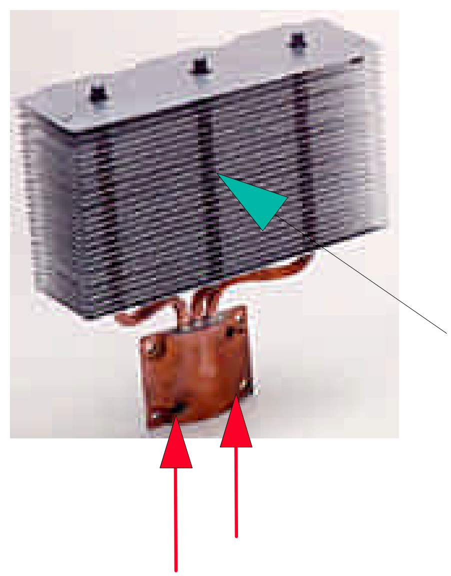


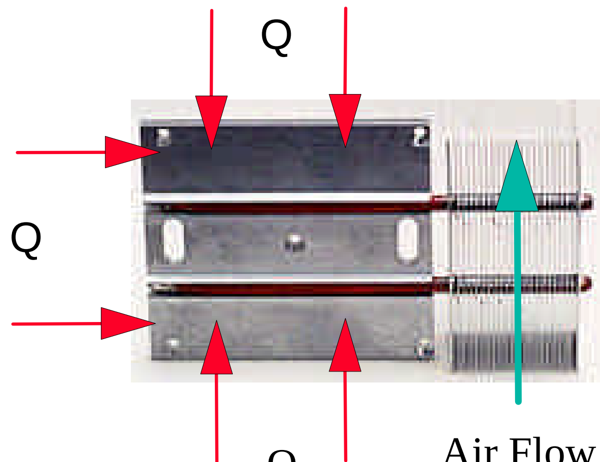
Cooling Technologies

Vapor Chamber Heat Spreader

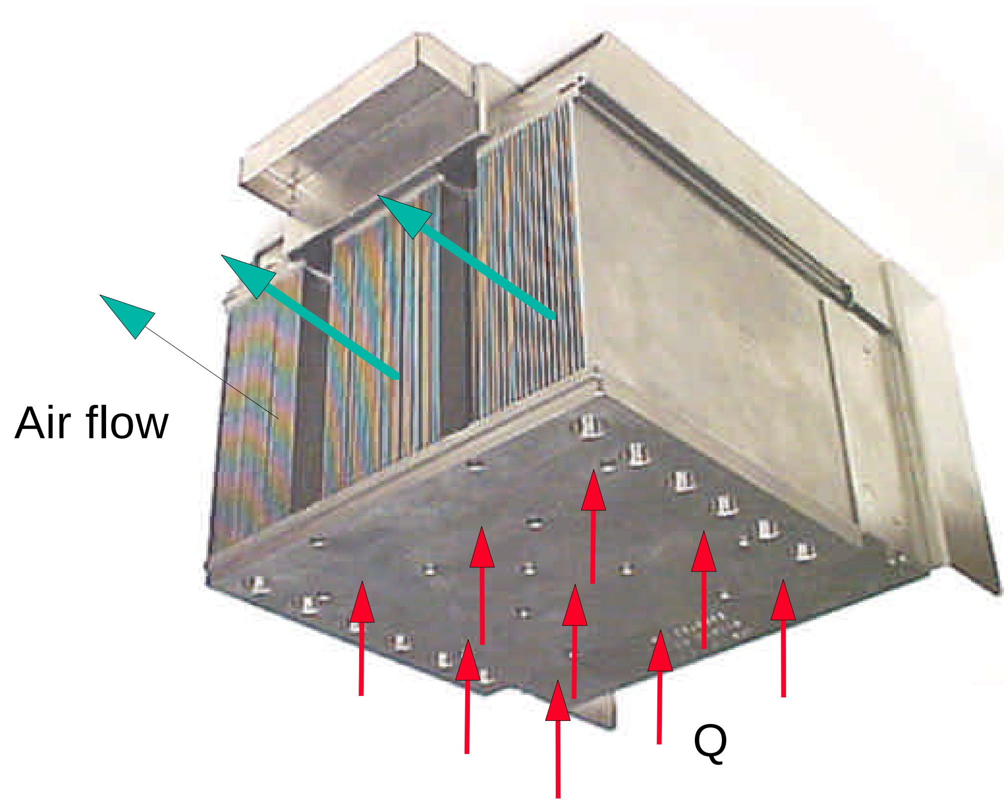


