ENERGY EFFICIENCY IN HIGH PERFORMANCE COMPUTING – An Industry Perspective

High Speed Computing, 2009

Tahir Cader, HP

April 27 – 30, 2009

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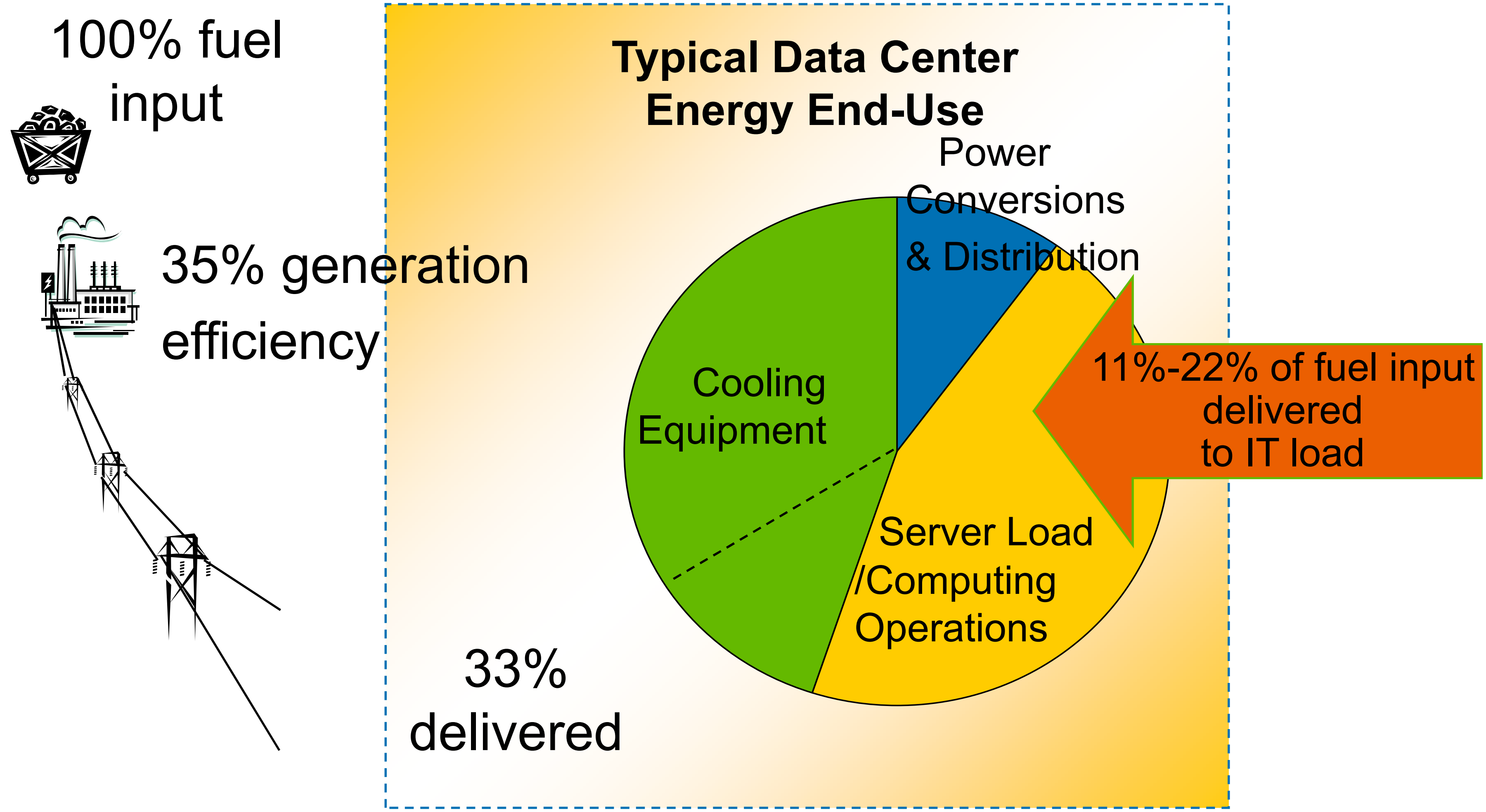
OVERVIEW

The presentation will cover…

- Energy Efficiency Issues
- The Evolving Data Center
- HPC1 Cluster Case Study
- Energy Efficiency Solutions for HPC
    - Monitoring, Visualization, & Control
    - Power Distribution & Management
    - Cooling - Air
    - Cooling - Free Air Cooling for HPC?
    - Cooling - Liquid
    - Containerized Data Centers for HPC?
- Onsite Power Generation and Microgrids
- Concluding Remarks

ENERGY EFFICIENCY ISSUES

Power Transmission/Distribution Losses



Making the case for microgrids and distributed generation

Source: P. Scheihing, DOE EERE

Top500 Power Consumption

Top10 Clusters

- Average power consumption is 1.32 MWatt
- Average power efficiency is 248 MFlop/s/Watt

Top50 Clusters

- Average power consumption is 908 kWatt
- Average power efficiency is 193 MFlop/s/Watt

Top500 Clusters

- Average power consumption is 257 kWatt
- Average power efficiency is 122 MFlop/s/Watt

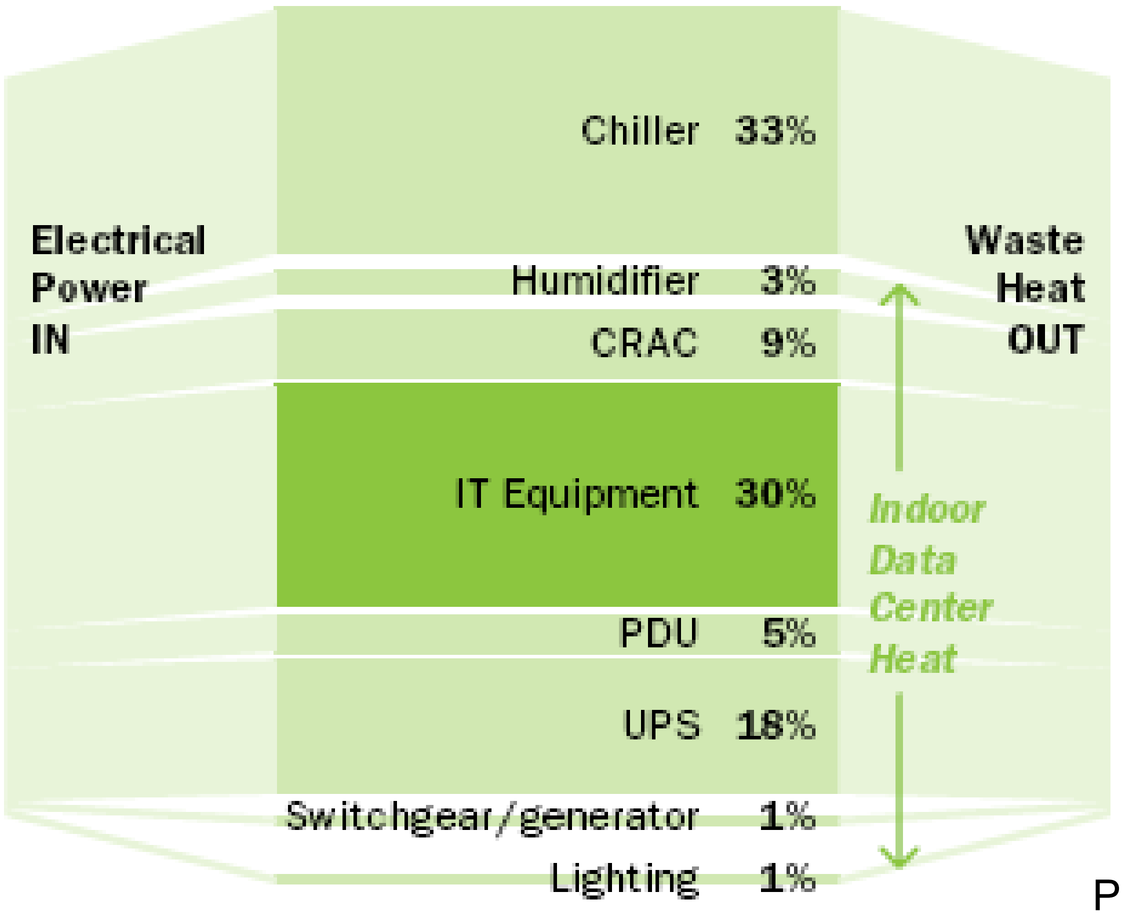
When including losses, Marquez of PNNL shows…

Average power efficiency for HPL

- No losses: 133 MFlop/s/Watt
- With power delivery losses: 80 MFlop/s/Watt
- With power & cooling losses: 52 MFlop/s/Watt

Source: http://www.top500.org/lists/2008/06/highlights/power

How Does a Data Center Use Power?



- *70% of a "typical" data center's power goes to Power & Cooling*
- *Percentage varies with data centers*
- *HP is working across the full spectrum to raise data center energy efficiency*
- *Figures to the left are "typical" of existing/ legacy data centers*

PUE = Power Usage Effectiveness

$$PUE = \frac{\text{Total Facility Power}}{\text{IT Equipment Power}}$$

Source: The Green Grid, 2007, "Guidelines for Energy-Efficient Datacenters" (www.thegreengrid.org). Notes: for PUE "lower is better"; DCiE = Data Center Infrastructure Efficiency, DCiE = 1/PUE, for DCiE "higher is better"

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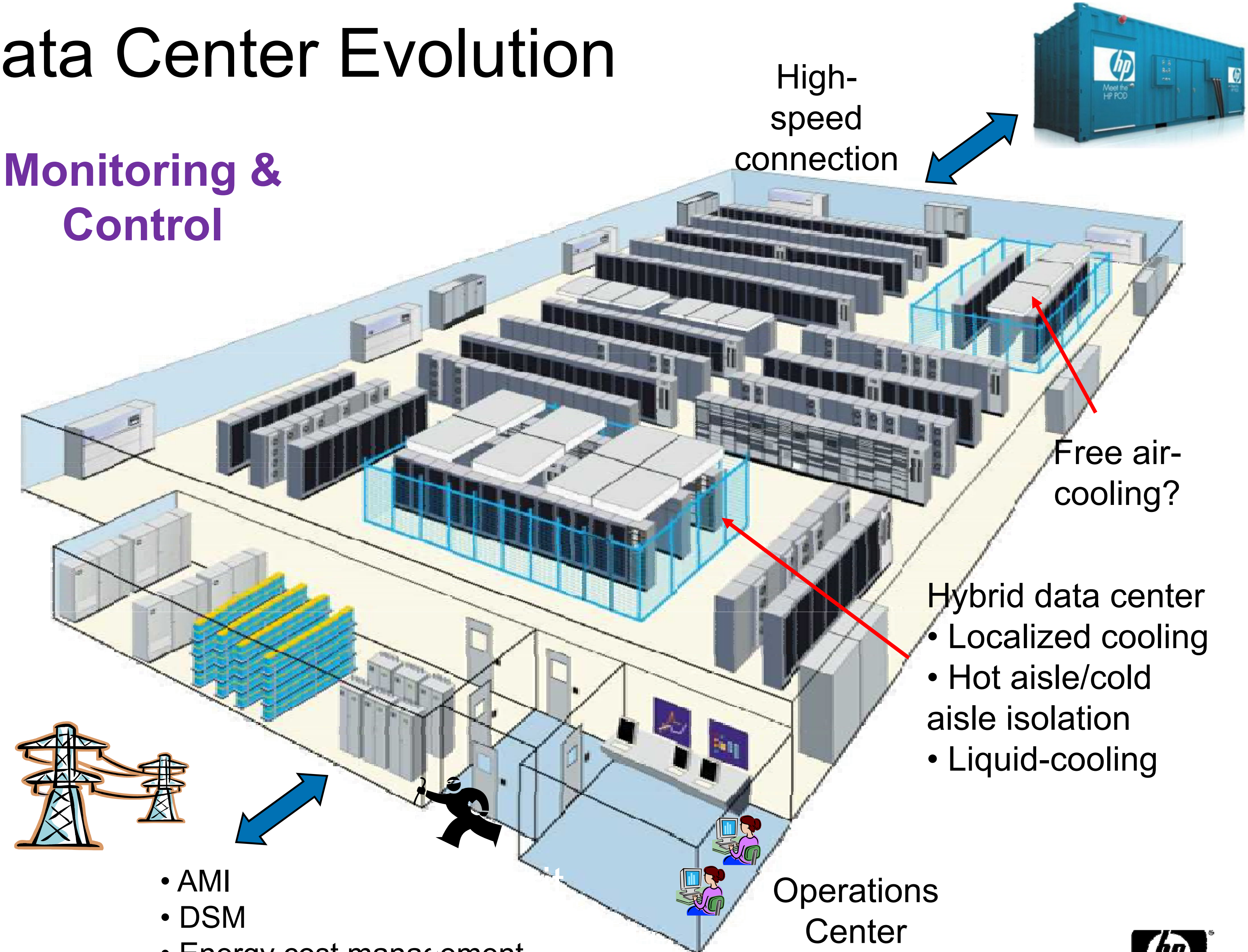
THE EVOLVING DATA CENTER

Data Center Evolution

Monitoring & Control



- AMI
- DSM
- Energy cost management
- Microgrid

HPC1 CLUSTER CASE STUDY

HPC1 Characteristics

Key analysis assumptions include:

- 250 compute (server) racks at 40 kW per rack
- 30 storage racks at 8 kW/rack
- 20 networking racks at 4 kW/rack
- Average PUE = 1.48 and 1.26
- Utility-to-rack power distribution efficiency of 80%
- Chilled water plant efficiency of 0.647 kW/ton
- Cluster runs 95% of the year
- Cluster runs at 85% of max utilization
- Total of 8,322 hours of operation annually
- Cost of energy of $0.05/kW-hr

HPC1 would be somewhere north of 1 PetaFlop

HPC1 Cluster Comparison

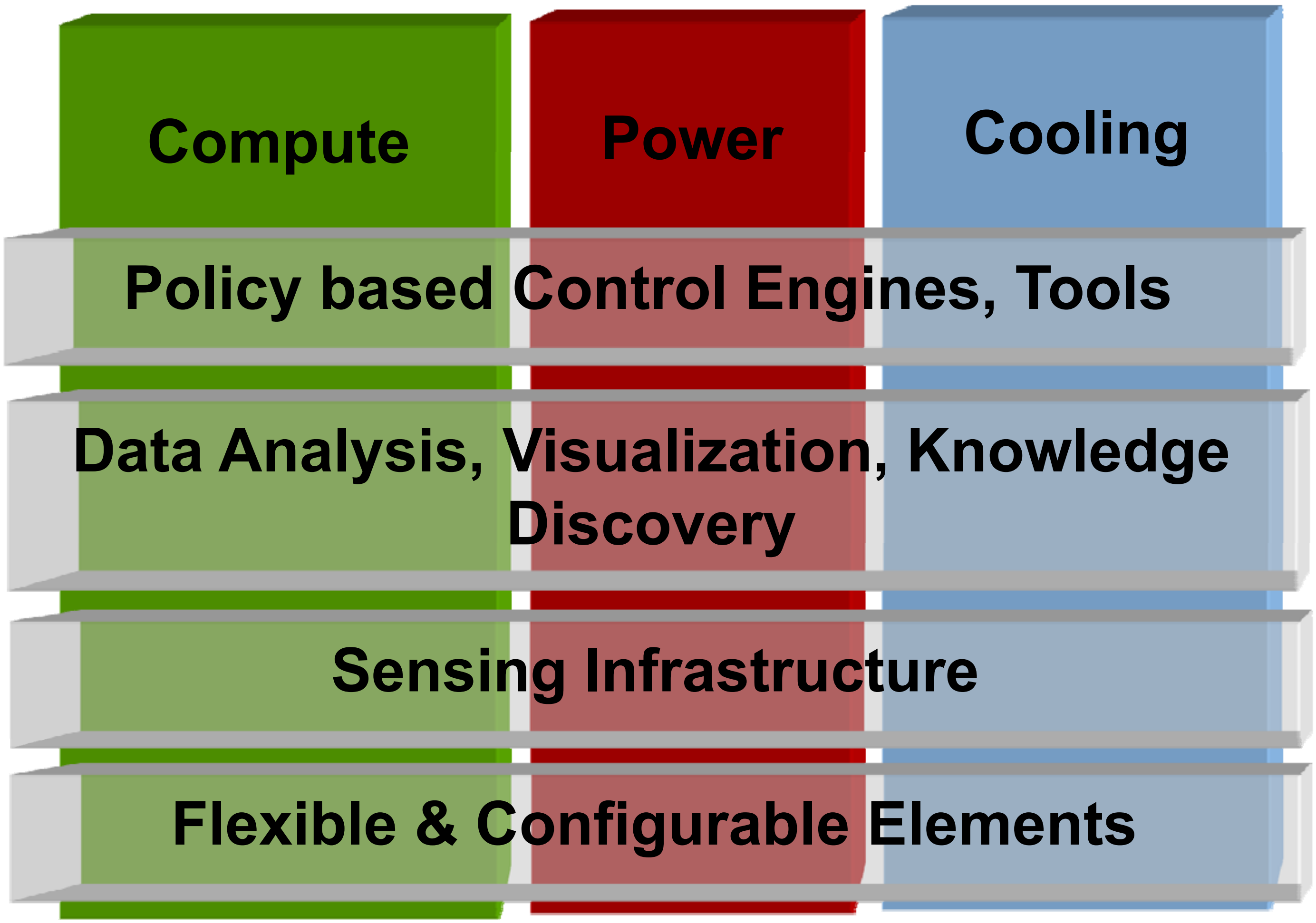
Typical HPC facility higher than this

				% decrease
PUE	**(-)**	1.48	1.26	15
Total Facility Power	**kW**	15274	13,018	15
IT Equipment Power	**kW**	10,320	10,320	0
Electrical Losses (IT)	**kW**	2,580	1,021	60
Chiller Plant Power	**kW**	2,374	1,677	29
Energy Consumption	**kW-hrs**	108,040,864	92,082,937	15
Cost of Energy	**$**	5,402,043	4,604,147	15

