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HIGH HEAT DENSITY SINGLE- AND TWO-PHASE COOLING OF DATA CENTERS

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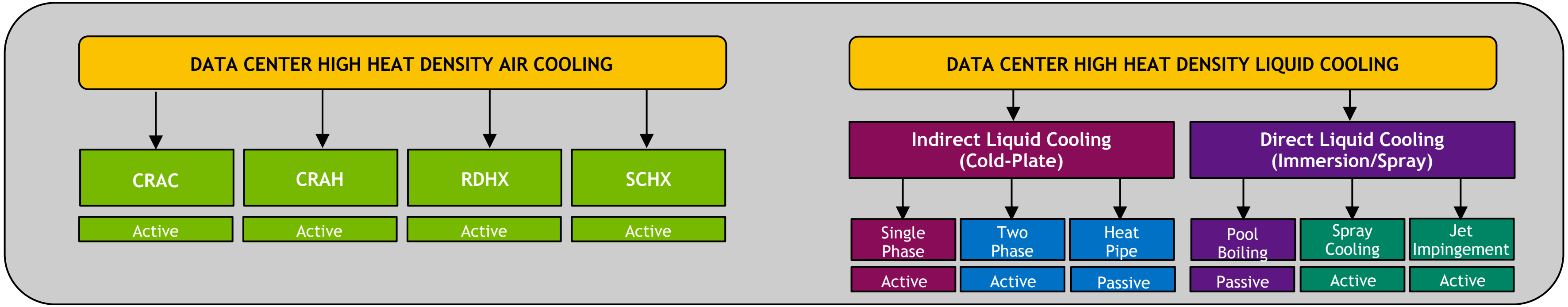
DATA CENTER COOLING CLASSIFICATIONS

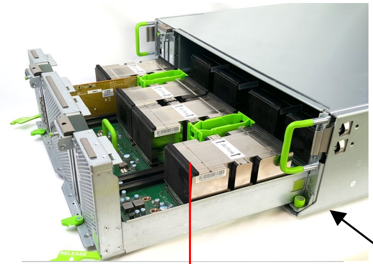


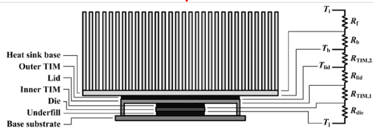
Cooling Classification	Air	Cold Plate Single-Phase	Cold Plate 2-Phase	Immersion	Spray/Jet Cooling
Cooling Method	Data Center Air Conditioners, Water/Refrigerant to Air Heat Exchangers	Water (treated), Water w/Propylene Glycol	Refrigerant: R134a, R515B, R1233zd, Engineered Fluids (3M Novec, HFE-7000)	Dielectric Fluids (Engineered), Dielectric Fluid (Oils) Refrigerants (R134a, Others)	Fluorinates (FC-75) Water
Examples	General compute, Hyperscale	Supercomputers, HPC, DGX Station, Gaming PCs	HPC, Multi-Node AI, DGX Station, Telecom/Edge	Mining, HPC, Intense Sustained Workloads	HPC 150W up to 1000W Electric vehicles
Advantages	Commonly Available	Proven Mainframe/HPC applications, Water system exist at data centers, Low pPUE vs. air cooling	Telecom Standards Alignment, 2-Phase more efficient than Water, Non-Conductive	No Cold Plates, 2-Phase, Inexpensive Oils	Higher HTC, wormer coolant, Reduced TCO, Eliminate hotspot
Issues	Upward Scale Limitations, Cooling Constrained, Noise	1-Phase Only, Electrically Conductive, Primary & Secondary Water Treatment	High Pressure, Flow distribution, Not Commonly used in Data Centers	Oils Combustible, Material Compatibility, Serviceability, Flammability	Higher cost, complexity, high pressure drop, clogging probability
Cooling Scale (bounding approximations)	Air: ~60kW/Rack	PG25: ~110kW/Rack	R134a: ~175kW/Rack	Pool Boiling (FC-72): max 3 W/cm^2K Spray Boiling (R134a): max 9 W/cm^2K Jet Impingement (R134a): max 10 W/cm^2K	Spray cooling(water): max 50 W/cm2 K Water multi-jet cooling: max 100 W/cm^2K