Examples of Heat Pipes Used in Electronics Cooling

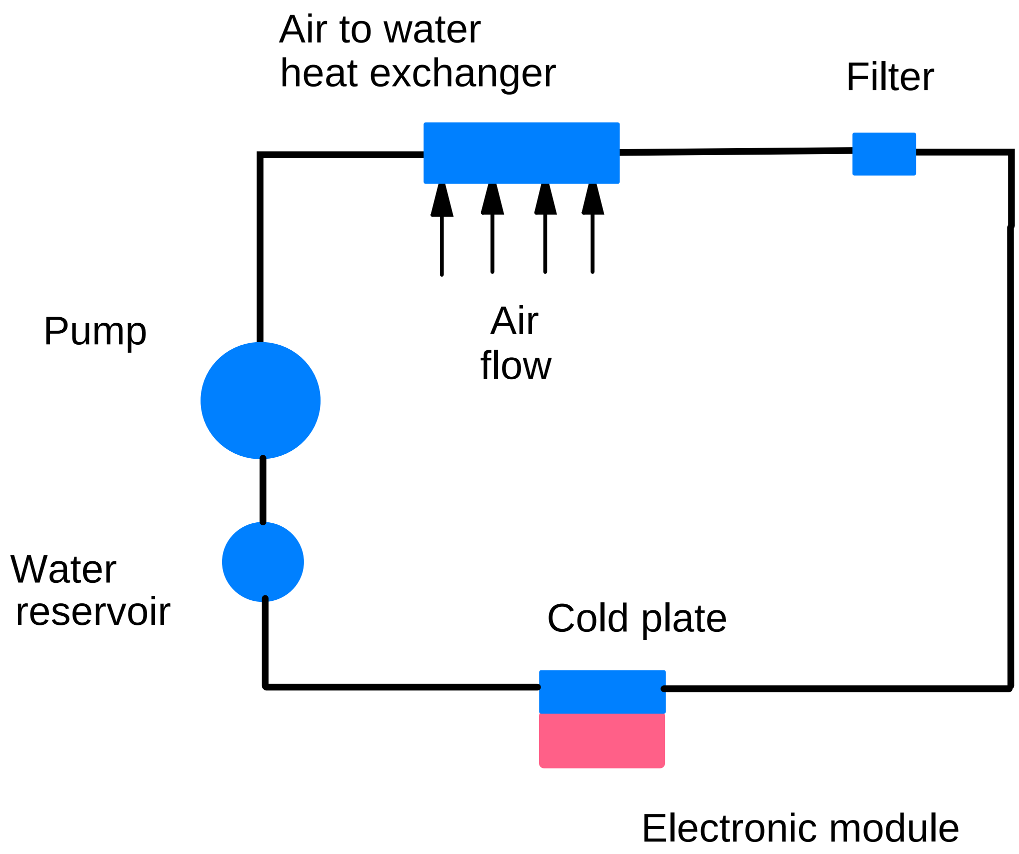




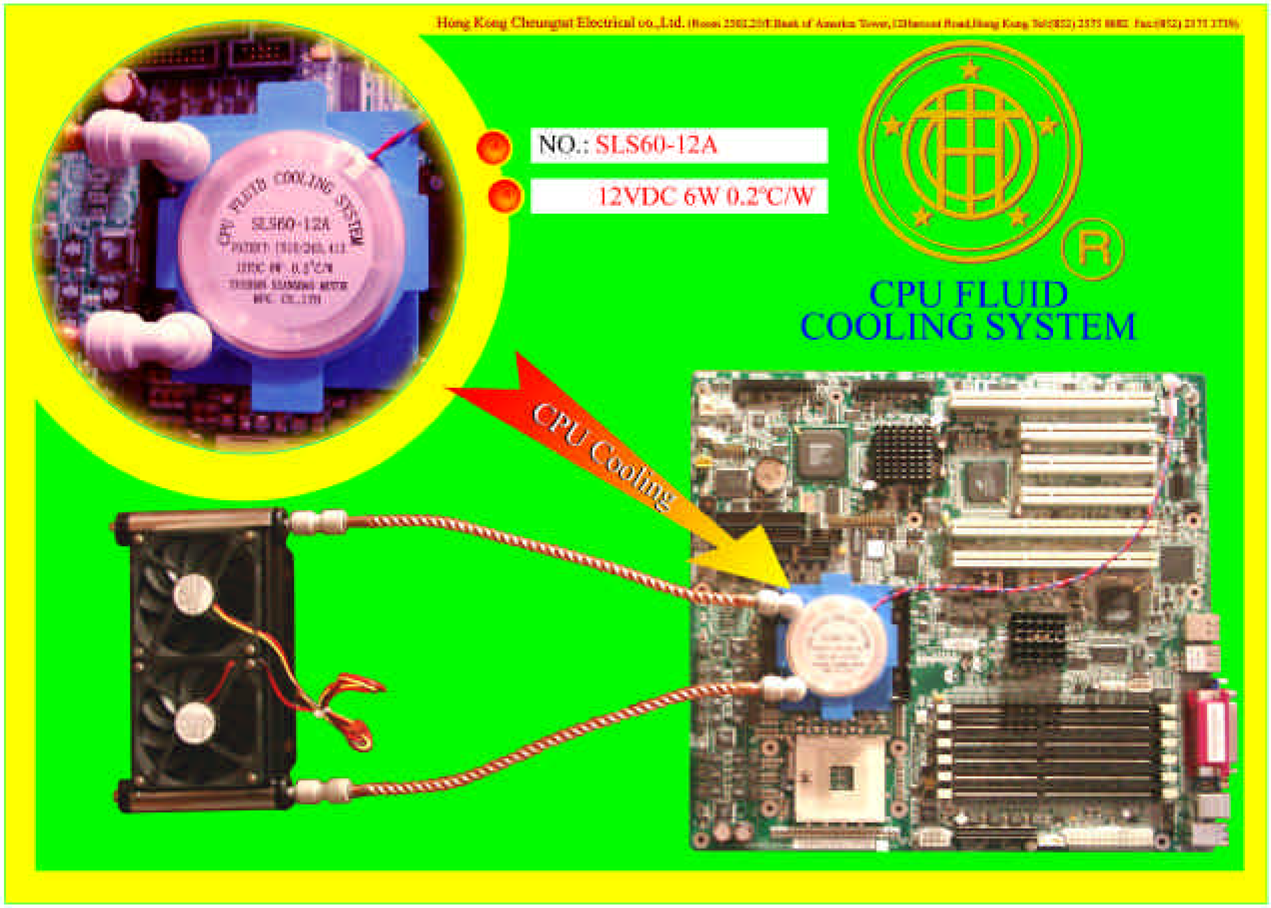
Example of a Large Air-Cooled Heat Sink for a High Performance Processor Module