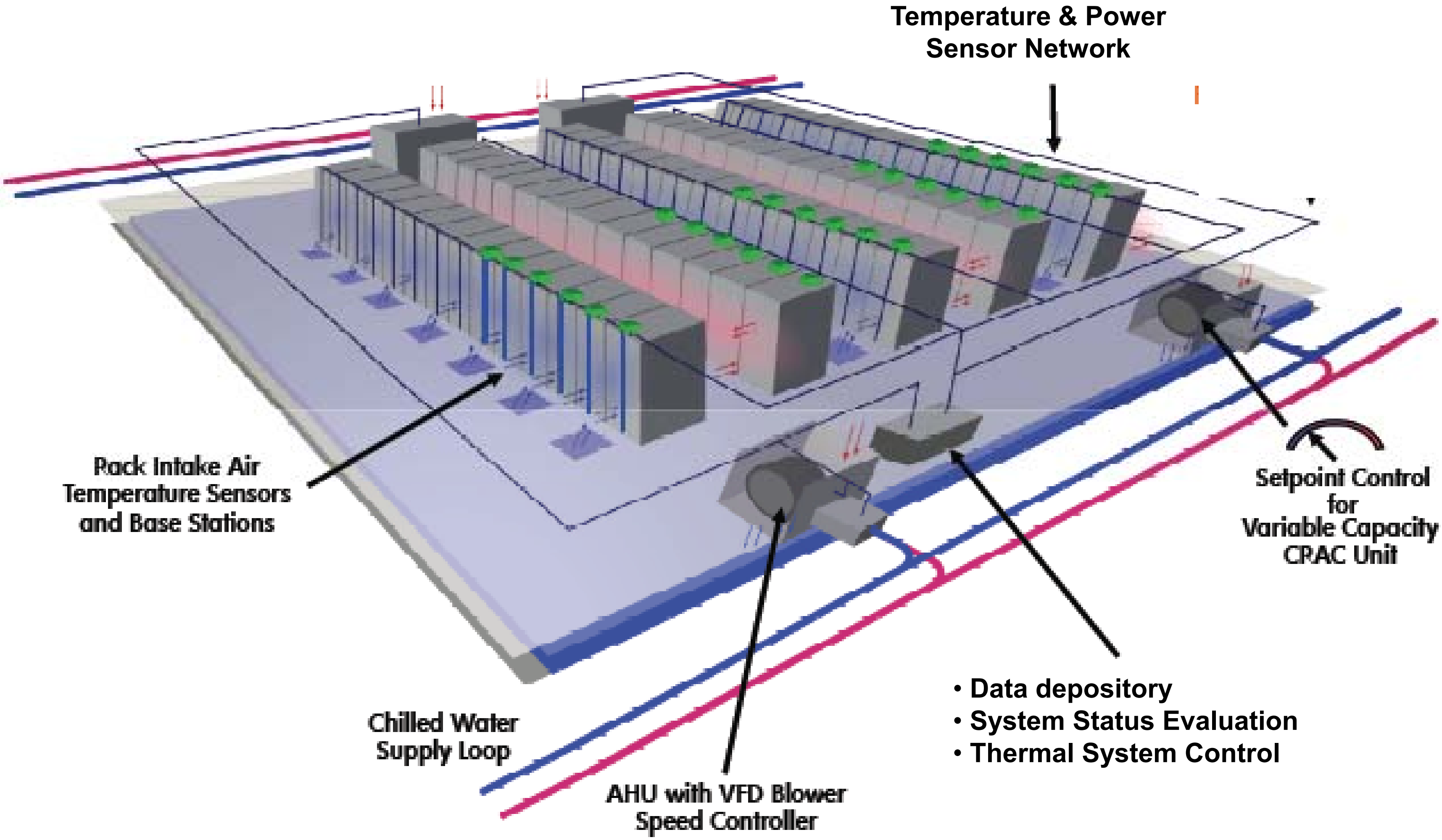
Annual

Data Center Monitoring, Visualization, & Control

Sustainable Data Center Solution



Monitoring & Control Implementation



HP R&D Lab Data Center

Facility Building Blocks

Chillers
- 3 air-cooled
- 2 water-cooled

Pumps
- 7 Primary
- 5 Secondary

CRAC units
- 55 units

Power
- 5x3MW gensets
- 900 kW cooling per floor

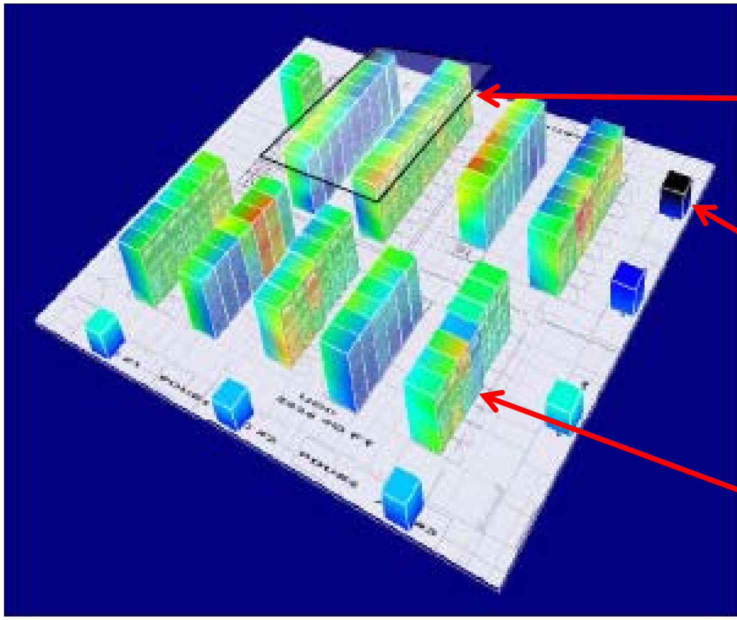
Sensor Network
- 7,500 sensors

5 floors, 75,000 ft^2

IT Building Blocks

- Servers
  - Non-Stop servers
  - Proliant servers
  - Blade servers
  - Custom Enclosures
- Storage (XP/EVA)
- Multiple Network topologies