AIR COOLING DESIGN

Server Thermal Design

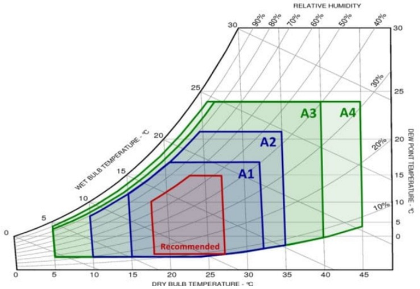
Air Cooled Server Design





- Heat Sink
- Heat Pipe
- Vapor Chamber
- Fan Speed Control (IT Equipment)
- Fan Wall For Rack

Data Center Engineering



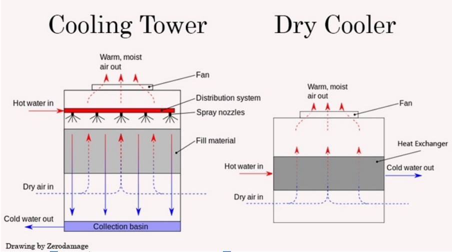
- Fan Wall For Rack
- Air
- Rack
- Raised/Non-raised floor
- Cold/ Hot Aisle
- Perforated Tiles
- MERV Filters
- Air Flow Management
- Air
- RDHX/ L2AHX
- Air

Chilled water System

Data Center Facility

Heat Recovery Systems
- Radiant Heating
- Under-Floor Heating
- Absorption Chillers

Classes	Typical Infrastructure Design		Facility Supply Water Temp (°C)	IT Equipment Availability
	Primary Facilities	Secondary/Supplemental Facilities		
W17	Chiller/Cooling Tower	Water-Side Economizer (Cooling Tower)	2-17	Now available
W27			2-27	
W32	Cooling Tower	Chiller or District Heating System	2-32	Not Generally Available, Dependent on Future Demand
W40			2-40	
W45	Cooling Tower	District Heating System	2-45	Not Generally Available, Dependent on Future Demand
W+			>45	Specialized Systems



ASHRAE W45

Air-side Economizer & IDEC

- Over Head Cooling Unit (OCU)
- CRAC/CRAH
- In-Row HX
- Side Cooling HX

ASHRAE W+ (> 45 °C)

Water-side Economizer

Condenser water System

Chillers

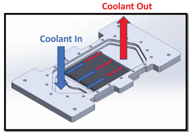
Air Cooled | Water Cooled

ASHRAE W17-W32

Chilled water System

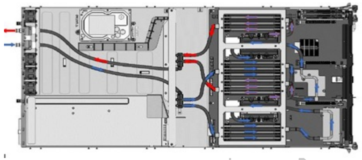
HYBRID LIQUID-TO-AIR COOLING

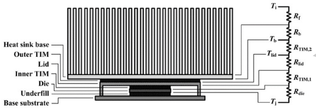
Server Thermal Design



Single Phase Micro channel Cold Plate

Hybrid of Air & Single-Phase Cooled Server Design





- Heat Sink
- Cold Plate
- Heat Pipe
- Vapor Chamber
- Fan Speed Control (IT Equipment)
- Fan Wall For Rack