Closed Loop Water Cooling System With Heat Rejection to Air



Closed Loop Water Cooling System With Heat Rejection to Air



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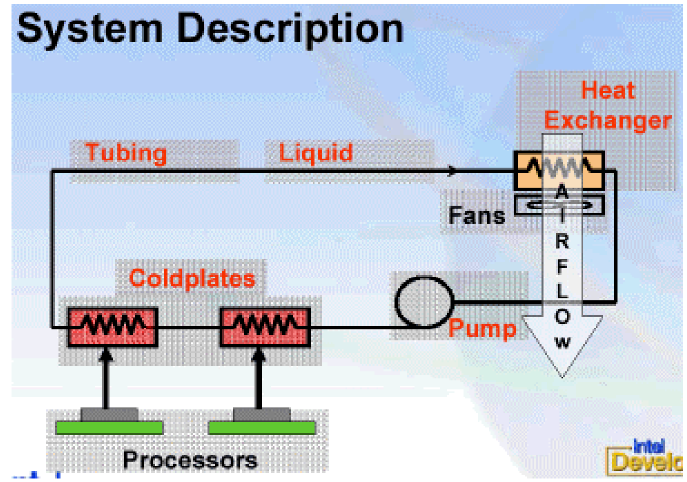
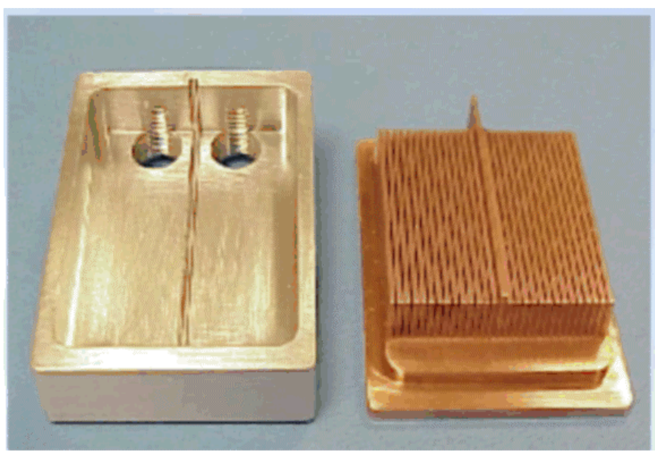
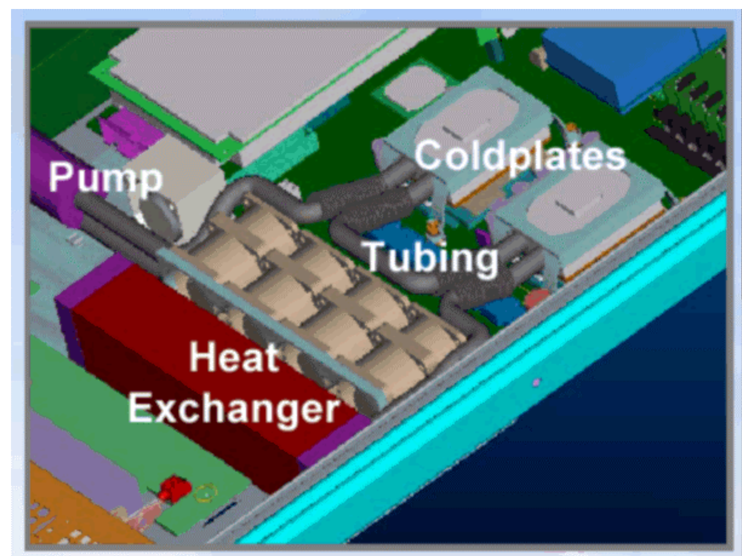
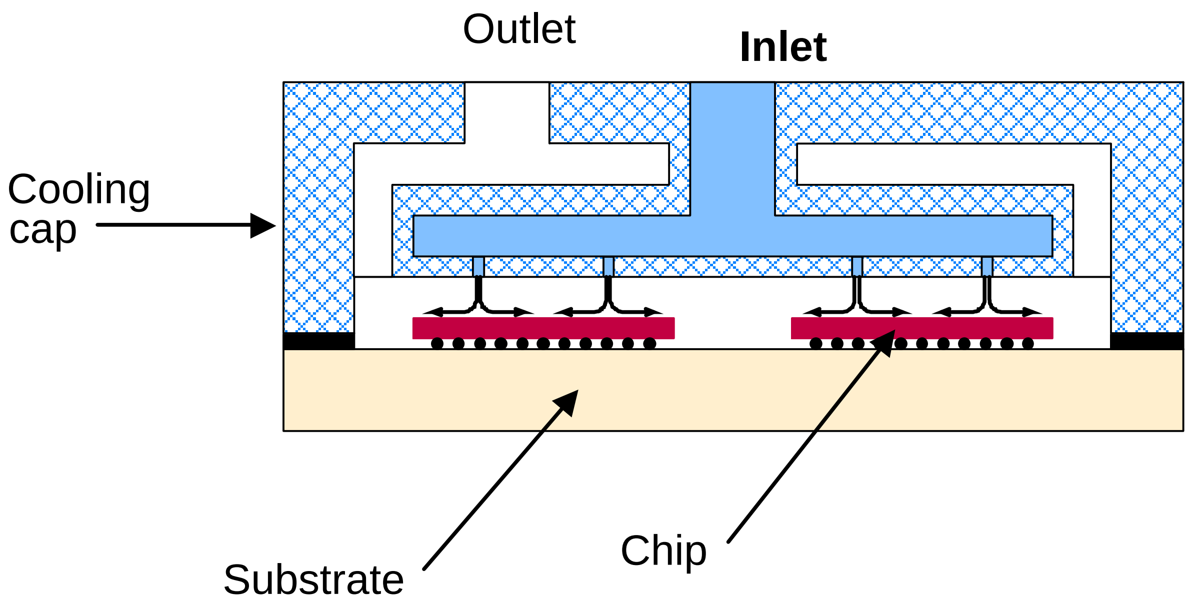