Visualization & Knowledge Discovery

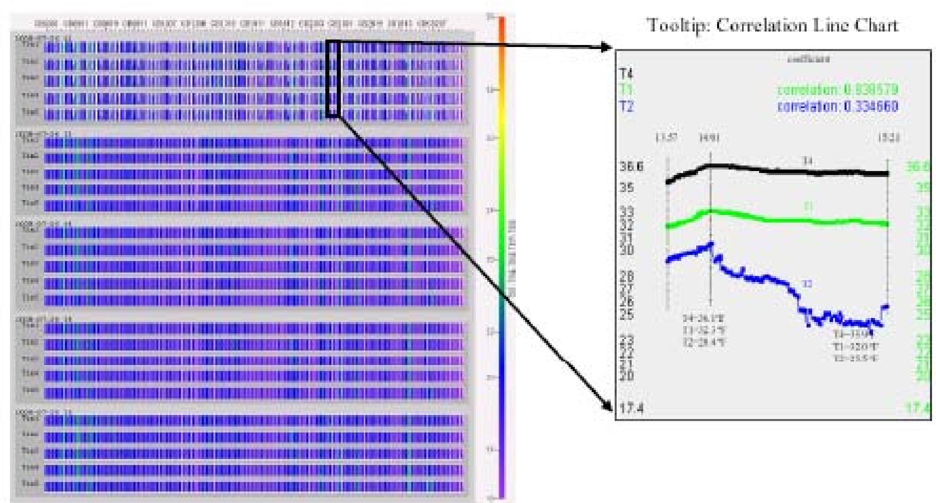


3D movie rendering

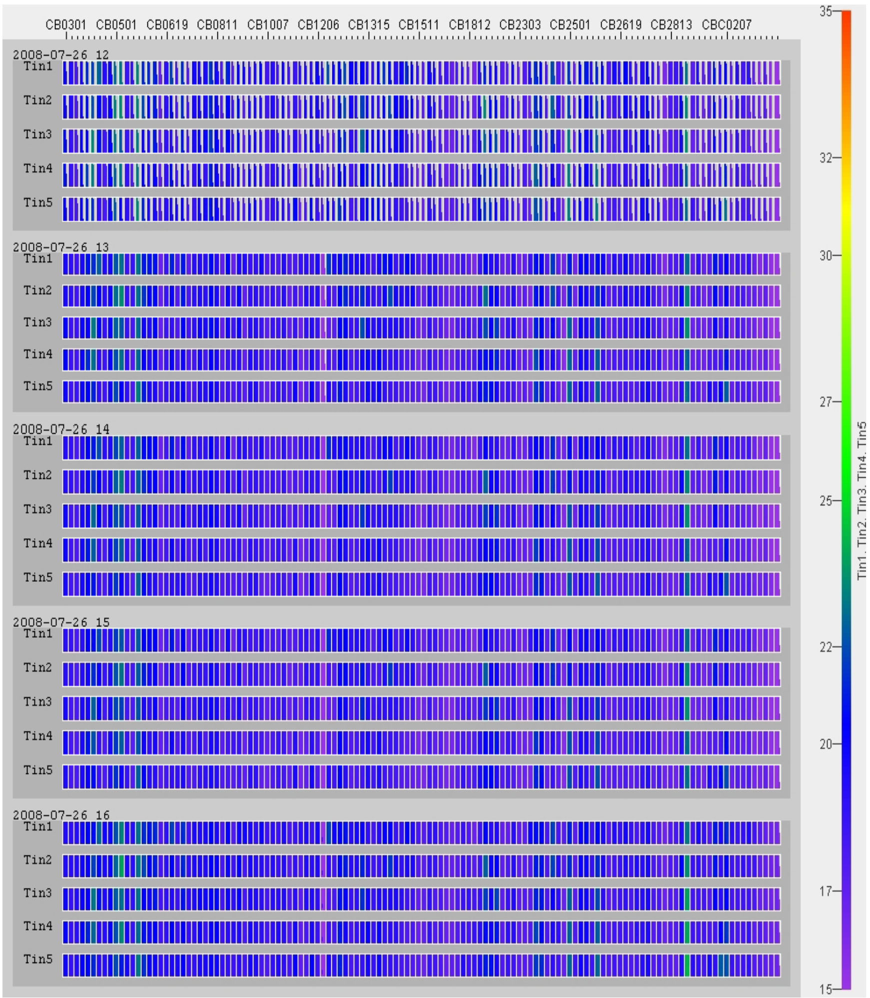
CRAH capacity

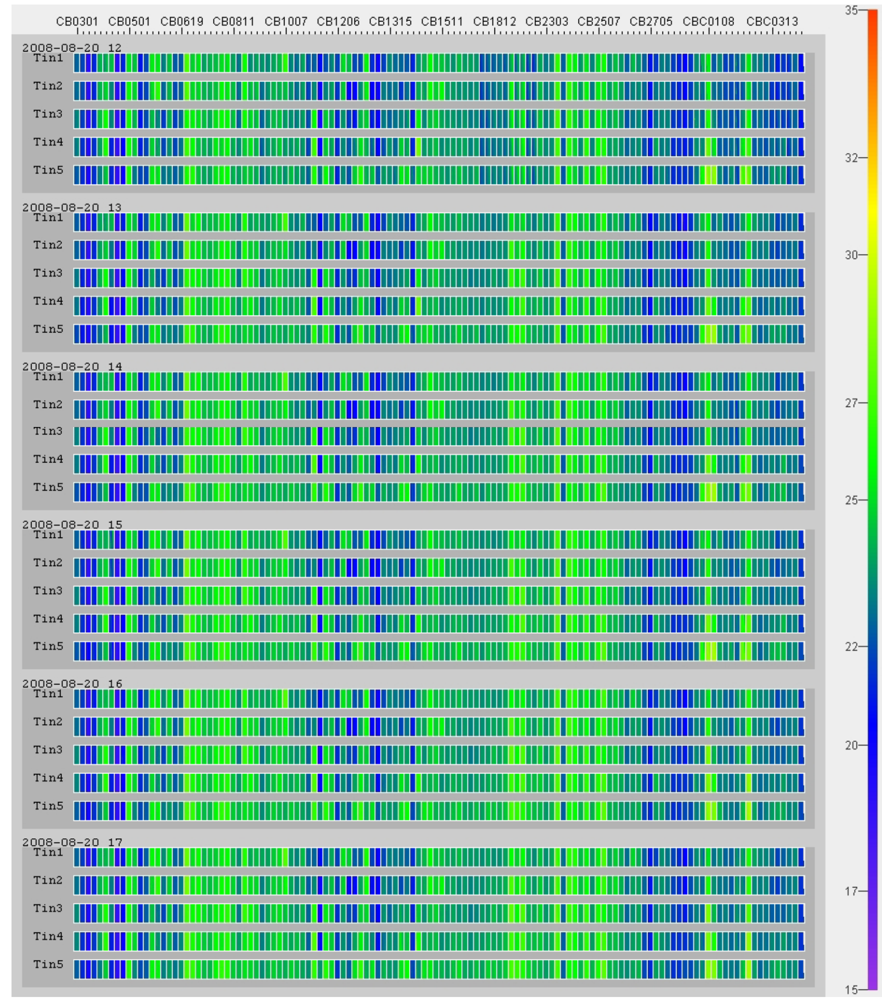
Rack temperatures

PDA-based data center health monitoring and viz



Visualization & Knowledge Discovery





Control Off

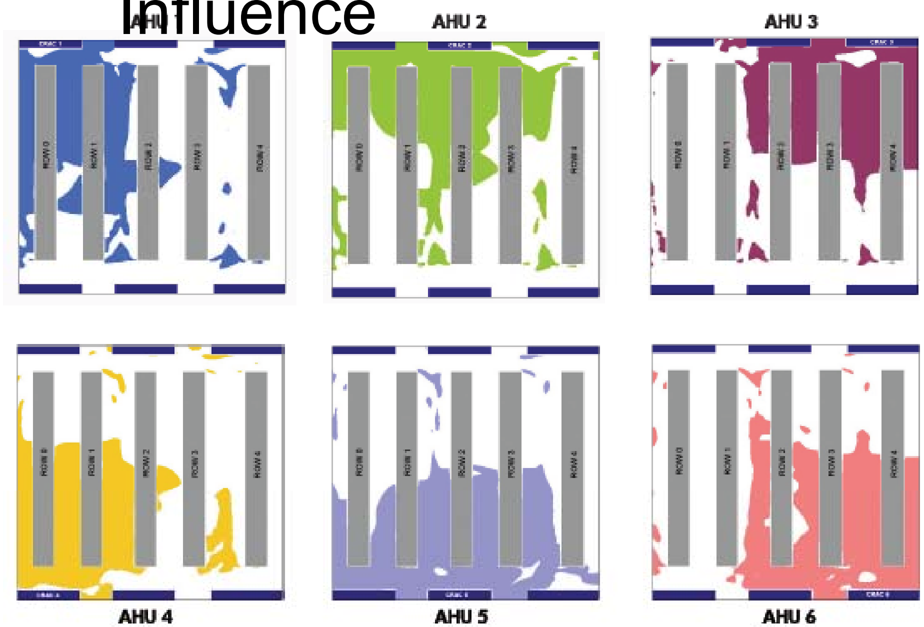
- **Racks over-provisioned**

Control On

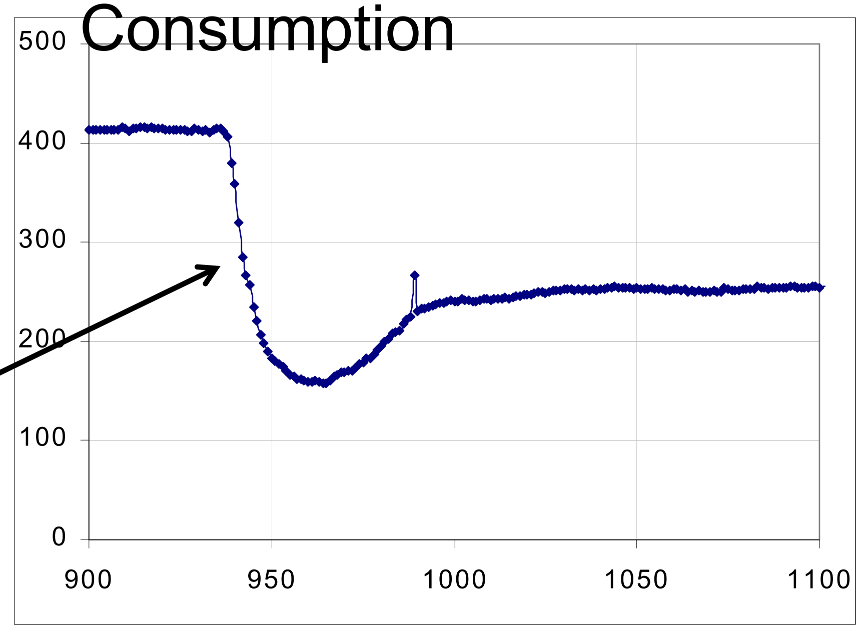
- **Reduces over-provisioning**

AHU Monitoring & Control

AHU Zones of Influence



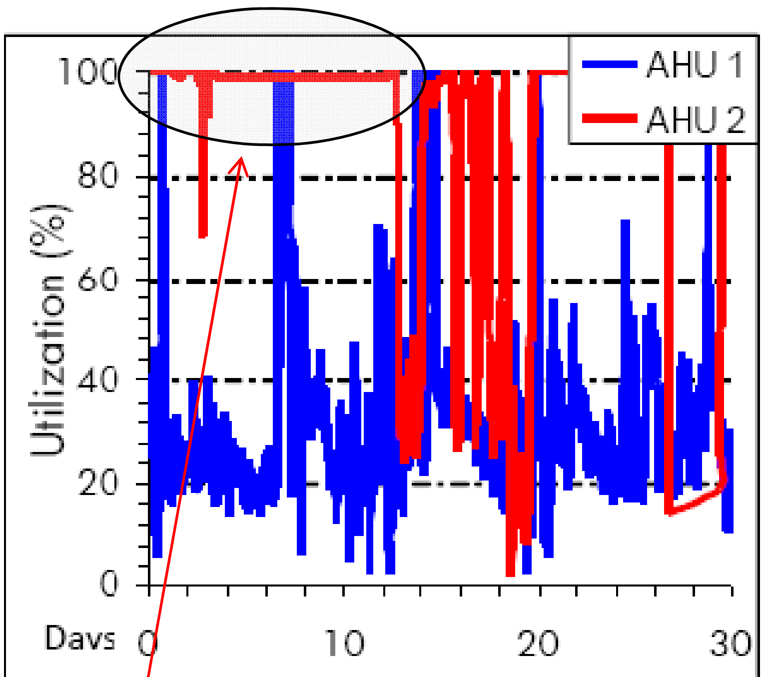
AHU Power Consumption



40% reduction in AHU power consumption

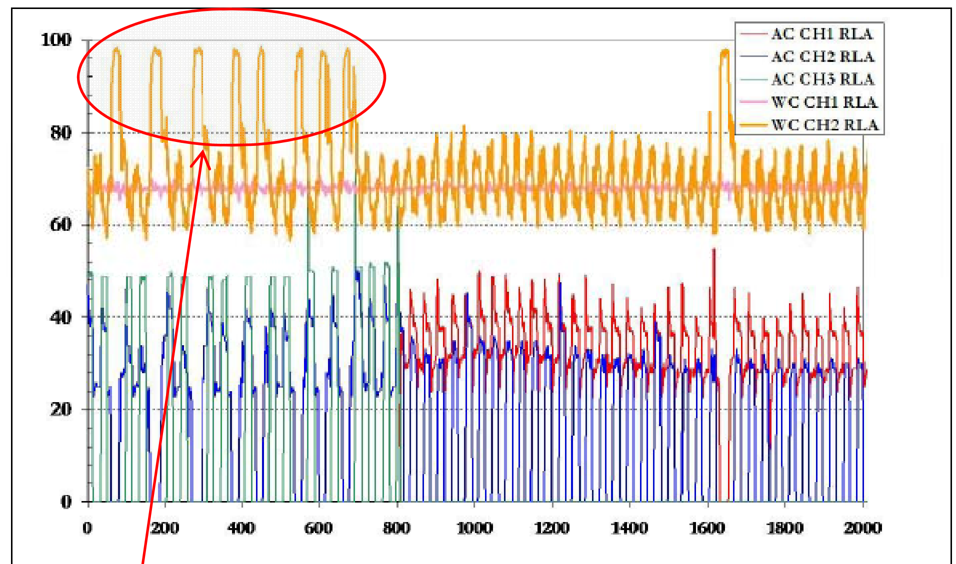
AHU & Chiller Monitoring & Control

Air Handler Chilled
Water Valve Utilization



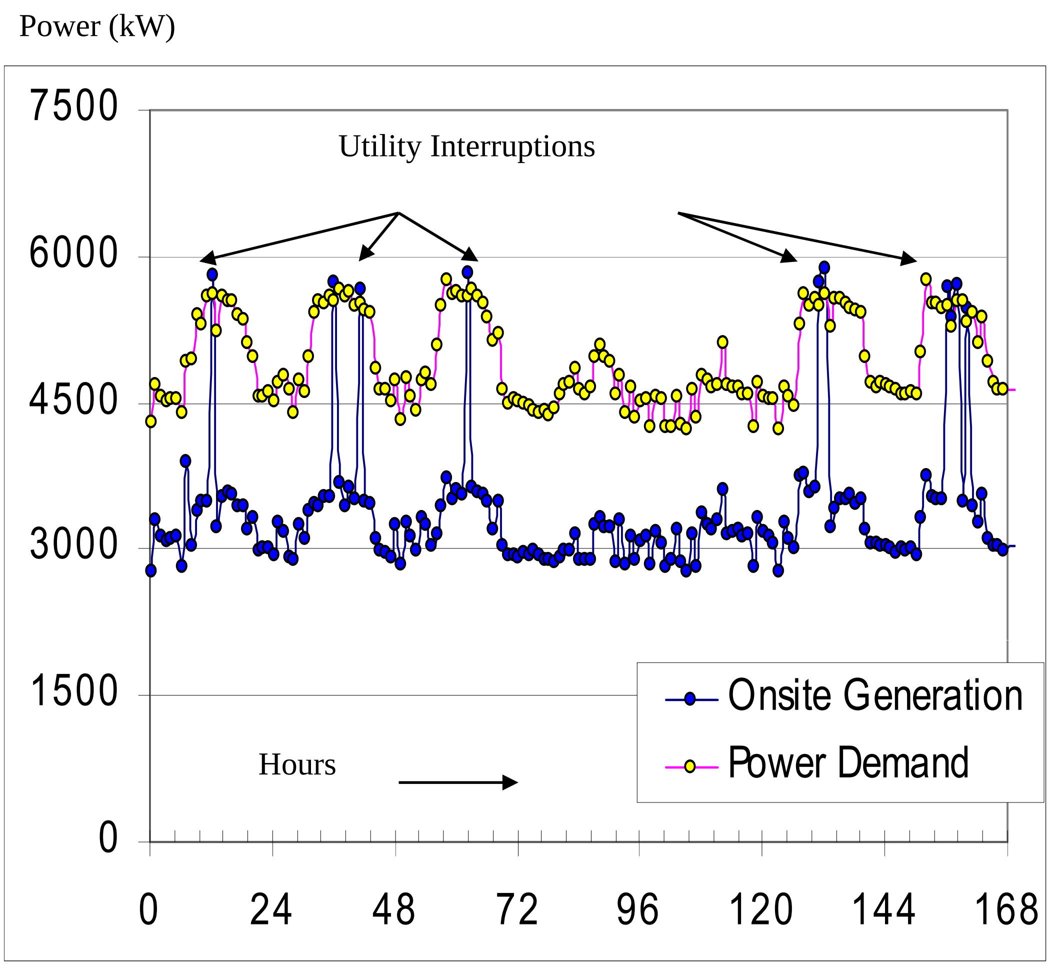
AHU 2 out of chilled water – jobs placed in alternate location

Chiller (5) Utilization



Damaging and energy inefficient chiller cycling monitored & controlled

Power Infrastructure



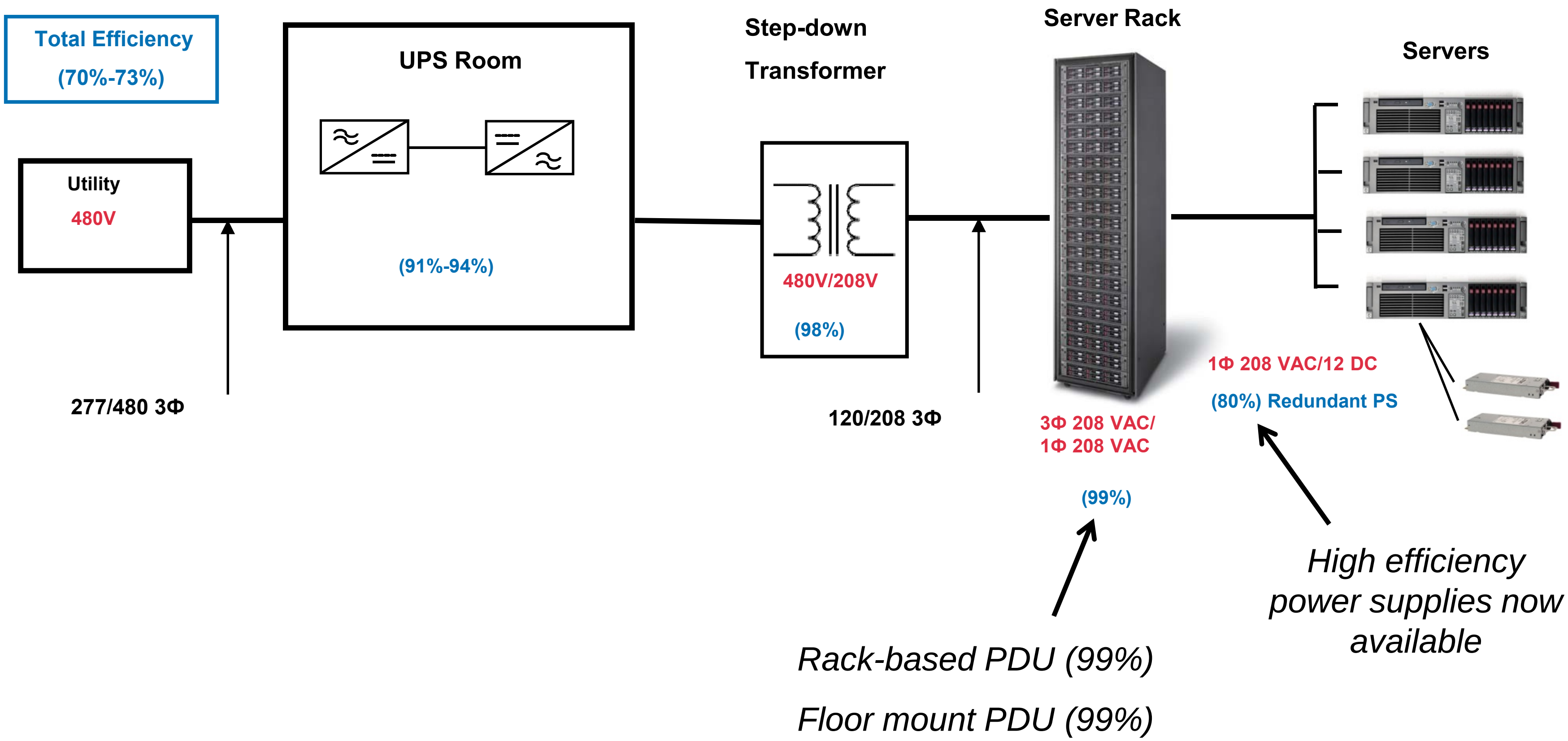
Monitoring and control enabled…

- Planning for utility outages
- Reliable operations & efficient failover
- Peak power shaving and optimal usage
- 20% reduction in facility power usage
- 30% reduction in diesel power consumption
- Mitigation of 7,500 tons of CO_2 annually

Failover performance is instructive for microgrid performance

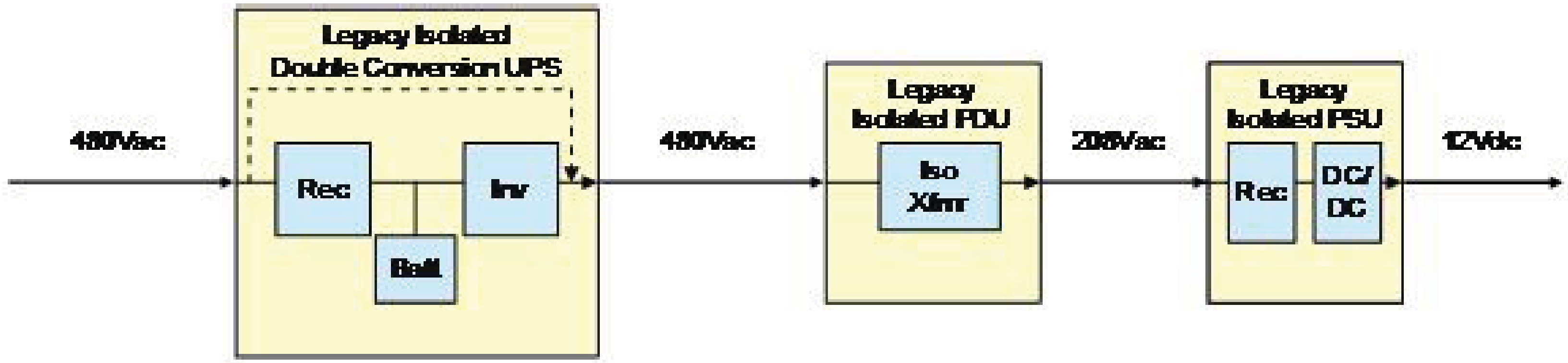
Power Distribution & Management

Data Center Power Distribution



Overall efficiency can be improved by…
- Proper selection and sizing of UPSs and server power supplies
- Reduction in the number of power conversion steps