Data Center Engineering

Secondary Side Classification

Classes	Temperature Range (°C)
S1	17-27
S2	27-37
S3	37-47
S4	>47

Data Center Facility

Classes	Typical Infrastructure Design: Primary Facilities	Typical Infrastructure Design: Secondary/Supplemental Facilities	Facility Supply Water Temp (°C)	IT Equipment Availability
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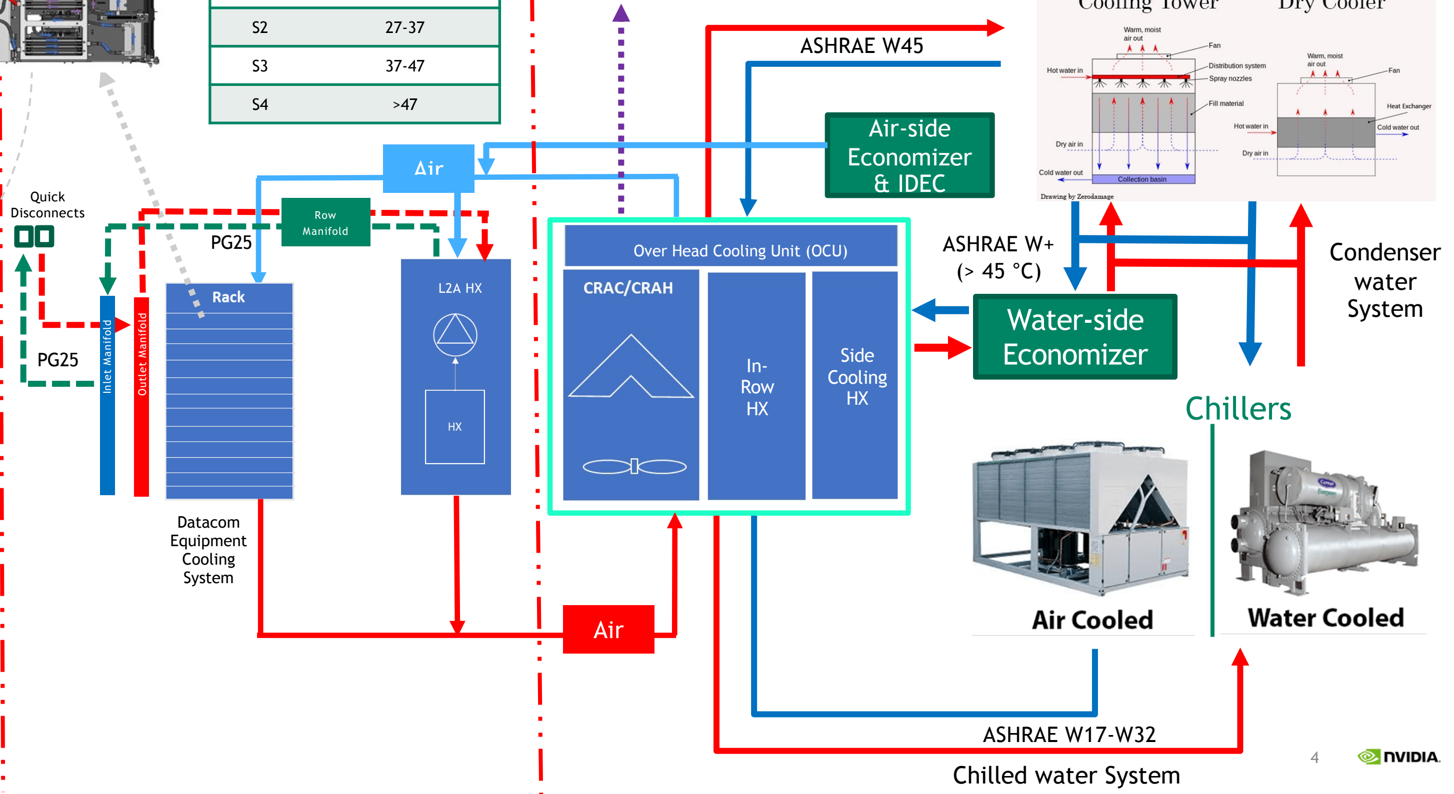

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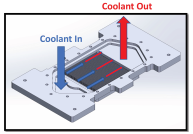
HYBRID LIQUID-TO-LIQUID COOLING