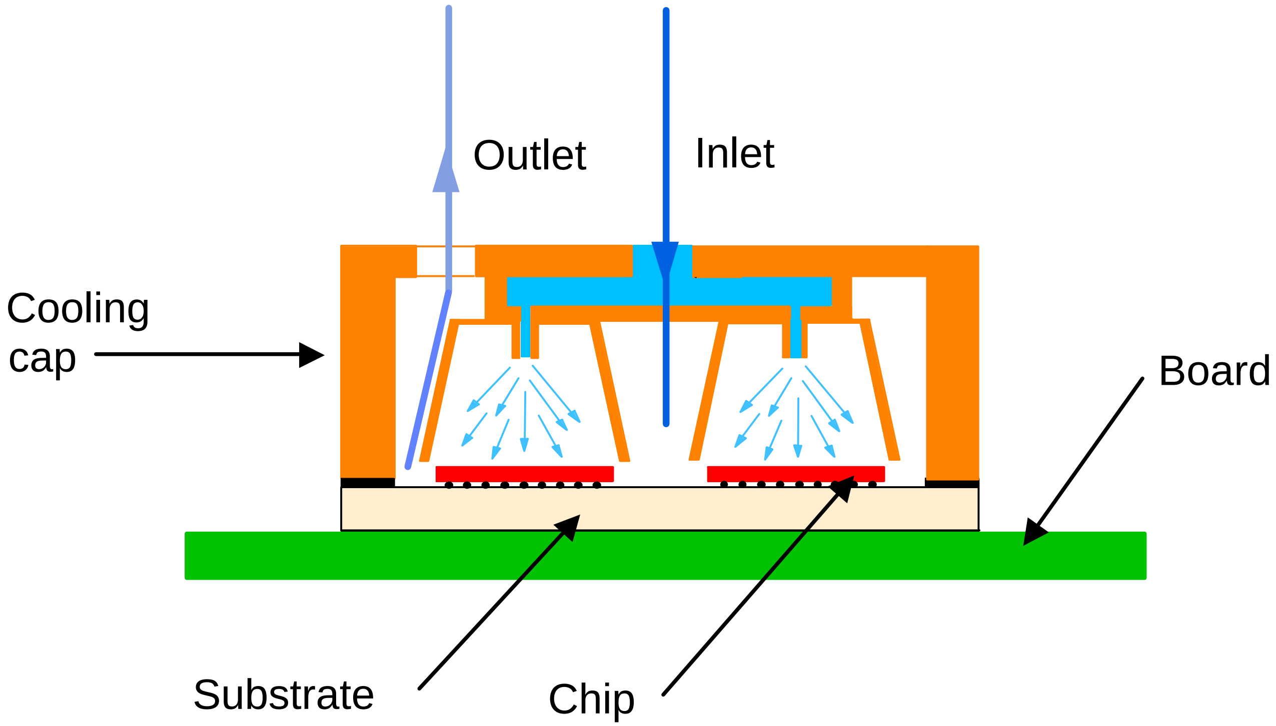




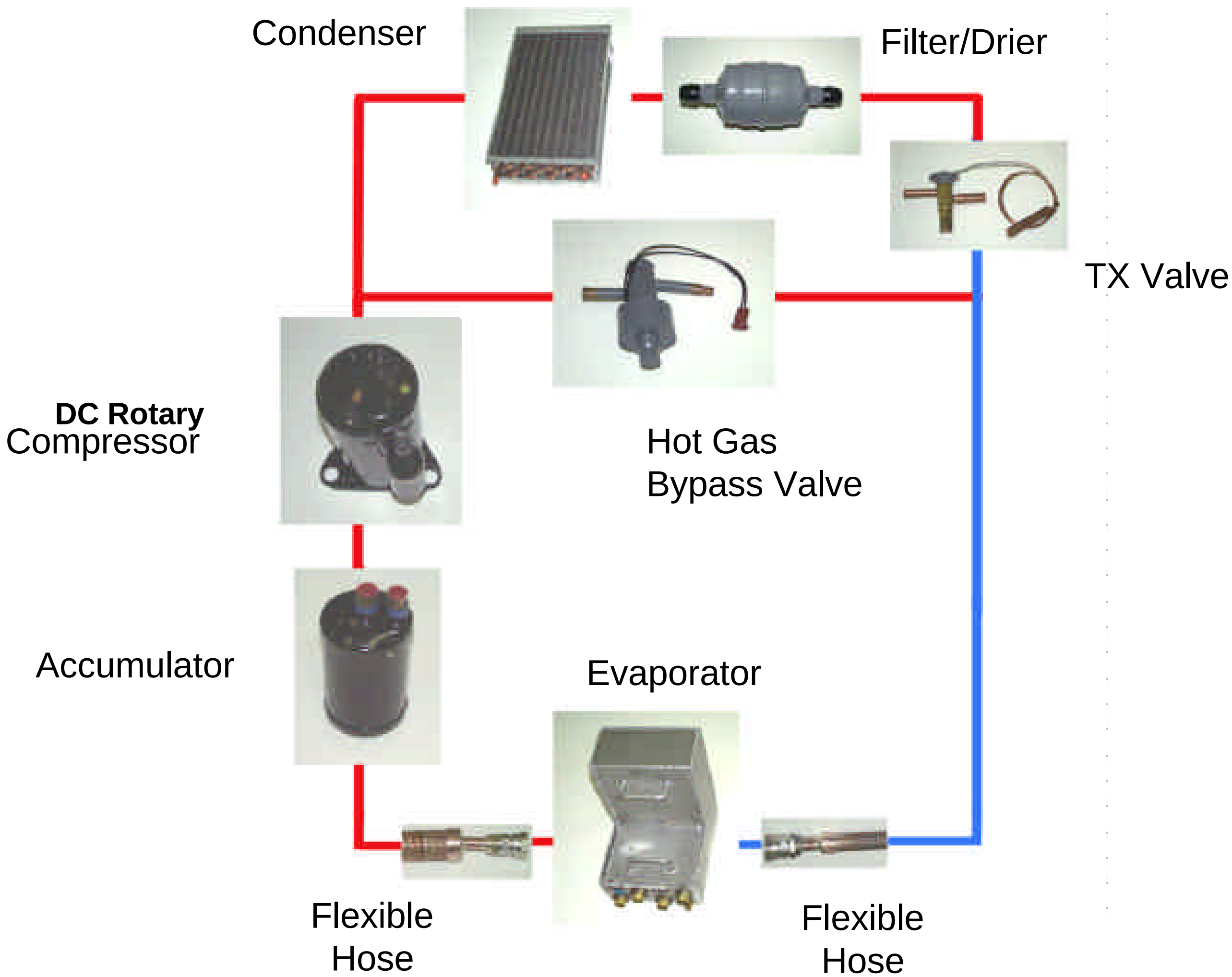
Liquid Jet Impingement Cooling



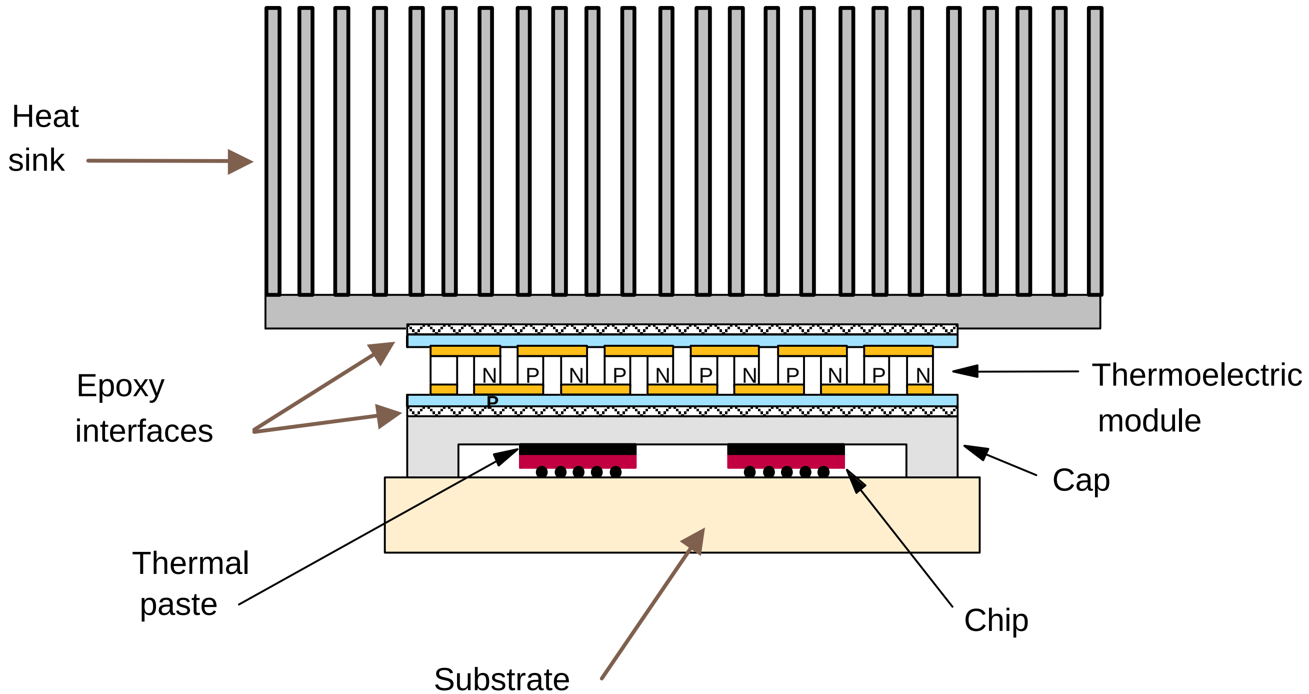
Liquid Spray Cooling



Refrigeration Loop and Components for Cooling a High Performance Processor

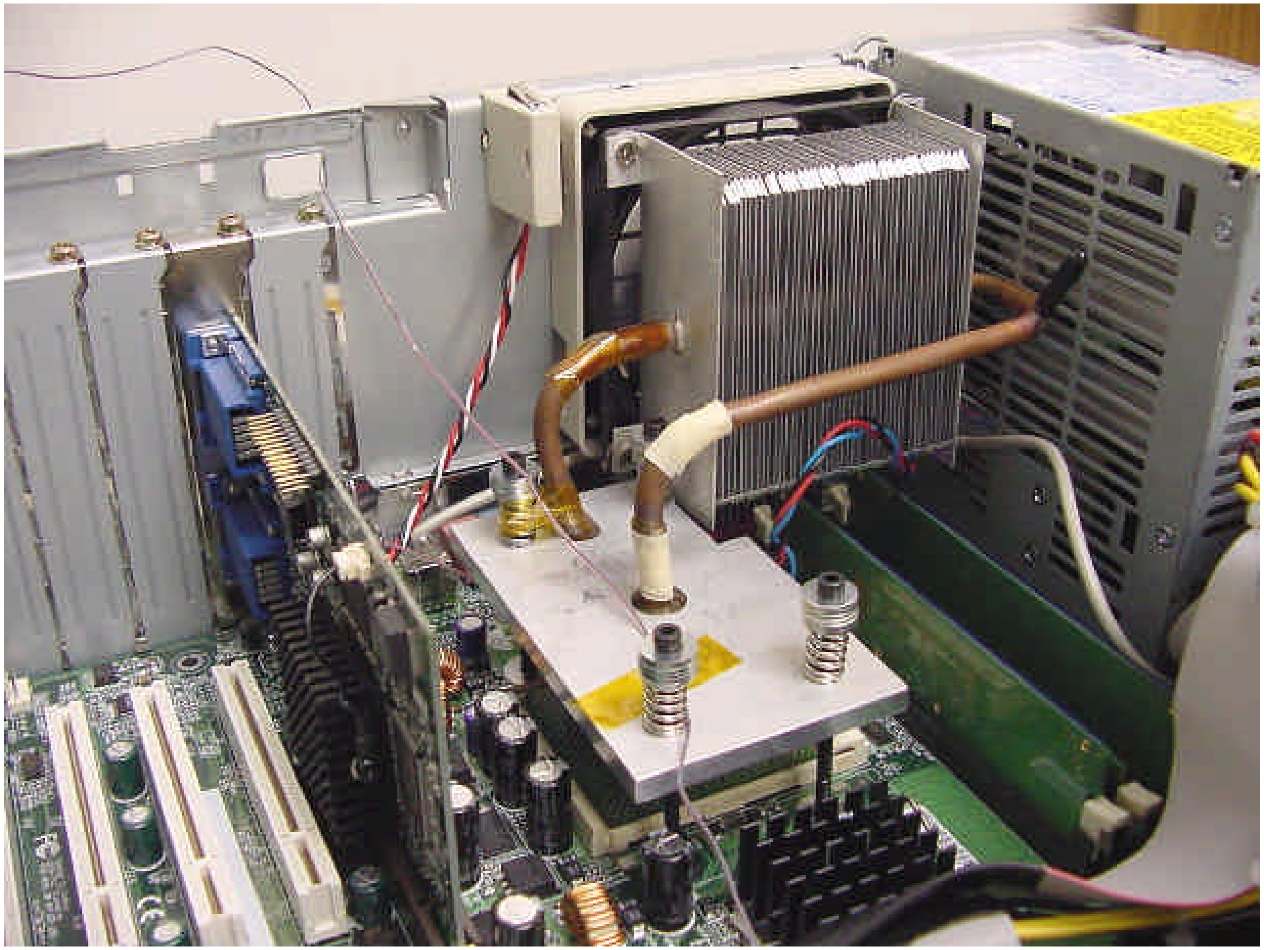