Data Center Power Distribution - TGG



US scenarios studied by
The Green Grid…

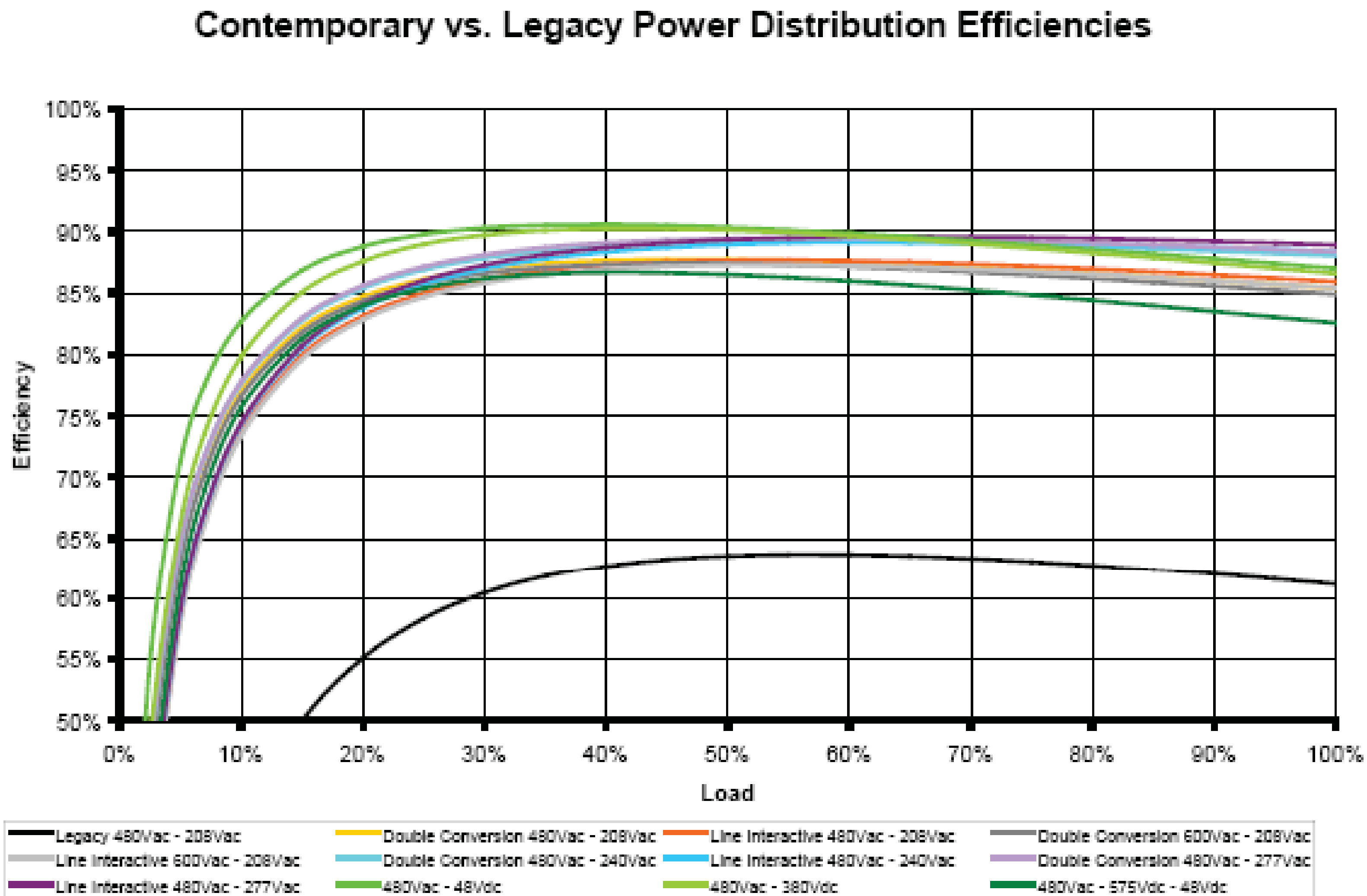
- 480 VAC – 208 VAC (legacy)
- 600 VAC – 208 VAC
- 480 VAC – 277 VAC
- 480 VAC – 240 VAC
- 480 VAC – 48 VDC
- 480 VAC – 575 VDC – 48 VDC
- 480 VAC – 380 VDC

Key findings…

- All optimized topologies show promise of 25% better efficiency than legacy systems (10 years old)
- Optimized DC is only 1 – 2% more efficient than optimized AC topologies

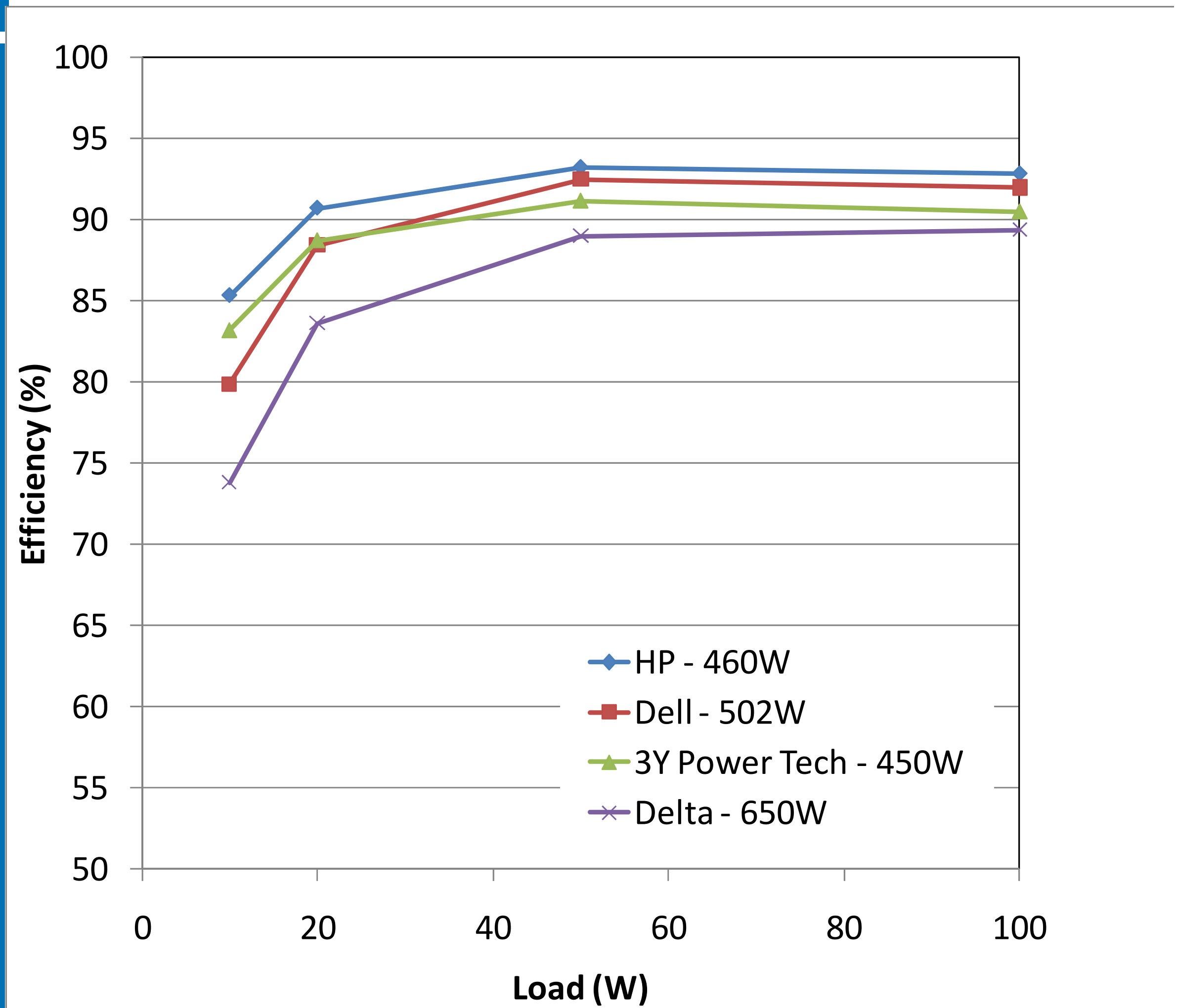
Source: The Green Grid, 2008, "Quantitative Efficiency Analysis of Power Distribution Configurations for Data Centers", White Paper 16 v1.0, (www.thegreengrid.org)

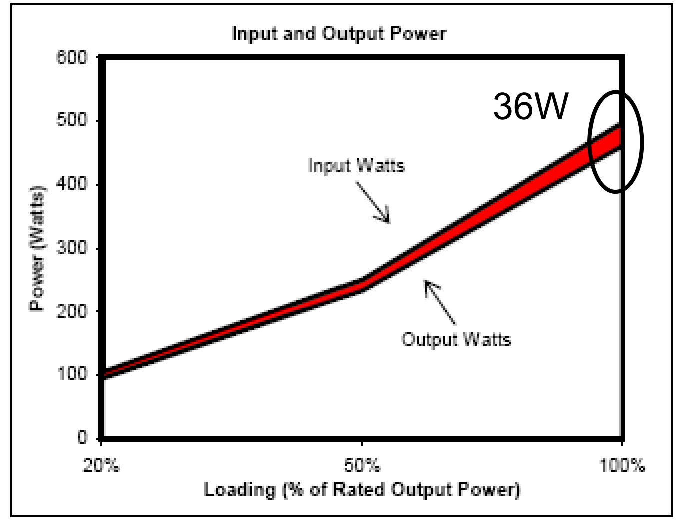
Data Center Power Distribution - TGG

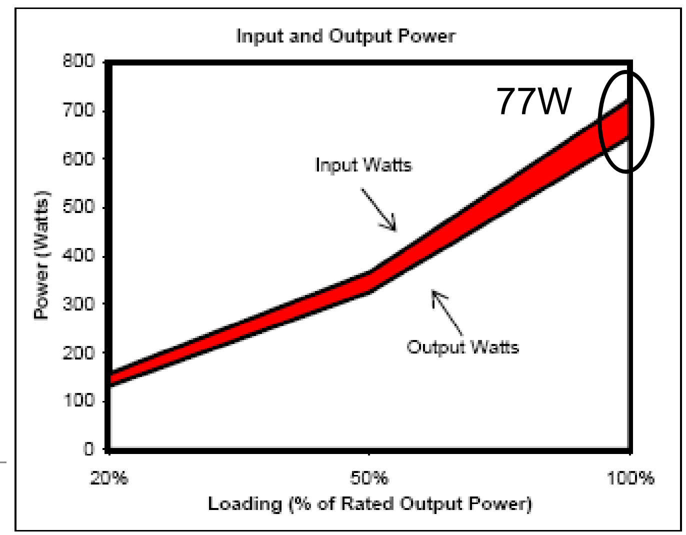


Source: The Green Grid, 2008, “Quantitative Efficiency Analysis of Power Distribution Configurations for Data Centers”, White Paper 16 v1.0, (www.thegreengrid.org)

Efficient Power Supplies



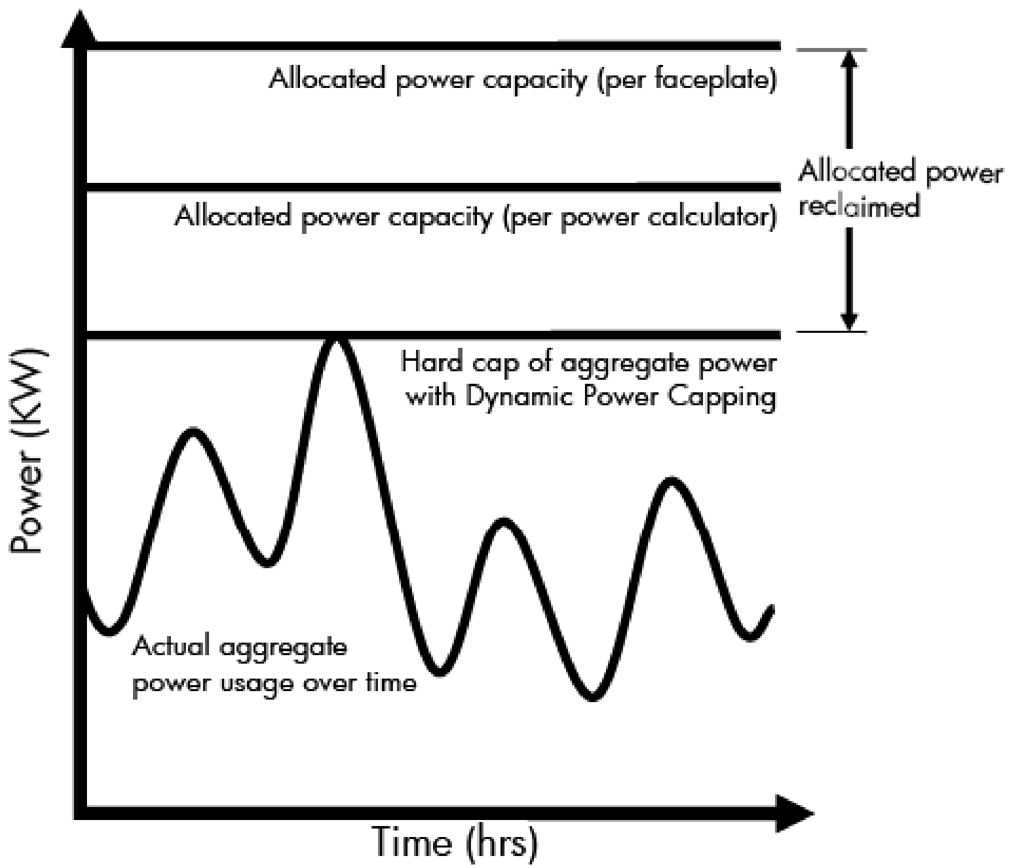




Source: 80Plus.org

Server Power Management

Dynamic Power Capping



- Supported on HP ProLiant and BladeSystem hardware
- Allows for capping at the server and blade chassis levels
- Frees up stranded power capacity
- Lowers facility TCO

Is Dynamic Power Capping of value to HPC?

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Cooling – Air

Air Requirements – HPC1 Cluster

The HPC1 Cluster will require…

- At least 2,841 cfm per compute rack
- 710,269 cfm for all compute racks only
- At least 2 grate tiles per rack (1,400 cfm per tile)
- 122 x 30 ton CRAHs
  - Not enough floor space for traditional floor mount CRAHs

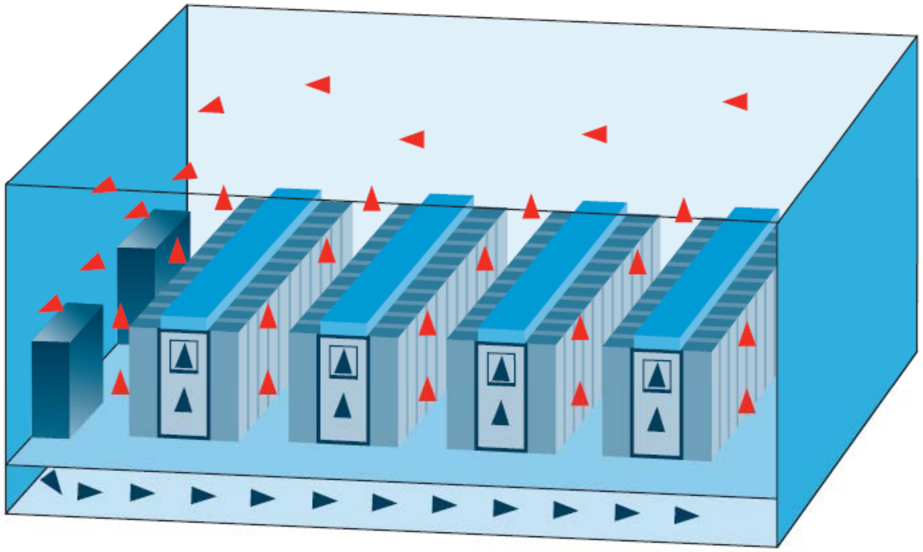
It will be extremely difficult to cool the cluster with traditional air-cooling approaches

Air-Cooling Industry Advances

Improvements to air-cooling are being achieved by…

- Reducing excess air supply and matching air supply to demand
- Preventing hot and cold air mixing via Cold Aisle Containment (CAC) and/or Hot Aisle Containment (HAC)
- Raising air supply temperature
- Raising chilled water supply temperature

Cold Aisle Containment (CAC)

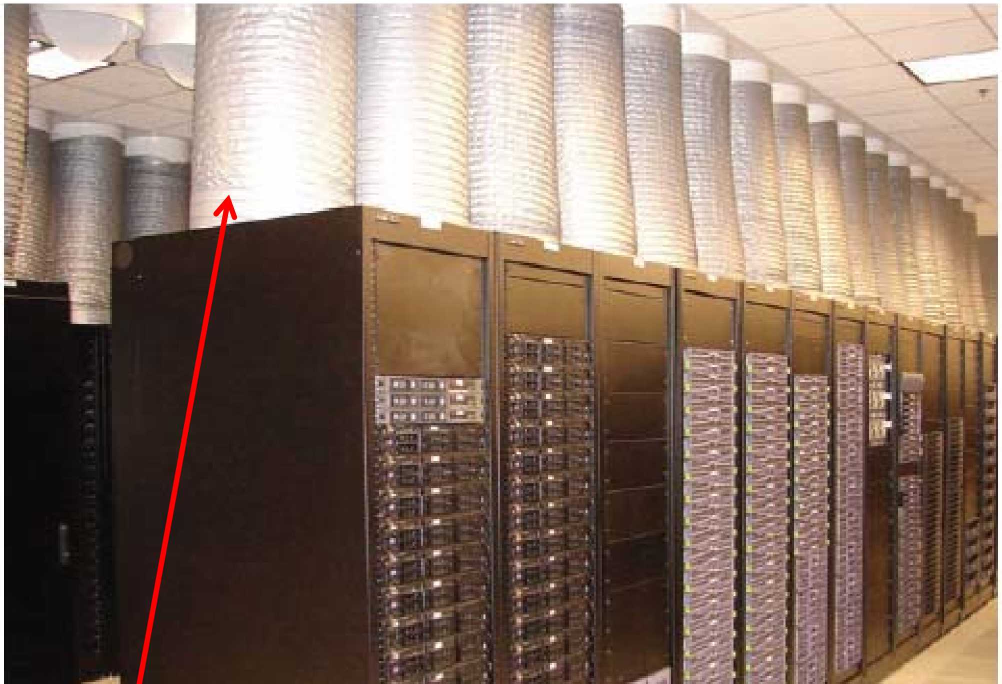


CAC study conducted by EDS, Rittal, and Liebert. CAC was compared to hot aisle/cold aisle performance.