Server Thermal Design



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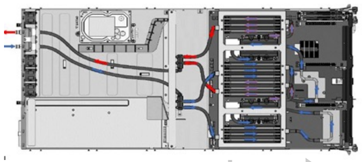

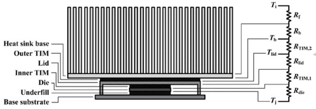

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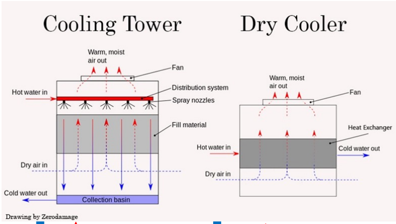

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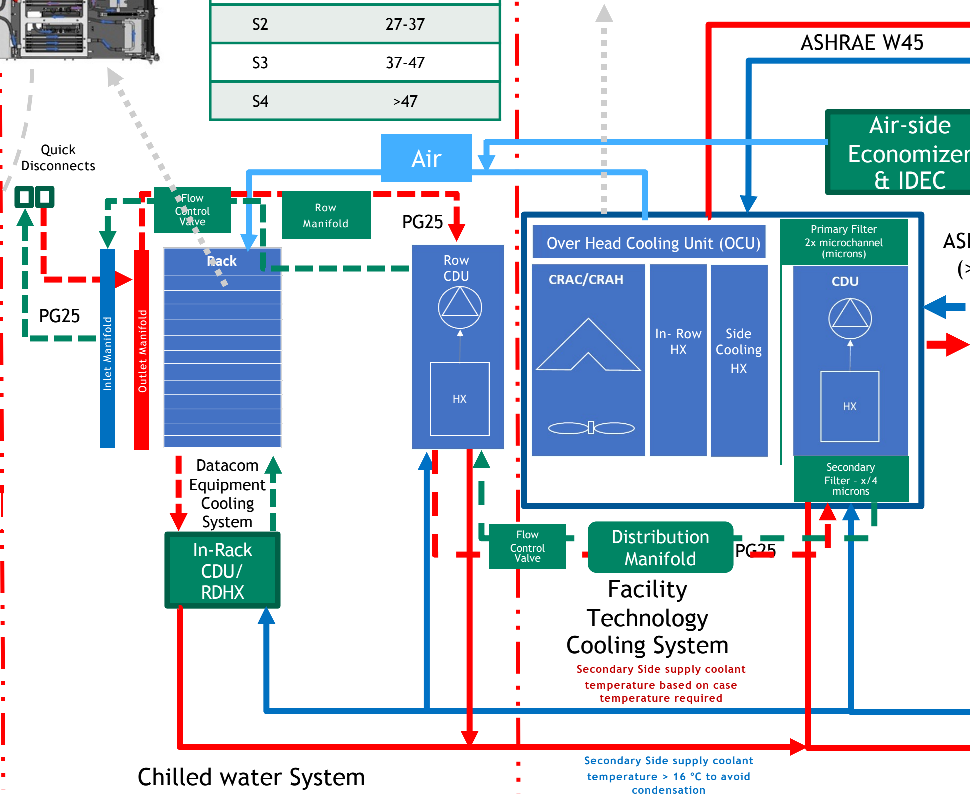