Cooling Enhancement of an Electronic Module With a Thermoelectric Cooler



Advanced Cooling Technology Development Activities

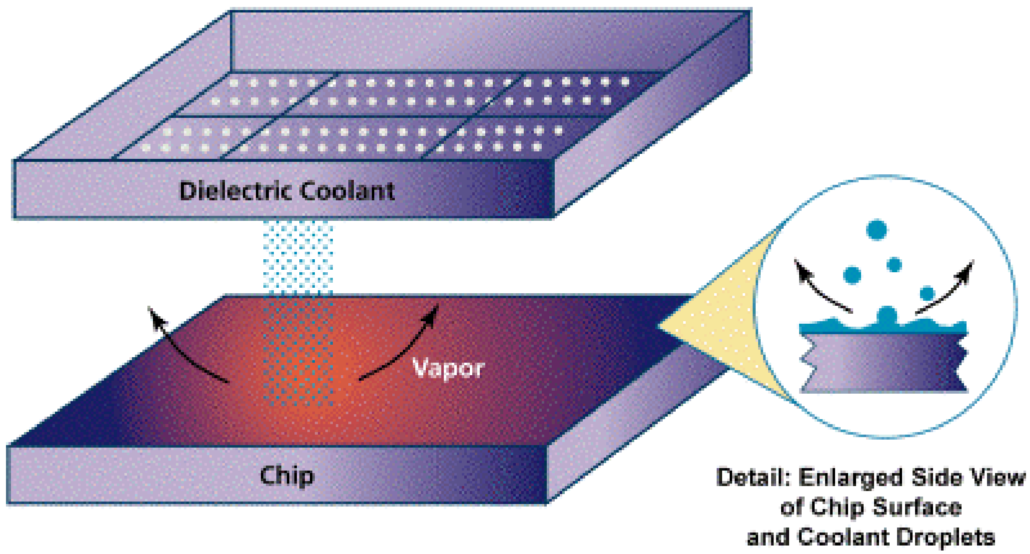
Two-Phase Thermosyphon Test Vehicle



Demonstrated for 85 W Intel Pentium 4 Processor in 2001.