CAC…

- Showed a 14 – 41% increase in energy efficiency
- Allowed the return air temp to rise from 20 to 30C, resulting in a 50% increase in CRAC capacity
- Allowed rack heat loads to increase from 3 kW to 20 kW
- Created a more uniform rack inlet air profile – vertical rack temp variation dropped from 20C to 1C

Hot Aisle Containment (HAC)



Exhaust ducts

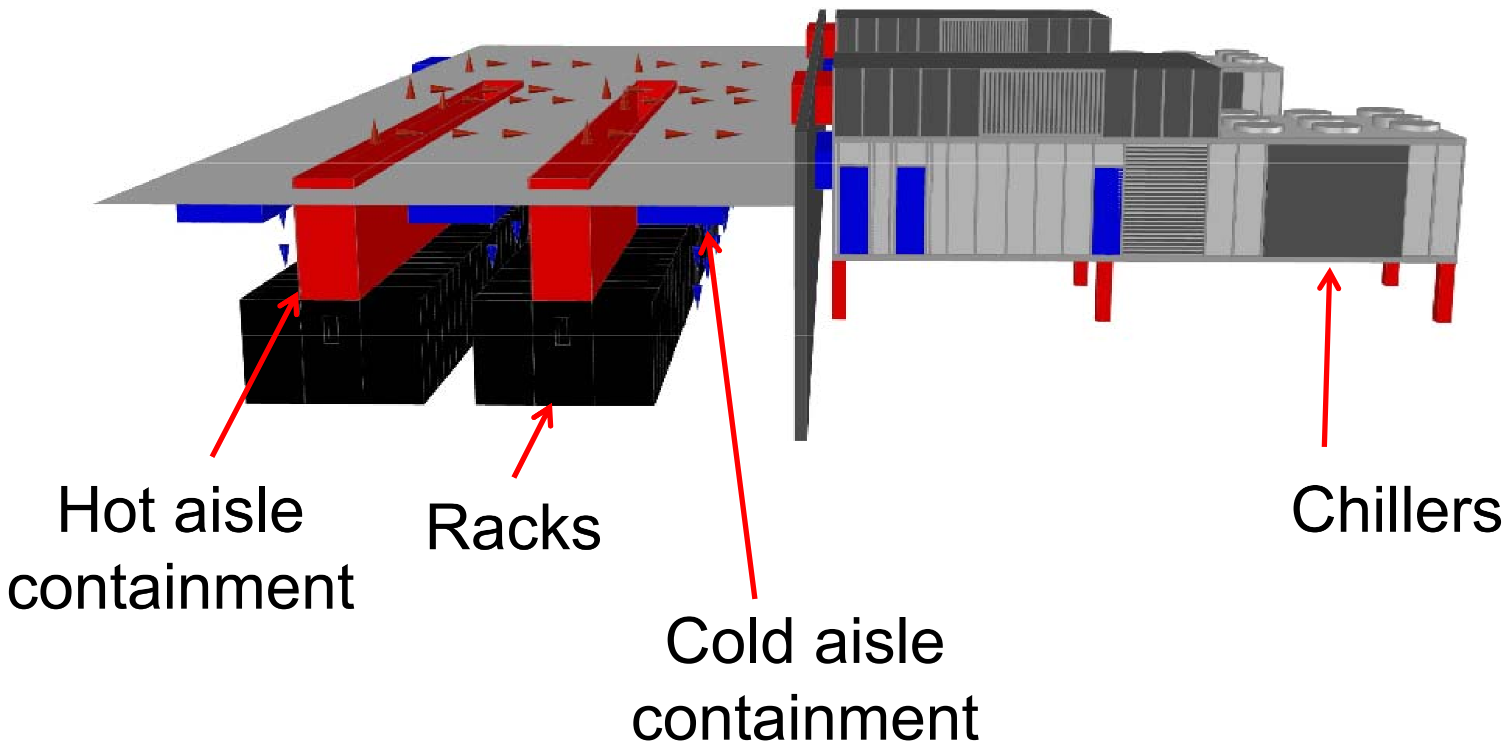
- Isolates the hot aisle
- Uses commercially available components
- Uses low power supplemental blower on exhaust side (68W)

Source: Martin et al., “High-Density Heat Containment”, ASHRAE Journal, Dec 2007.

Cold & Hot Aisle Containment

Switch Communications data center

See video at…http://www.switchnap.com/pages/video.php



Source: Switch Communications, www.switchnap.com

Cooling - Free Air Cooling for HPC?

ASHRAE TC9.9 Guidelines

ASHRAE TC9.9 issues guidelines for the environmental conditions for IT equipment.

2004	Temperature	Relative Humidity
Recommended	20 - 25 C	40% - 55%
Allowable	15 - 32 C	20% – 80% (17C DP)

2008 Revised	Temperature	Relative Humidity
Recommended	18 - 27 C	5.5C DP – 60% RH (15C DP)
Allowable	15 - 32 C	20% – 80% (17C DP)

No air quality guidelines provided

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HP ProLiant DL280c G6 Specs

System Inlet Temperature	Operating	10° to 35°C (50° to 95°F) at sea level with an altitude derating of 1.0°C per every 305 m (1.8°F per every 1000 ft) above sea level to a maximum of 3050 m (10,000 ft), no direct sustained sunlight. Maximum rate of change is 10°C/hr (18°F/hr). The upper limit may be limited by the type and number of options installed. System performance may be reduced if operating with a fan fault or above 30°C (86°F).
	Non-operating	-30° to 60°C (-22° to 140°F). Maximum rate of change is 20°C/hr (36°F/hr).
Relative Humidity (non-condensing)	Operating	10 to 85% relative humidity (Rh), 28°C (82.4°F) maximum wet bulb temperature, non-condensing.
	Non-operating	5 to 95% relative humidity (Rh), 38.7°C (101.7°F) maximum wet bulb temperature, non-condensing.

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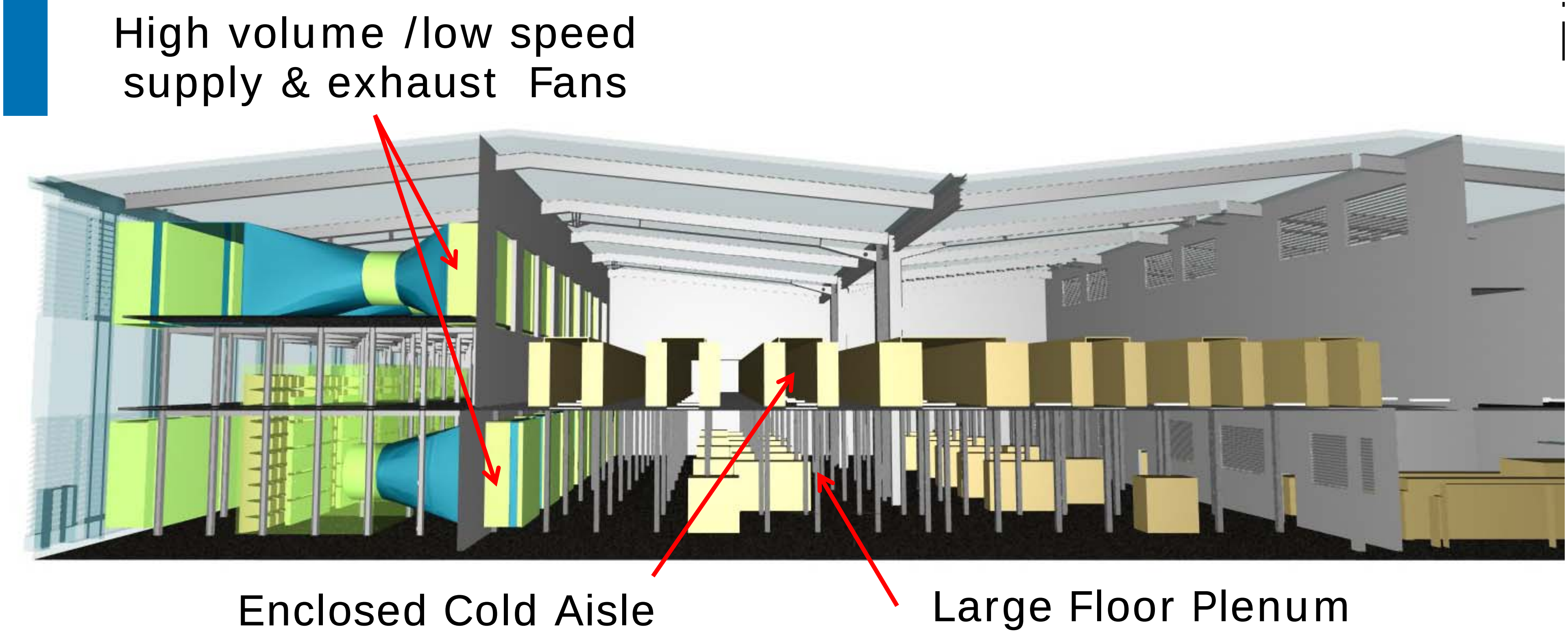
Free Air-Cooled Data Center



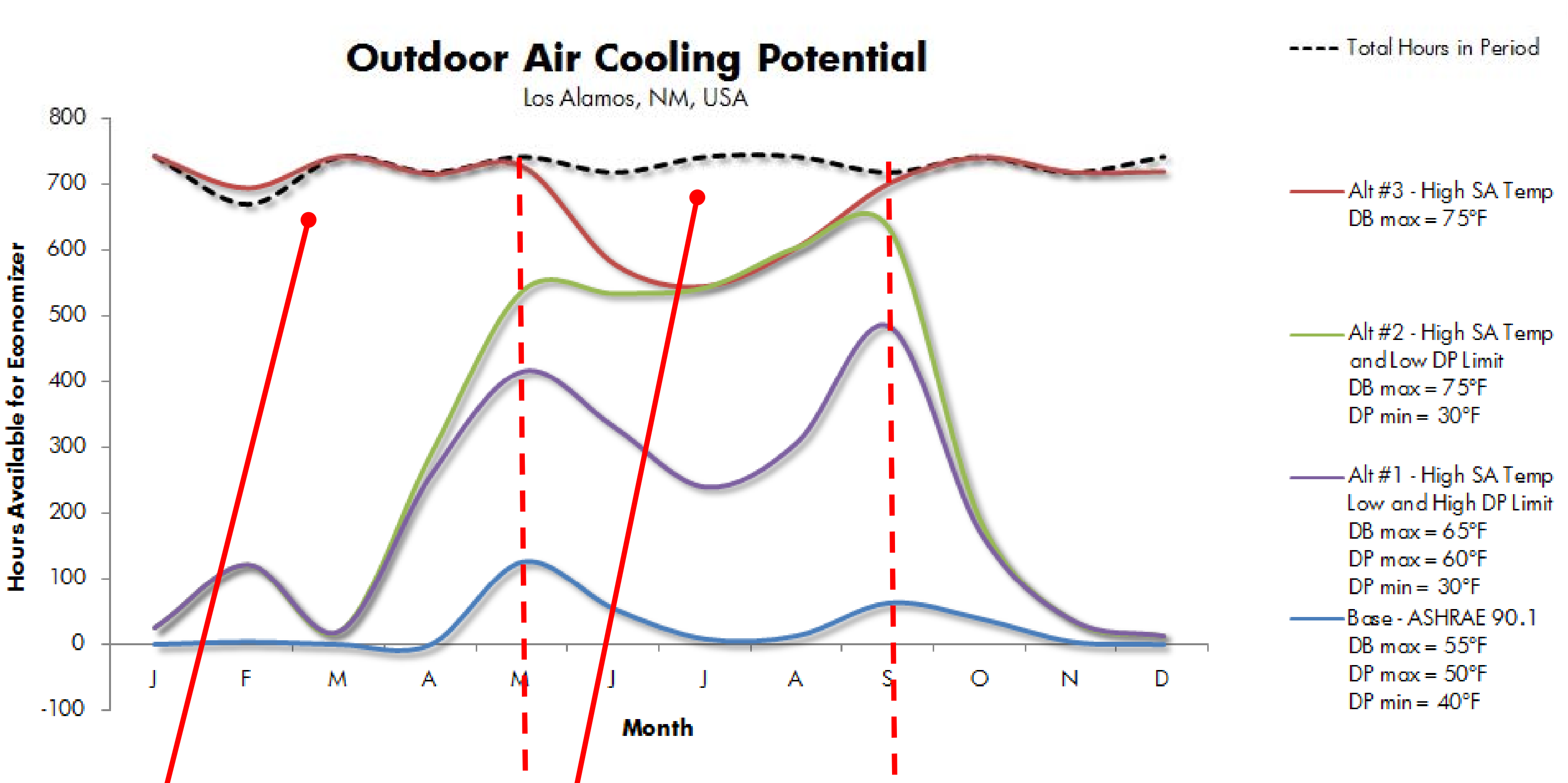
Data center run by EDS/HP

Free Air-Cooling Results

Data center uses…

•100% outside air for roughly 99% of the year
• Mixture of fresh and return air to maintain a supply air temp of 20C
• Pressurized spray system to humidify the air when necessary
• Mechanical cooling via packaged air-cooled chillers when necessary
• Full air re-circulation mode when outside air specs are not met
• Specialized filtration to minimize pressure drop

Free Air-Cooling – LANL?



Supplemental heating

Supplemental cooling

Cooling – Liquid

Liquid-Cooling…Standards?