Air Cooled

Water Cooled

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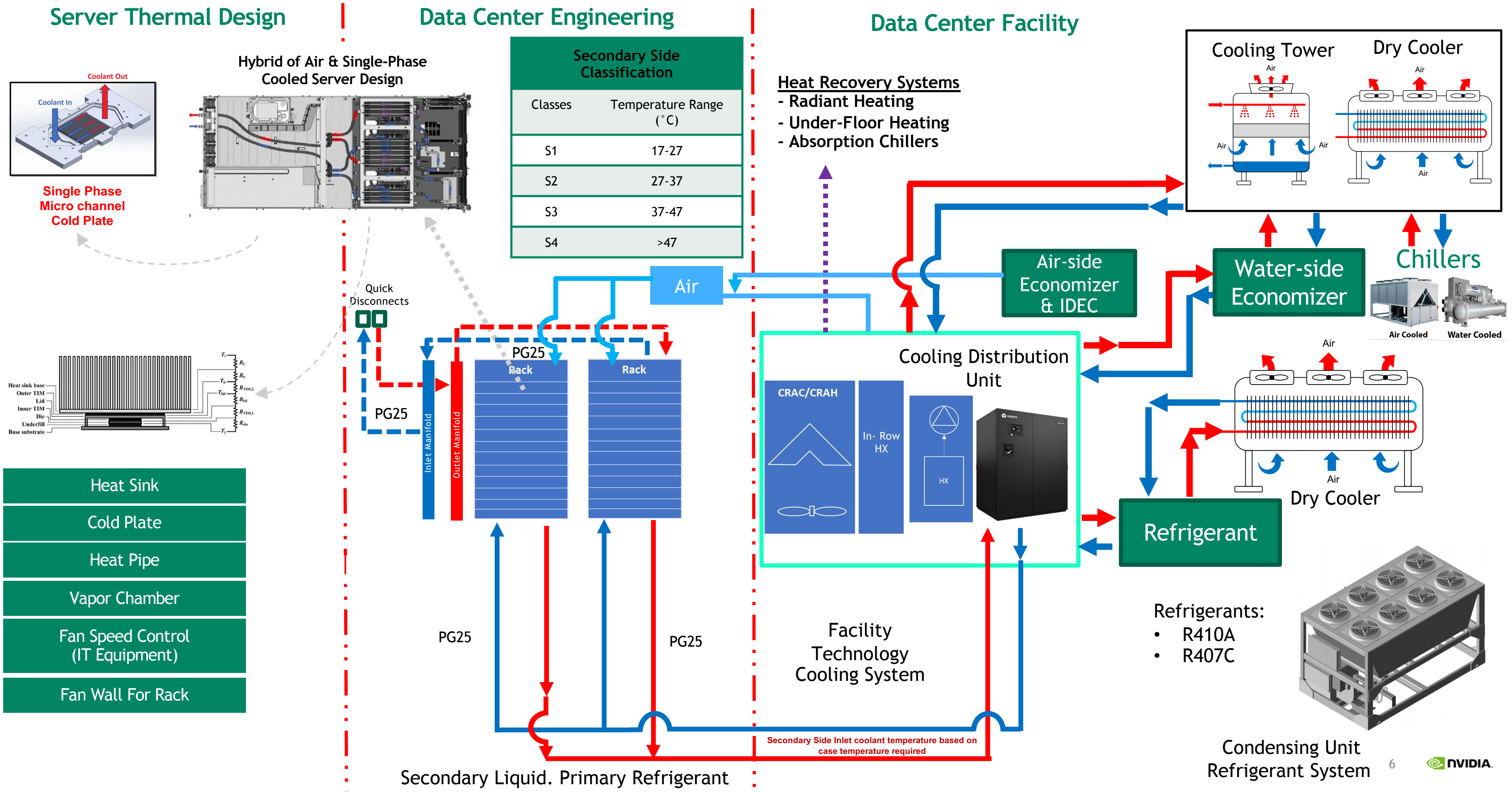
HYBRID LIQUID-TO-REFRIGERANT COOLING