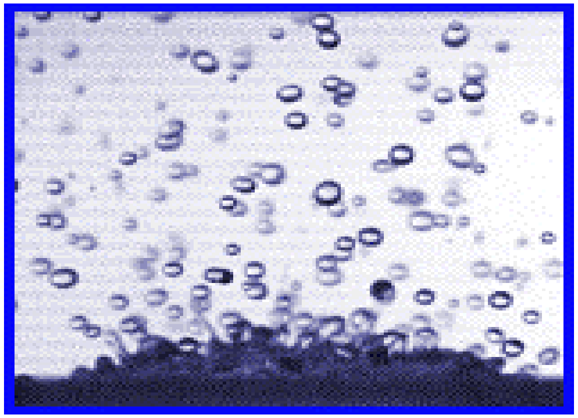
"Heat Out of Small Packages", Y. Joshi, *Mechanical Engineering*, Vol. 123, pp. 56-58, Dec. 2001.

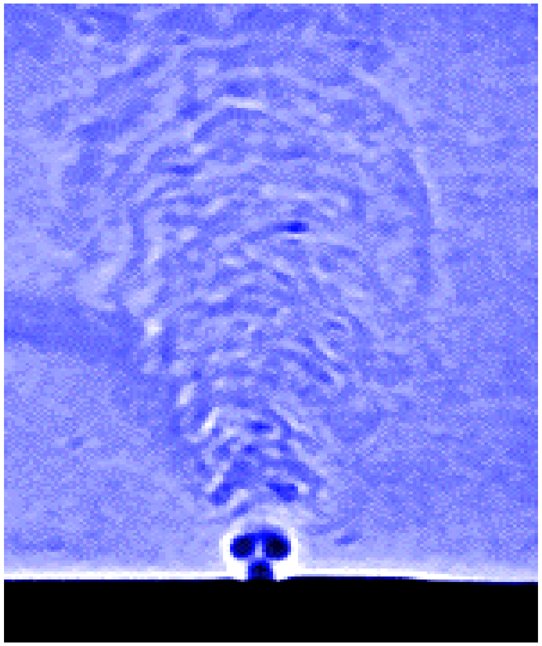
Recent Research (DARPA HERETIC)
Spray Cooling (Carnegie Mellon University)



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

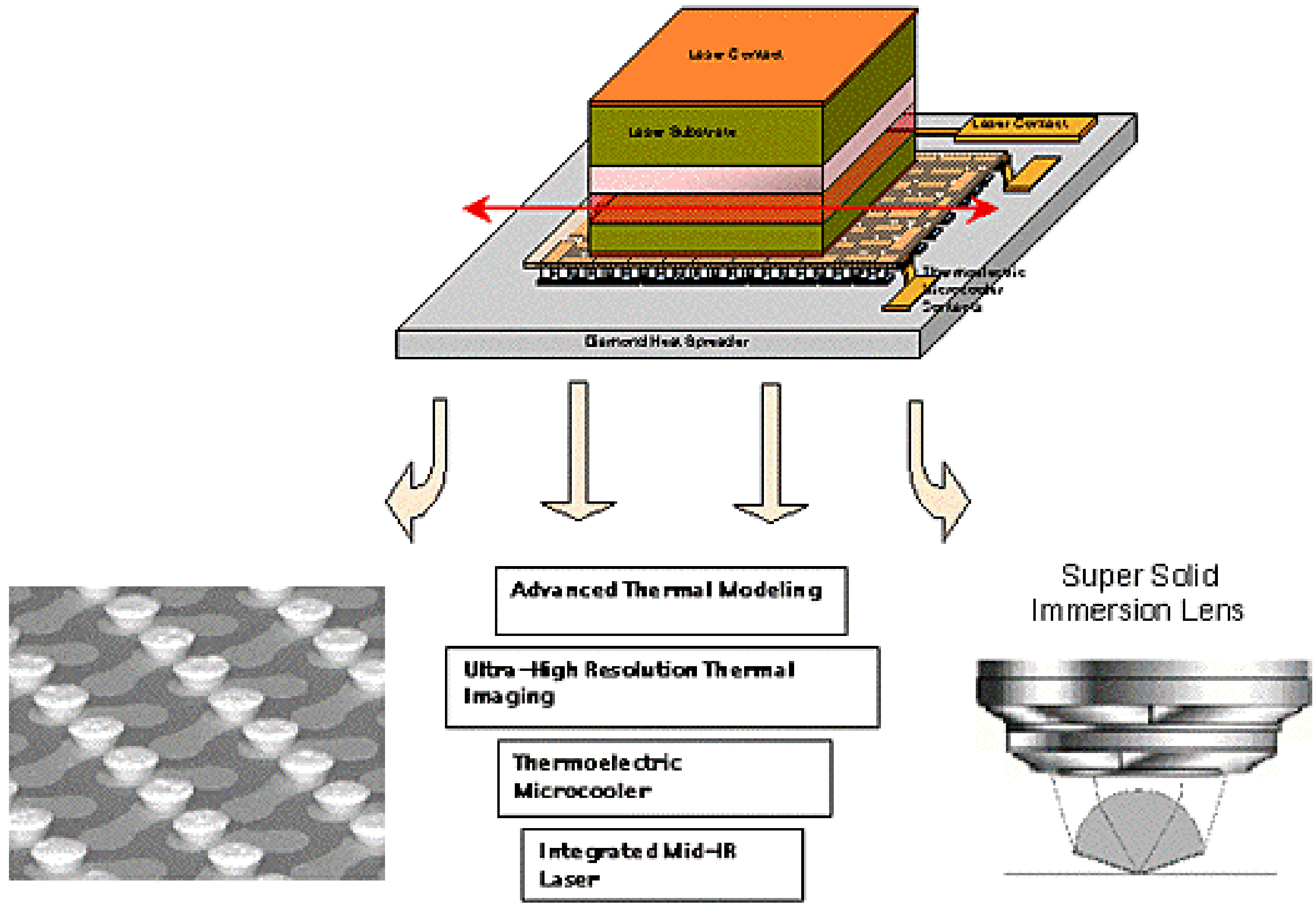
Recent Research (DARPA HERETIC)
Droplet Atomization and Microjets (Georgia Tech)





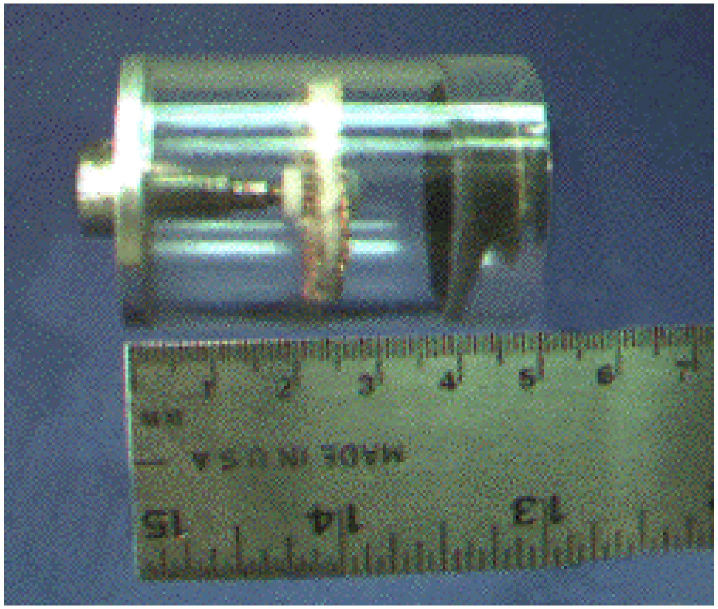
http://www.darpa.mil/MTO/HERETIC/projects/4.html