The general status of liquid-cooling in the data center…

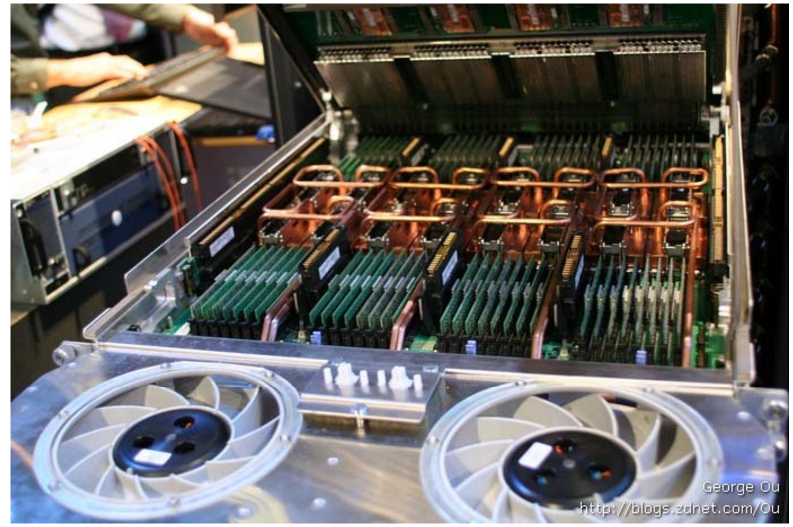
- No standards…yet
- No serious efforts towards developing a standard at this time
- Lots of publications and best practices
- Several commercial offerings – primarily liquid-cooled rack enclosures

<u>Some Resources:</u>

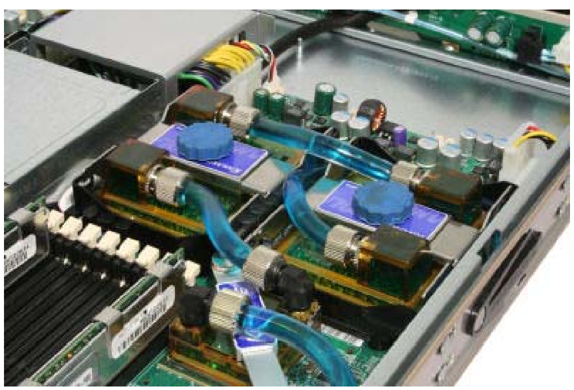
1. ASHRAE TC9.9, 2007, “Liquid-Cooling Guidelines for Datacom Equipment Centers”,
2. Salim, M., and Lui, Y., 2005, “Energy and Cost Analysis of Rittal Corporation Liquid Cooled Package”, Rittal Corporation white paper.
3. Beaty, D., and Schmidt, R., 2004, “Back to the Future: Liquid cooling Data Center Considerations”, ASHRAE Journal, pp. 42 – 46.
4. Sorell, V., and Rodgers, T., 2004, “Will Liquid Cooling Solutions Save Energy?”, Syska Hennessy Group White Paper #6 (www.syska.com)
5. Sorell, V., Cader, T., Westra, L., and Marquez, A., 2008, “Liquid-Cooling in Data Centers”, ASHRAE Winter Annual Meeting.

Liquid-Cooling – Device Level

PNNL's NW-ICE (dielectric)

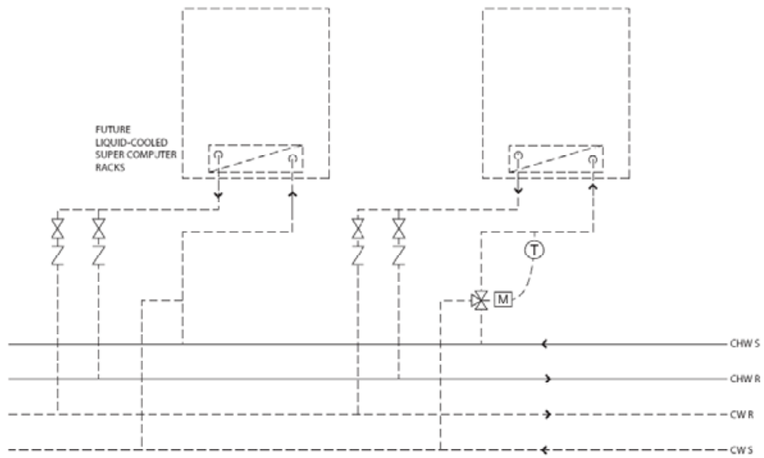


IBM p575 (water)
(http://blogs.zdnet.com/Ou/?p=861)

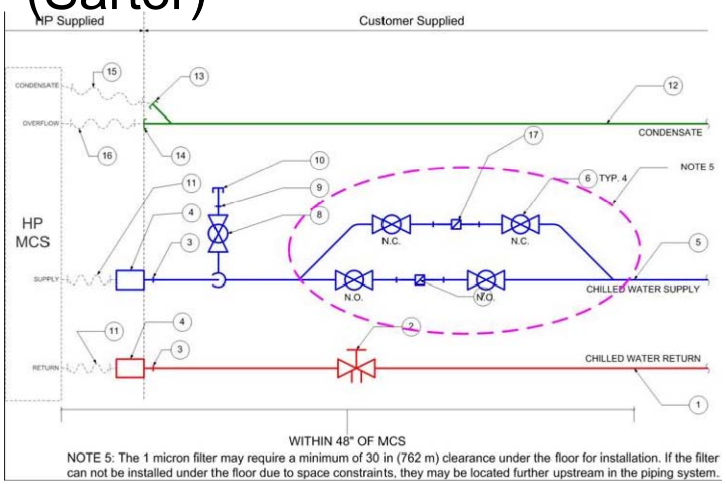


Boston (water)
http://www.boston.co.uk/news
_articles/newsletters/07-11/

Liquid-Cooling – Facility Preparation

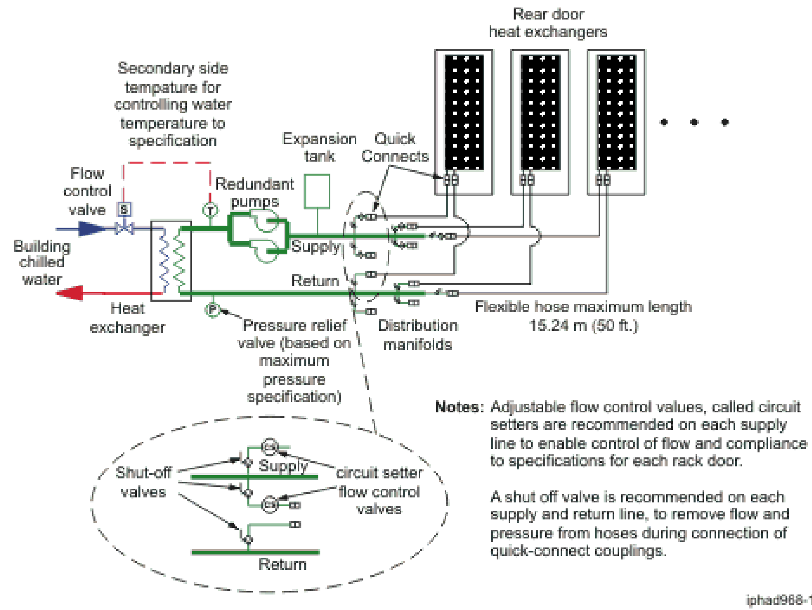


LBNL implementation (Sartor)



HP MCS Generation2

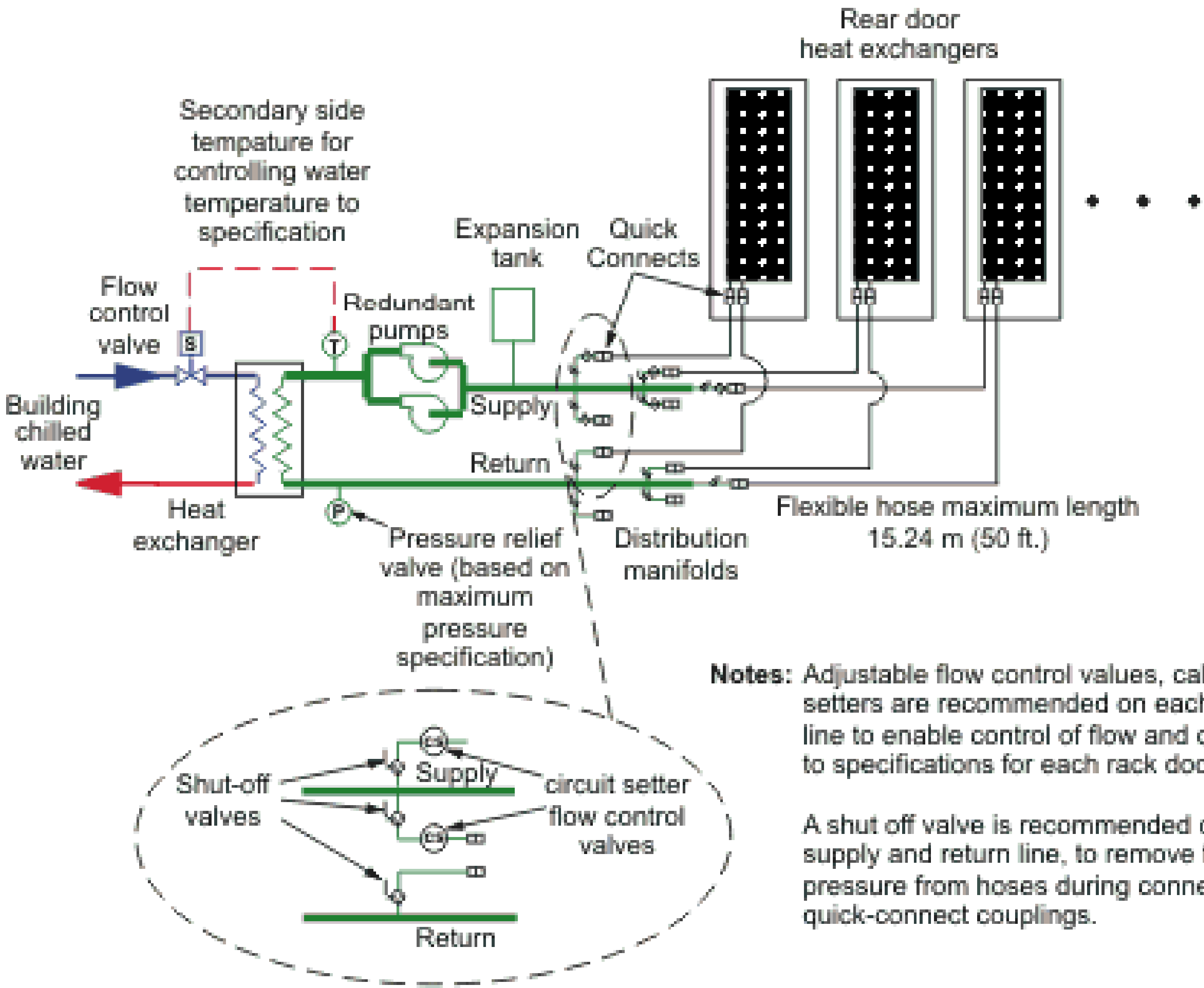
Implementation of rack plumbing



IBM Rear Door HX

Liquid-Cooling – Facility Preparation

IBM Rear Door HX



Notes: Adjustable flow control values, called circuit setters are recommended on each supply line to enable control of flow and compliance to specifications for each rack door.

A shut off valve is recommended on each supply and return line, to remove flow and pressure from hoses during connection of quick-connect couplings.

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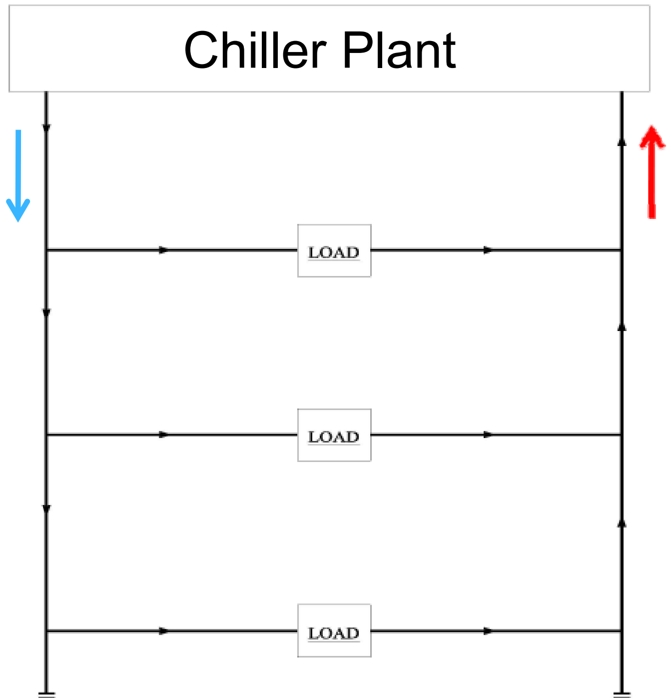
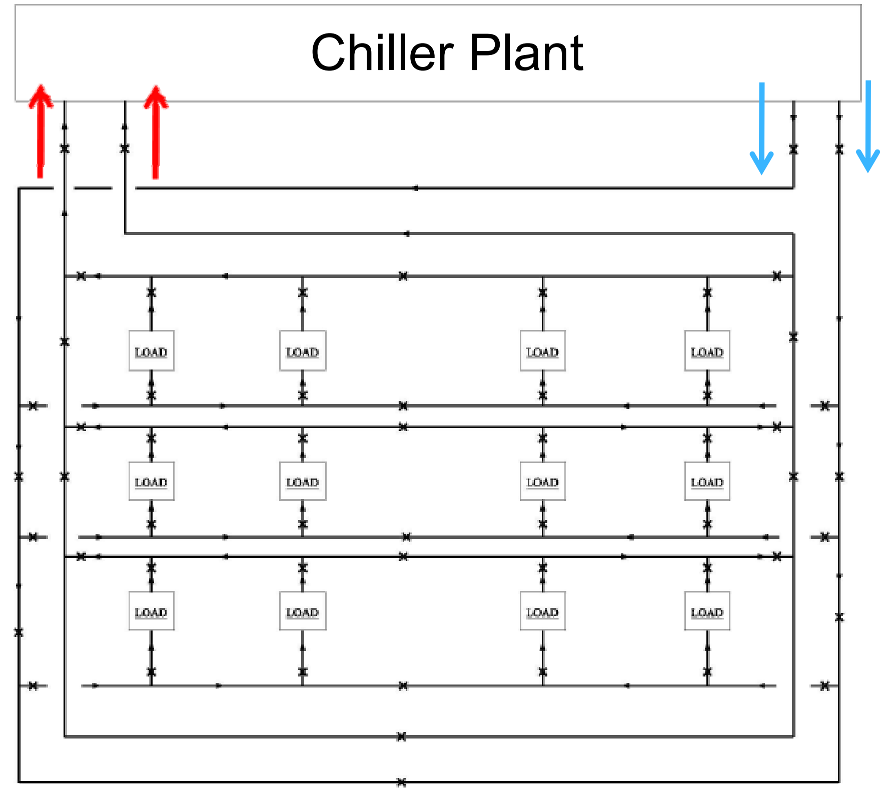
Liquid-Cooling – Facility Preparation

Floor level plumbing



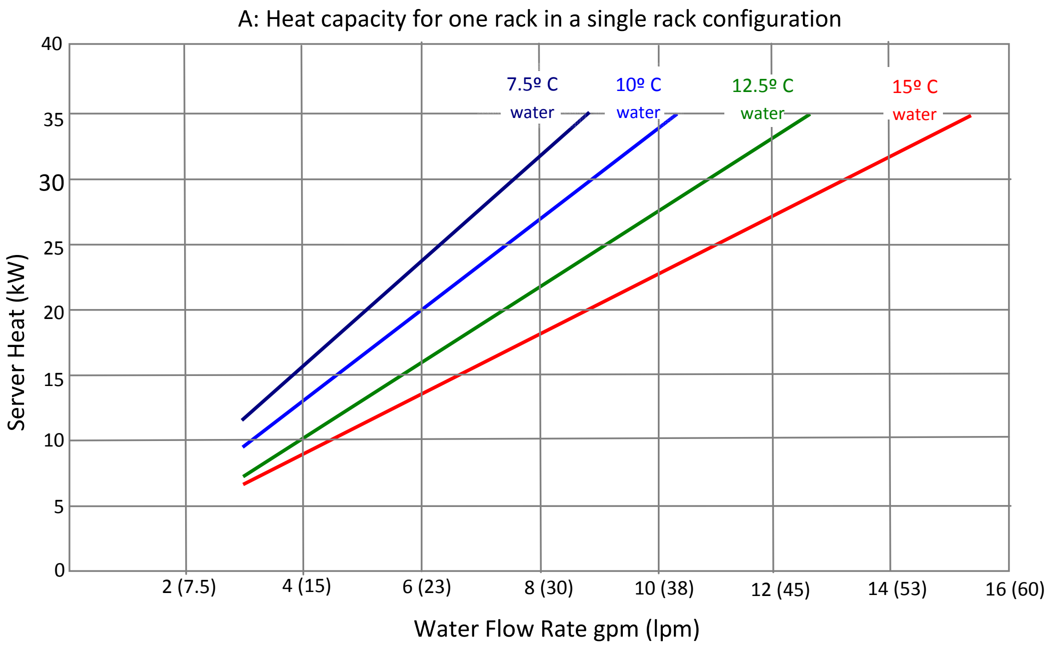
Direct Return
- Least expensive
- Lowest redundancy
- Lowest reliability