Secondary Side Classification

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S4	>47

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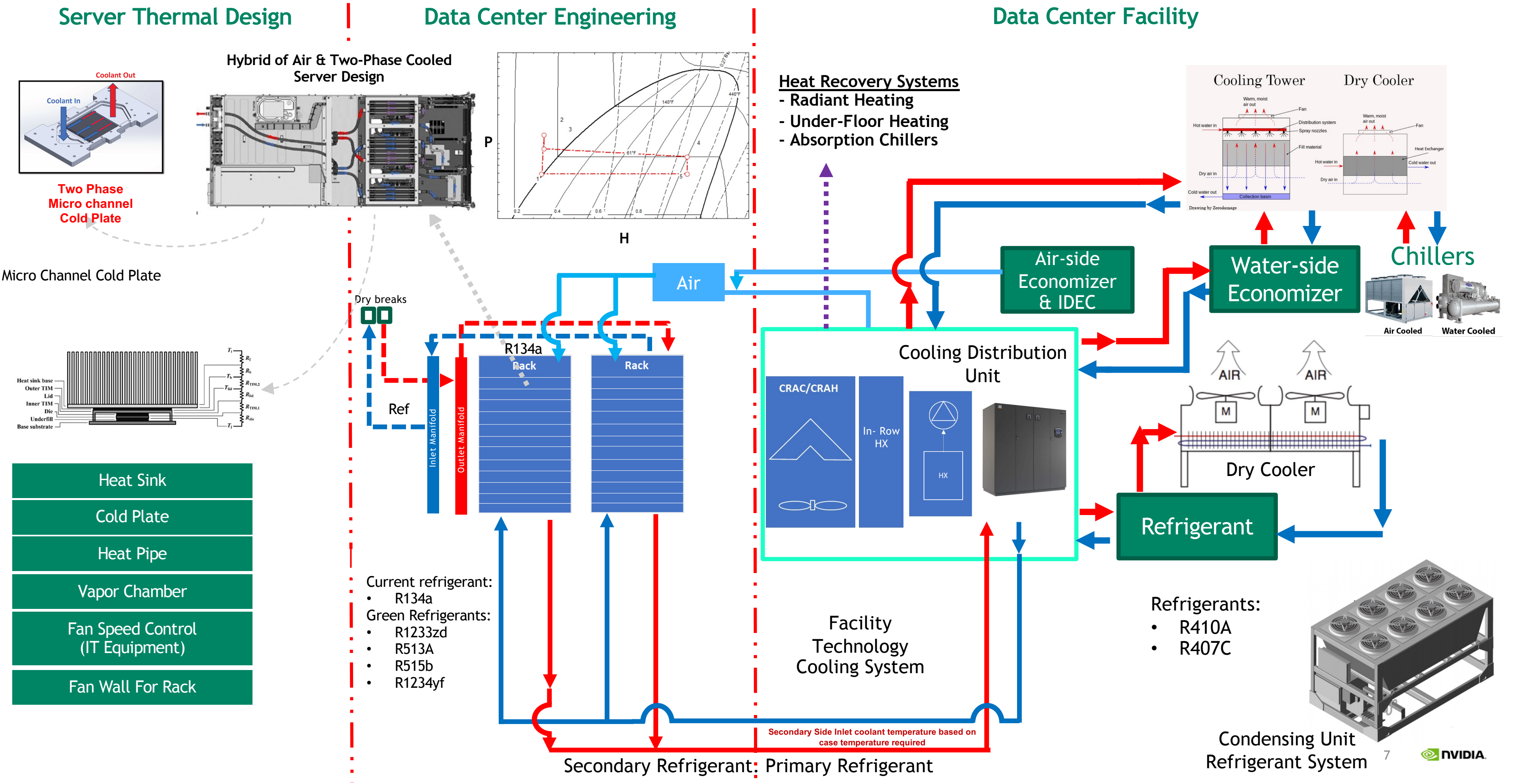
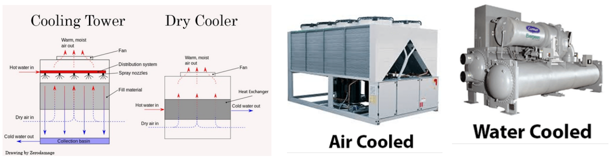
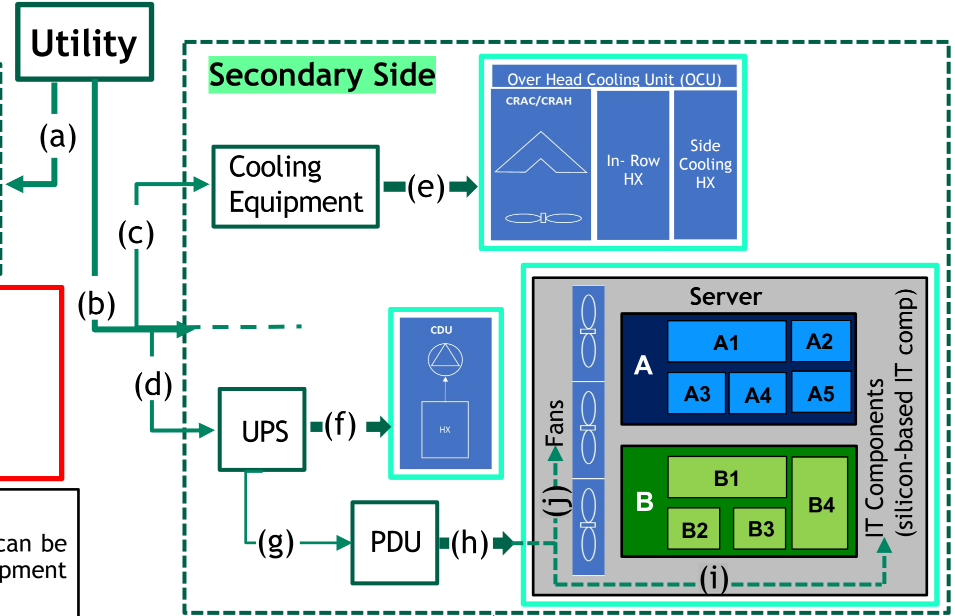
HYBRID REFRIGERANT-TO-REFRIGERANT COOLING