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



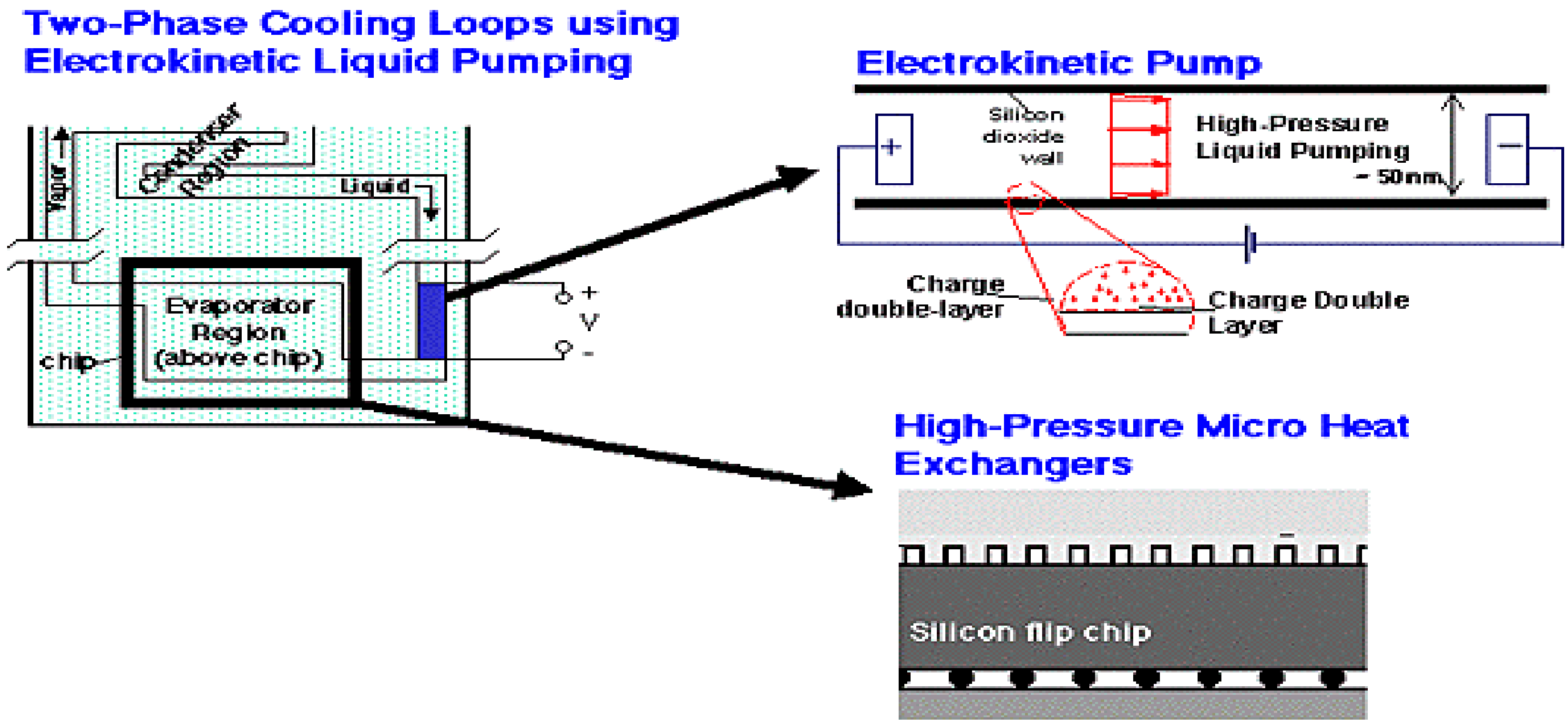
http://www.darpa.mil/MTO/HERETIC/projects/5.html

Recent Research (DARPA HERETIC) Thermoacoustic Refrigerators (Rockwell)



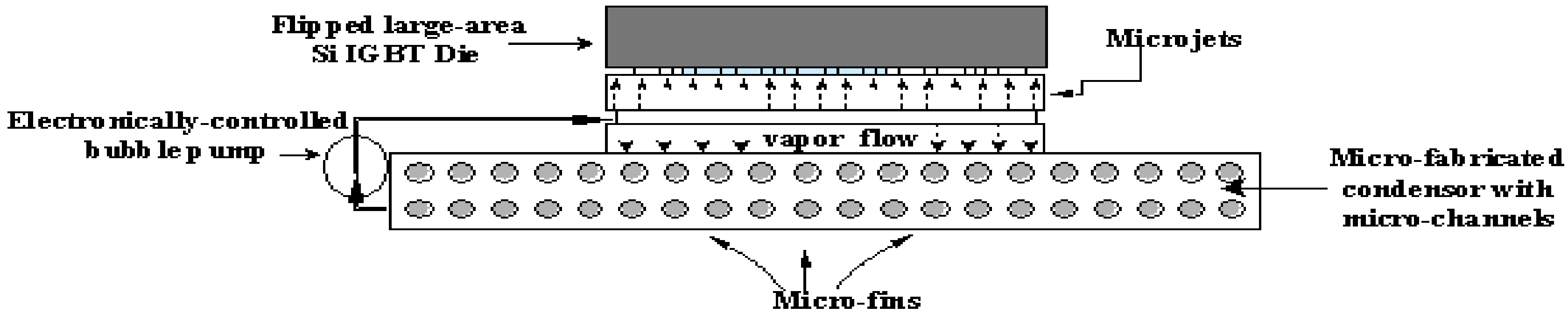
http://www.darpa.mil/MTO/HERETIC/projects/6.html