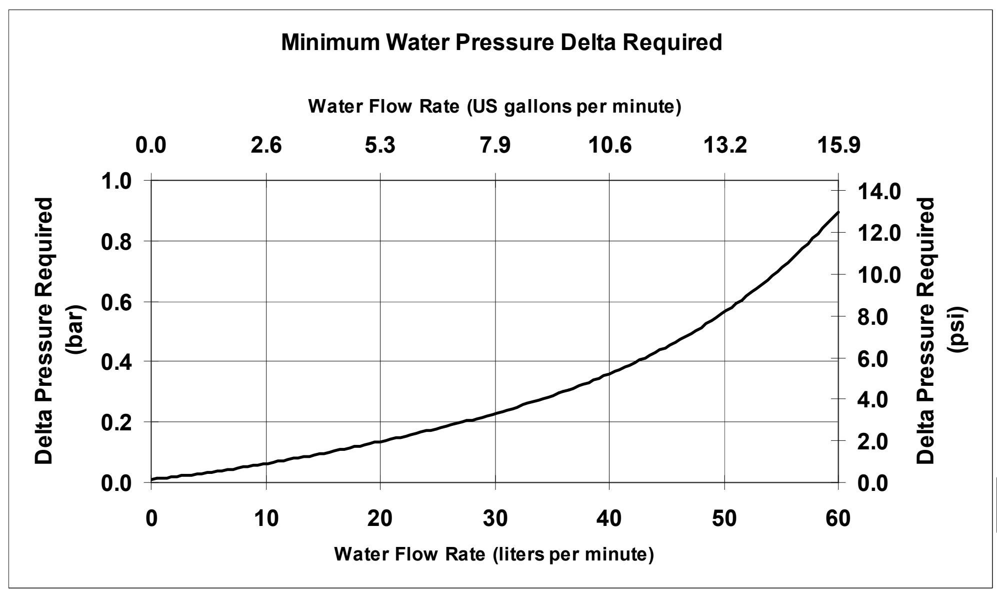
Source: **ASHRAE



Double-Ended Loop With Dedicated Cross Branches
- Most expensive
- Highest redundancy
- Highest reliability

HP MCS G2 Technical Performance





CONTAINERIZED DATA CENTERS FOR HPC?

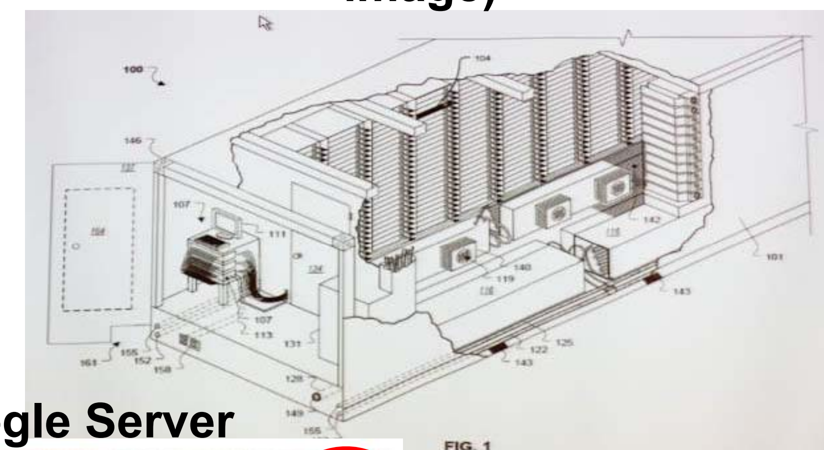
Containerized DCs

Features include…

- **Rapid deployment**
- **Ease of expansion**
- **Low footprint**
- **High energy efficiency…PUE < 1.2 reported**

Illustration Courtesy of Microsoft

Google Data Center (patent image)



Google Server

Off-the-shelf velcro

Server-based 12 VDC UPS

HP POD Key Features

Industry-standard Flexibility

22 x 50U, 19” full-depth industry-standard
racks support HP, Dell, IBM, Sun, Cisco, etc.

Best-in-class Density

Support for 3,520 compute nodes,
12,000 LFF drives

Integrated delivery and support services, WW

Pre-integrated, configured and tested, 6 weeks from order to shipping

High Energy Efficiency

PUE ratio as low as1.2, utilizing 65F chilled water temp, high efficiency power distribution technologies

invent

HP POD Performance

Results from HP POD commissioning tests…

- High density cooling capacity of 600 kW
- 27 kW+ per rack with 25C server inlet air
- Maximum of 22 racks per POD

Estimated compute capacity…

- 4 x BL2x220c chassis per rack, 32 servers per chassis
- 2 sockets per server, 2.5 GHz processor per socket, quad core
- 2.5GHz * 4 Flops/tick * 4 cores * 2 sockets = 80 GFlops/server
- 80 GFlops * 80 chassis * 32 servers/chassis = ~205 peak TFlops

Utilities required by the POD…

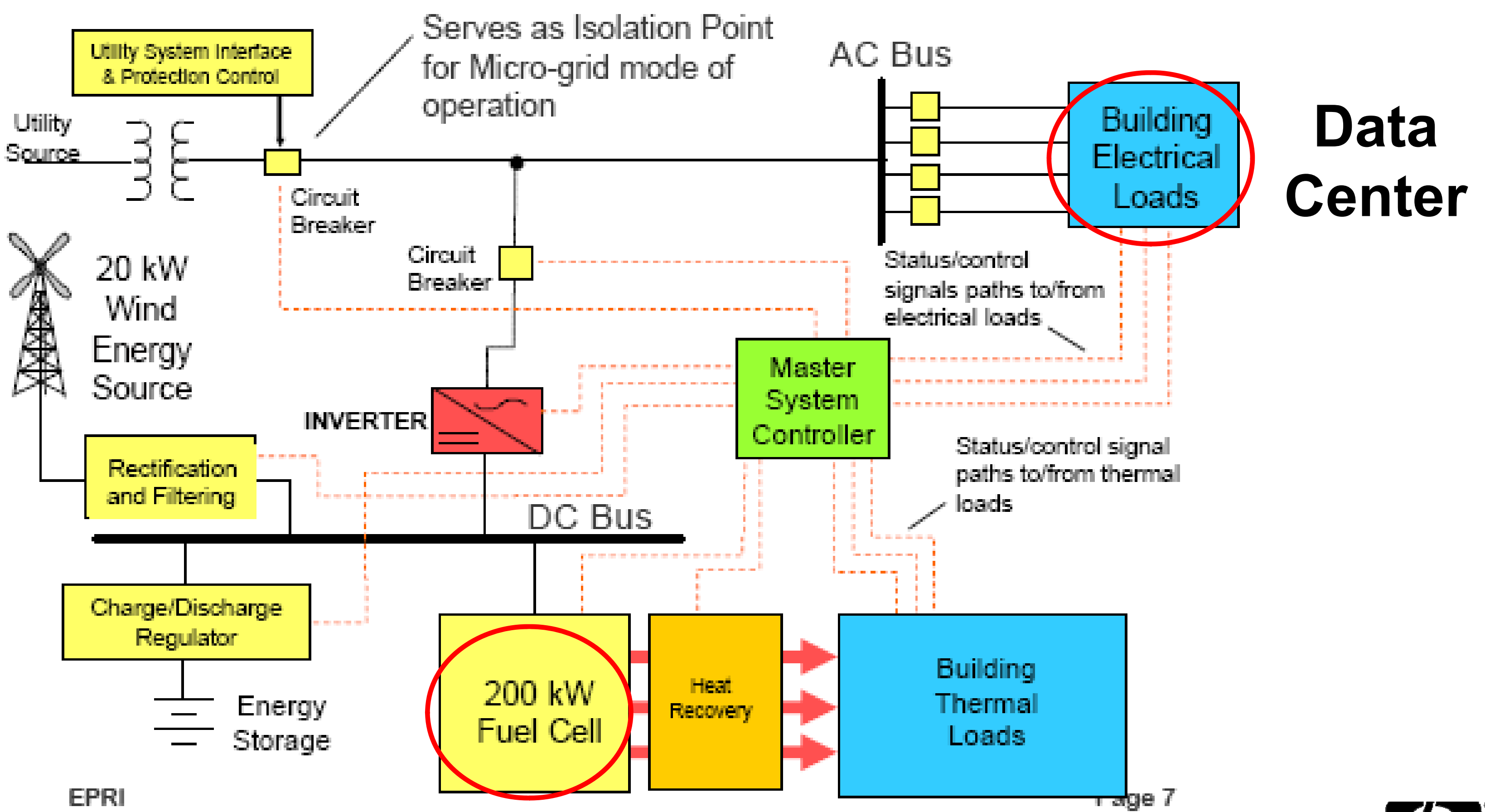
- Power, chilled water, network connection

Testing with higher performance CPUs to be undertaken

ON-SITE POWER GENERATION & MICROGRIDS

Microgrids

A Single Building Microgrid with Multiple Sources, Storage, and Heat Recovery



Fuel Cell with waste heat re-use

Combined Heat & Power in Data Centers

Facility Name	City	State	Prime Mover	Capacity (kW)	Op Year
Telecommunications Facility	Burlingame	CA	Microturbine	120	2003
Chevron Accounting Center	Concord	CA	Recip Engine	3,000	1988
Guaranty Savings Building	Fresno	CA	Fuel Cell	600	2004
Citibank West FSB Building	La Jolla	CA	Microturbine	60	2005
QUALCOMM, Inc.	San Diego	CA	Gas Turbine	11,450	1983/2006
WesCorp Federal Credit Union	San Dimas	CA	Microturbine	120	2003
ChevronTexaco Corporate Data Center	San Ramon	CA	Fuel Cell	200	2002
Network Appliance Data Center	Sunnyvale	CA	Recip Engine	825	2004
Flint Energies Service Center Facility	Warner Robins	GA	Fuel Cell	5	2002
Zoot Enterprises	Bozeman	MT	Recip Engine	500	2003
First National Bank of Omaha	Omaha	NE	Fuel Cell	800	1999
AT&T	Basking Ridge	NJ	Recip Engine	2,400	1995
Continental Insurance Data Center	Neptune	NJ	Recip Engine	450	1995
Verizon Communications	Garden City	NY	Fuel Cell	1,400	2005
Verizon	Ontario	CA	Microturbine	360	2007
Verizon	Pomona	CA	Microturbine	360	2007
Undisclosed End User	Undisclosed	NJ	Microturbine	840	2008
Computer Sciences Corporation	Newington	CT	Microturbine	1,170	2009

Source: “Opportunities for Combined Heat and Power in Data Centers”, ORNL Report, March 2009 (subcontract number 4000021512).

hp invent

CONCLUDING REMARKS

Concluding Remarks

1. The data center is evolving – owners/operators have to be ready for new implementations
2. There are significant short-term opportunities for raising energy efficiency as PetaScale Computing approaches the mainstream
3. Additional work is necessary to prepare for Exascale Computing
   - Power & Cooling Aware computing has to become mainstream
   - Job schedulers have to work in tandem with data center management systems
4. Energy cost management has to be part of everyday operations

BACK-UP SLIDES

End-to-End Approach

Design, Analysis
Modeling
Consulting
Delivery

Power Distribution & Management

Efficient distribution
UPS
PDU, PDR
Power supplies

Delivery

Servers, Storage, Networking, Software

Consumption

Management

iLO, OA
SIM, OV

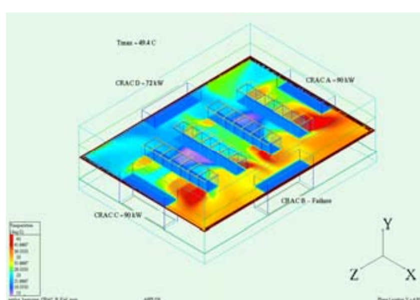
EDS an HP company

Integrity Servers
ProLiant Servers
Storage
Networks
Virtualization
Workload Mgmt

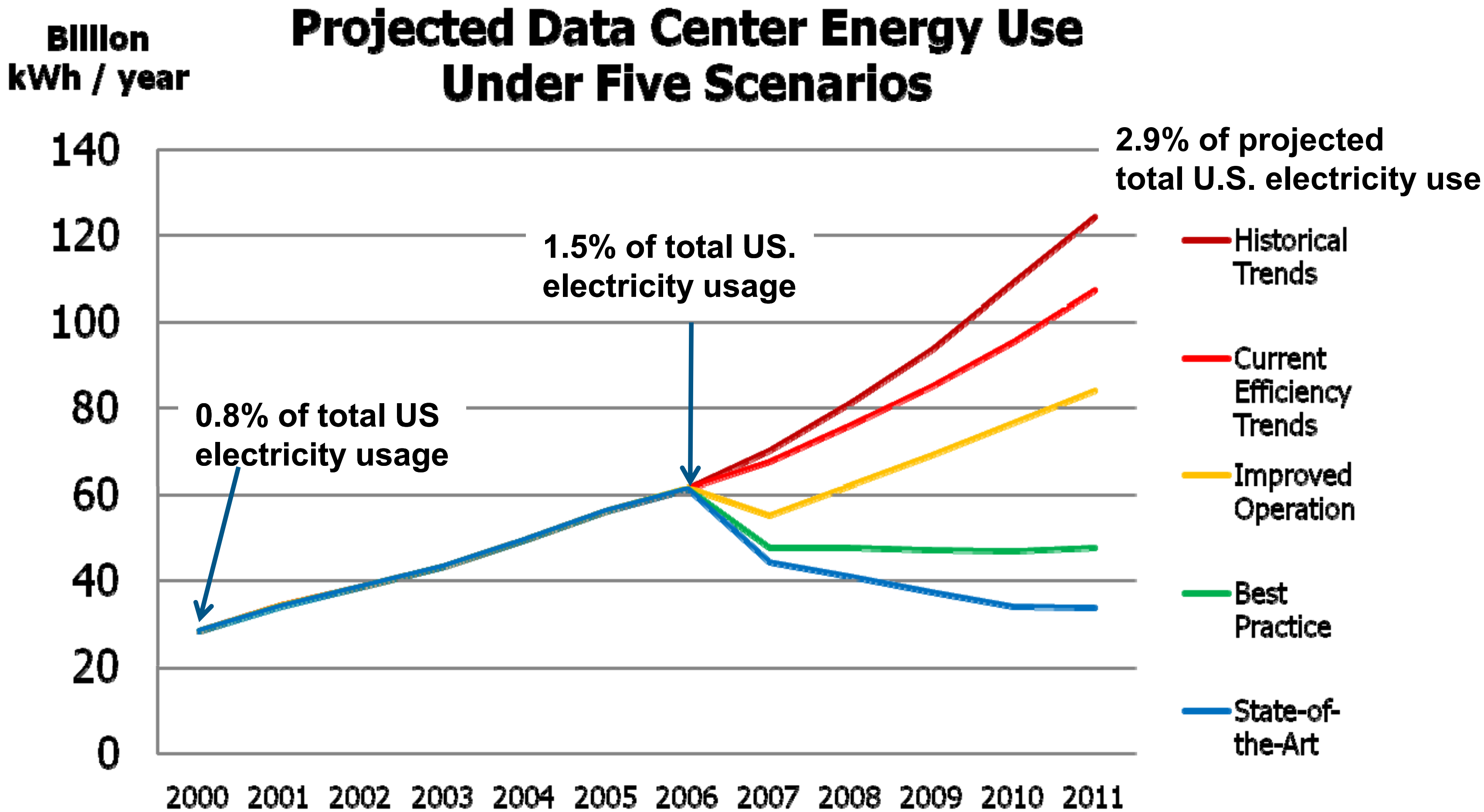
Extraction

Cooling Subsystems

Advanced Cooling Technologies

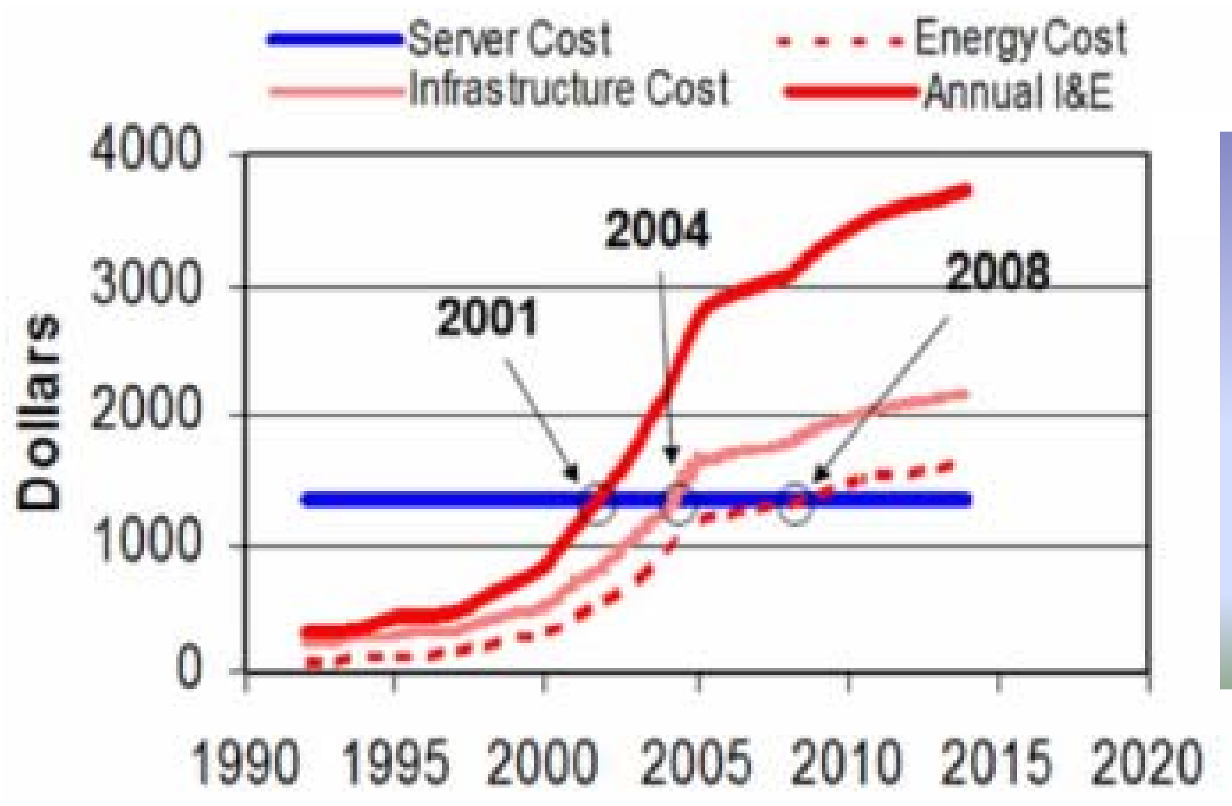


EPA and Energy Star



EPA Report to Congress on Server and Data Center Energy Efficiency; August 2, 2007

The Cost to Power & Cool a Server Has Exceeded the Cost of the Server…



•Annual Amortized Costs in the Data Center for a 1U Server

•(3 yr server life, 10 yr infrastructure life)

•HP has invested heavily to reduce customers' I&E costs

Source: Belady, C., 2007, "In the Data Center, Power and Cooling Costs More than IT Equipment it Supports", Electronics Cooling Magazine (Feb issue).

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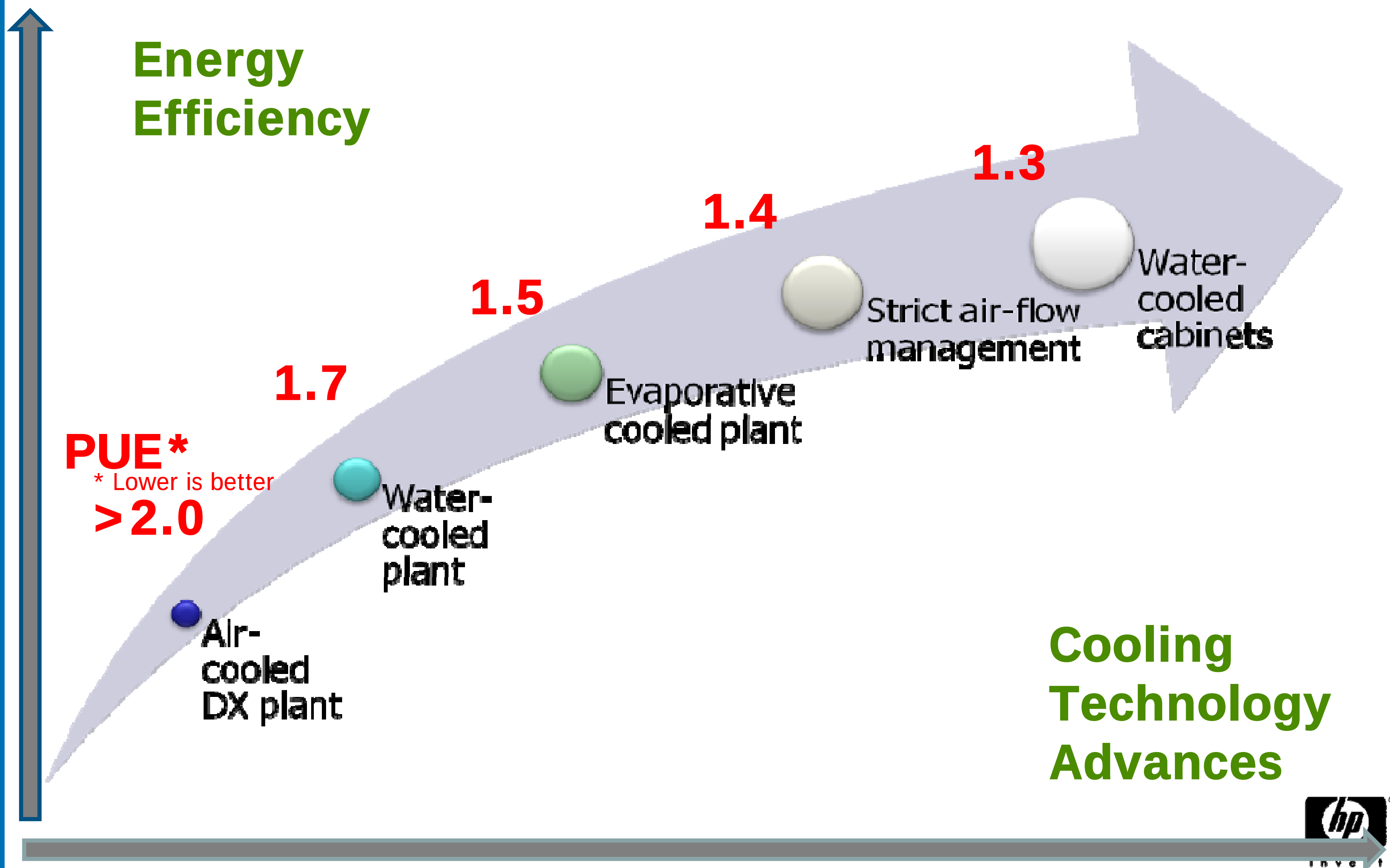
Designing for Cooling Efficiency



Rittal LCP – Total Cost of Ownership

Study:
Salim, M., and Lui, Y., 2005, “Energy and Cost Analysis of Rittal Corporation Liquid Cooled Package”, Rittal Corporation white paper.

Objective:
Compare the TCO of an air-cooled facility to that of a facility that deploys liquid-cooled racks

Key Findings:
For new data centers, LCP-based data centers…
- Have 15 – 30% lower construction costs
- Have 40 – 60% higher costs for the cooling equipment
- Can achieve 35 – 45% savings in required real estate (use fewer but higher density racks)
- Use 10 – 20% lower air blower power
- Use 12 – 14% less power for the chilled water plant

Rittal LCP – Total Cost of Ownership

DESIGN COMPARISON

		SCHEME 1A	SCHEME 1B	SCHEME 2A	SCHEME 2B
		Hot/Cold Aisle	Rittal LCP Rack	Hot/Cold Aisle	Rittal LCP Rack
Data Center Power Load	Total Power (KW)	470		2,160	
Physical Data	Length (Ft)	46	36	125	70
	Width (Ft)	46	38	80	78
	Area (Sqft)	2,116	1,368	10,000	5,460
	Average Area Loading (W / Sqft)	222	344	216	396
Computer Density	Number of Racks	56	30	405	144
	Average Rack Loading (KW / Rack)	8.39	15.67	5.33	15.00
Computer Cooling Requirements	Equipment Capacity (KW)	118	15	118	15
	Minimum Cooling Unit (Qty)	3.97	31.33	18.25	144.00
	Total Required Cooling Unit (Qty)*	4	32	19	144
	Redundancy	N+1	N+1	N+1	N+1
	Redundant Unit (Qty)	1	4	1	18
	Total Cooling Unit (Qty)	5	36	20	162

* 425 MBH (118 kW) cooling capacity chilled water unit with 15 hp blower motor.

INITIAL COST ANALYSIS

Criteria		SCHEME 1A	SCHEME 1B	SCHEME 2A	SCHEME 2B
		Hot/Cold Aisle	Rittal LCP Rack	Hot/Cold Aisle	Rittal LCP Rack
Construction Cost	Construction	$317,400.00	$205,200.00	$1,500,000.00	$819,000.00
	Raised Floor Construction	$31,740.00	$16,416.00	$150,000.00	$65,520.00
	Drop ceiling cost (plenum)	$11,638.00	-	$55,000.00	-
	Drop ceiling return grills	$250.00	-	$1,250.00	-
	Perforated tile cost	$3,200.00	-	$12,000.00	-
	Mechanical Construction	$98,091.00	$173,632.00	$310,000.00	$610,585.00
	Electrical wiring	7,100	19,900	18,500	84,000
	Total Construction Cost	469,419	415,148	2,046,750	1,579,105
Cooling Equipment cost	CRAH	100,000	-	400,000	-
	CRAH Installation	50,000	-	200,000	-
	LCP Cabinet cost	-	360,000	-	1,728,000
	LCP cabinet installation	-	15,000	-	72,000
	CDU	-	not required		not required
	CDU installation	-	not required	-	not required
	cabinet/rack cost	61,600	-	445,500	-
	cabinet/rack installation	28,000	-	202,500	-
	Total Cooling Equipment Cost	239,600.00	375,000.00	1,248,000.00	1,800,000.00
	Total Initial Cost	709,019.00	790,148.00	3,294,750.00	3,379,105.00

Salim, M., and Lui, Y., 2005, “Energy and Cost Analysis of Rittal Corporation Liquid Cooled Package”, Rittal Corporation white paper.

Rittal LCP – Total Cost of Ownership

ENERGY ANALYSIS - UNIT, ENVELOPE & LIGHTS

		SCHEME 1A	SCHEME 1B	SCHEME 2A	SCHEME 2B
		Hot/cold Aisle	Rittal LCP Rack	Hot/Cold Aisle	Rittal LCP Rack
Unit Fan Power Consumption	Unit Fan Power Consumption (KW)	11	1.2	11	1.2
	Total Cooling Unit (Qty)	5	36	20	162
	Total Fan Power consumption (KW)	56	43	224	194
Fan Energy Use	Per year (KWHr/Year)	489,924.90	378,432.00	1,959,699.60	1,702,944.00
Fan Energy Cost	Per year ($/Year)	$48,992.49	$37,843.20	$195,969.96	$170,294.40
Fan Energy Saving	Per year ($/Year)	$11,149.29		$25,675.56	
Lighting Power Consumption	1.8 KW/sqft (KW)	3830.0	2478.1	18100.0	9882.6
Lighting Energy Use	Per year (KWHr/Year)	33550.4	21690.5	158556.0	86571.6
Lighting Energy Cost	Per year ($/Year)	$3,355.04	$2,169.05	$15,855.60	$8,657.16
Lighting Energy Saving	Per year ($/Year)	$1,186.00		$7,198.44	

ENERGY ANALYSIS - CENTRAL PLANT

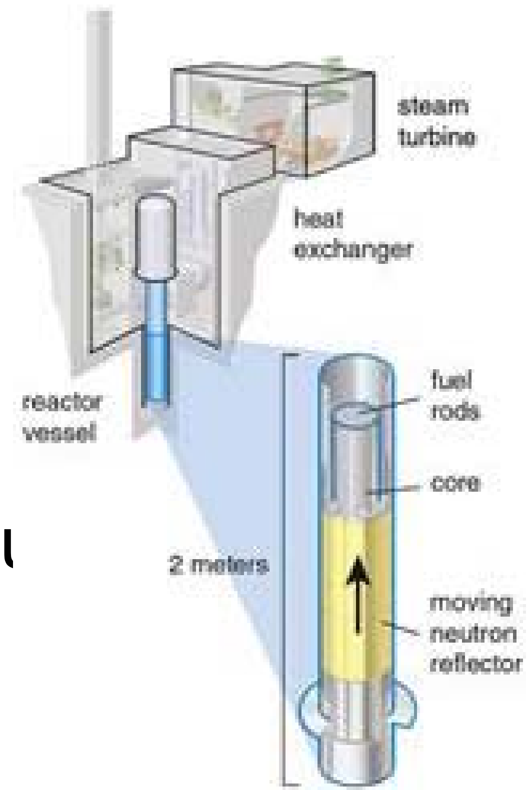
		SCHEME 1A	SCHEME 1B	SCHEME 2A	SCHEME 2B
		Hot/Cold Aisle	Rittal LCP Rack	Hot/Cold Aisle	Rittal LCP Rack
Data Center Power Load	Tower Power (KW)	470		2,160	
Unit Flow Rate	Flow Rate (GPM)	79.0	11.0	79.0	9.8
	Total Cooling Unit (Qty)	5	36	20	162
	Total Chilled Water Plant Flow Rate (GPM)	395.0	395.0	1,580.0	1,580.0
Chilled Water	Entering Chilled Water Temperature (Deg F)	48.0	56.3	48.0	55.4
	Entering Chilled Water Temperature (Deg K)	282.0	286.7	282.0	286.1
	Differential Chilled Water Temperature (Deg K)	4.6		4.1	
Center Plant Power	Excellent (KW)	141.0	121.3	648.0	568.3
	Average (KW)	258.5	222.4	1,188.0	1,041.9
	Poor (KW)	611.0	525.8	2,808.0	2,462.6
Center Plant Energy Use	Excellent (KWHr/Year)	1,235,160.0	1,062,855.2	5,676,480.0	4,978,273.0
	Average (KWHr/Year)	2,264,460.0	1,948,567.8	10,406,880.0	9,126,833.8
	Poor (KWHr/Year)	5,352,360.0	4,605,705.8	24,598,080.0	21,572,516.2
Center Plant Energy Cost	Excellent ($/Year)	$123,516.00	$106,285.52	$567,648.00	$497,827.30
	Average ($/Year)	$226,446.00	$194,856.78	$1,040,688.00	$912,683.38
	Poor ($/Year)	$535,236.00	$460,570.58	$2,459,808.00	$2,157,251.62
Center Plant Energy Saving	Excellent ($/Year)	$17,230.48		$69,820.70	
	Average ($/Year)	$31,589.22		$128,004.62	
	Poor ($/Year)	$74,665.42		$302,556.38	

Salim, M., and Lui, Y., 2005, "Energy and Cost Analysis of Rittal Corporation Liquid Cooled Package", Rittal Corporation white paper.

Your own nuke?

- Toshiba 4S
  - Super-Safe
  - Small
  - Simple
- 10 MW for 30 years
- Installed in cylindrical concrete vau
- 30 meters underground
- Not cheap, but maybe cheaper

1. than a diesel generator



Source: M. Ryan, "A Nuke on the Yukon", *American Scientist*, **97**(2), 112-113, (March-April 2009) doi:10.1511/2009.77.112