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



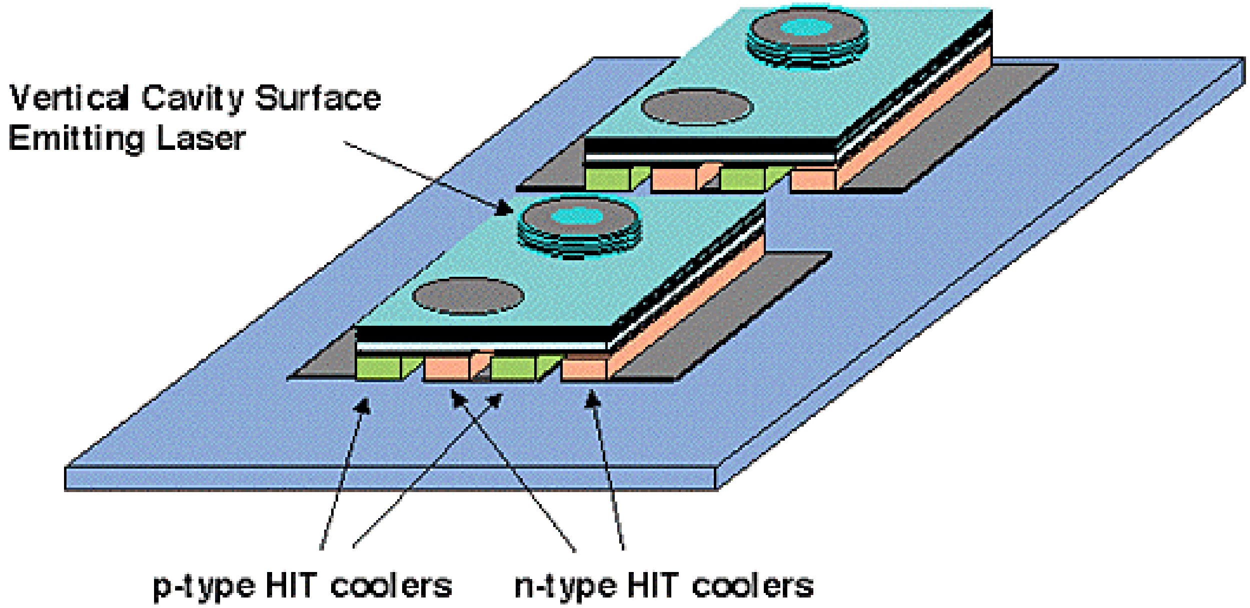
http://www.darpa.mil/MTO/HERETIC/projects/7.html

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

Research Needs

Thermal Spreaders

- Inexpensive, high thermal conductivity with closer TCE match to silicon
- Algorithms for optimizing thermal/mechanical design of thermal spreaders
- Improved thermal spreading within a chip – alleviate hot spots
- Correlations and Analytical models of dryout and rewetting of micro-channels and micro-porous structures to facilitate design of micro-heat pipes

Thermal Interfaces

- Thermal pastes, epoxies, and elastomers with high thermal conductivity nanoparticles
- New interface materials based on carbon nanotubes and other materials
- Novel techniques/materials to minimize bonded interfacial stresses
- Correlations and analytical relations to predict fatigue life of bonded interface materials
- Standardized method to characterize thermal interface performance
- Self contained solid-to-solid phase change materials or micro-encapsulated materials as suitable interface mateirals for a range of applications including harsh environments

Research Needs (continued)

Heat Pipes

- Flexible heat pipes
- Heat pipes that handle high heat fluxes
- Low cost heat pipes that can transport heat effectively over large distances (>0.5 m)
- Designs to reduce the graviational orientation impact on heat pipe efficiency, especially for avionics applications
- Heat pipe technology capable of withstanding harsh environments
- Sound numerical models and optimization tools for predicting the performance and operational limits, including dry-out, in heat pipes
- Correlations and algorithms for thermosyphon (i.e. wickless heat pipe) designs

Research Needs (continued)

Air Cooling

- Models and correlations to predict heat transfer in transition and low Reynolds number flow over packages and in heat sink passages
- Low Reynolds number turbulence models for use in CFD codes
- Heat sink design and optimization procedures for the minimization of heat sink thermal resistance subject to mass and volume constraints
- Advanced manufacturing techniques for metal and composite material heat sinks
- Concepts for higher head-moderate flow, low noise, compact fans
- Novel, low power consumption, low acoustic emission micro-fans for forced convection cooling in notebook computers and handheld electronics including low-frequency and ultrasonic piezoelectric fans
- High pressure/high flow blowers with low acoustical power

Research Needs (continued)

Water Cooling

- Miniaturized components that have high reliability and provide enhanced performance (e.g. pumps and heat exchangers)
- MEMS and meso-scale components to create low cost, low noise, water-to-air heat exchangers
- MEMS and meso-scale components to create low cost, package-size cold plates
- Microchannel heat sinks with novel integrated micropumps to minimize package volume for high heat flux applications
- Methods to enable direct water cooling of chips or chip packages

Direct Liquid Immersion

- Single + two-phase heat transfer correlations for new families of dielectric coolants
- Nanofluids: nanoparticles in dielectric coolants to enhance heat transfer characteristics
- Convective + phase change correlations that account for highly non-uniform HF conditions
- CHF models to account for highly non-uniform heat fluxes
- Characterization of boiling and two-phase flow in narrow passages and 3D structures
- MEMS/meso-scale components to enhance convective, pool + flow boiling heat transfer
- Correlations and models for evaporative spray cooling heat transfer

Research Needs (continued)

Sub-Ambient and Refrigeration Cooling

- Highly reliable miniaturized components such as compressors, condensers, and evaporators
- MEMS / meso-scale components to create low-cost, low noise refrigerators using solid-state, vapor compression, or absorption cycles
- MEMS / meso-scale components to create low-cost, pacakge-size cold plates
- New thermoelectric materials and fabrication methods that can improve the performance of thermoelectric coolers

Low Temperature Refrigeration

- Application of auto-refrigerating cascade (ARC) systems to provide low temperature cooling of electronics packages
- Application of mechanically cascaded (2-stage) refrigeration systems to provide Low temperature cooling for electronic packages

Summary and Conclusions

- CMOS will continue to be the pervasive semiconductor technology for both memory and logic.
- Chip size may decrease with continued 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.
- New cooling technology/system will be needed to handle increased heat load at product (rack) level.
- Data center thermal management will be a significant challenge
- High thermal conductivity interface material is needed for heat sink applications.
- 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
  - 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

Significant 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

"Imagination is more important than knowledge."

Albert Einstein

"Everyone is trying to accomplish something big,
Not realizing that life is made up of little things."

Frank A. Clark
Cowles Syndicate

"Perseverance – There is no substitute for hard work."

Thomas A. Edison

"The harder you work the luckier you get."

Gary Player

Career = f (EQ, IQ, AQ, WQ, …)

Where,

EQ = Emotional quotient

IQ = Intelligence quotient

AQ = Adversity quotient

WQ = Work quotient

Do not look back to the good old days; instead, look ahead to the better new days.