PUE/TUE ANALYSIS OF HYBRID DATA CENTERS

Primary Side





Power line

Decreasing

Increasing

$$PUE = \frac{a+b}{h}$$

$$ITUE = \frac{h}{i}$$

$$TUE = PUE \times ITUE = \frac{a+b}{i}$$

- *PUE*: Power Usage Effectiveness
- *ITUE*: IT Usage Effectiveness
- *TUE*: Total Usage Effectiveness

On the primary side:
Power consumption reduces by using liquid cooling and can be further decreased by a choice of more efficient equipment such as adiabatic coolers or optimized chillers (**a** ↘)

$$PUE(\downarrow) = \frac{a(\searrow) + b(\searrow)}{h(\searrow)}$$

$$TUE(\downarrow) = \frac{a(\searrow) + b(\searrow)}{i}$$

❖ *i* stays constant

	Air cooling	Hybrid cooling	Percentage of Change
PUE	1.18	1.14	3.4 %
TUE	1.45	1.19	18 %

❖ *PUE* & *TUE* drops as a result of more efficient performance!
❖ Reduction of server fan power consumption
❖ Less cooling equipment power consumption
❖ Lower facility power usage

Air Cooling

Air Cooling (100%)
IT Components
A (A1, A2, …, A5)
B (B1, B2, …, B4)

j	↘
h	↘
f	↗
e	↘
b	↘

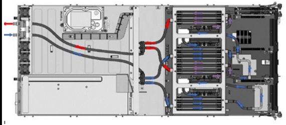
Hybrid Cooling

Air Cooling (X%)	Liquid Cooling (100-X)%
IT Components	
A (A4, A5))	A (A1, A2, A3)
B (B3, B4))	B (B1, B2)

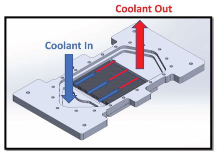
Cooling Distribution Unit (CDU) consumes less power relative to CARH/CRAC/RHX. (f<e)

❑ Inside the server:
- Motherboard/ board
- Fans

❑ On each board:
- Air-cooled components
- Liquid-cooled components



Hybrid (Indirect) Cooling
Air and Liquid Cooled components



Micro channel
Cold Plate

REFRIGERATION SYSTEMS DESIGN & ANALYSIS TOOLS

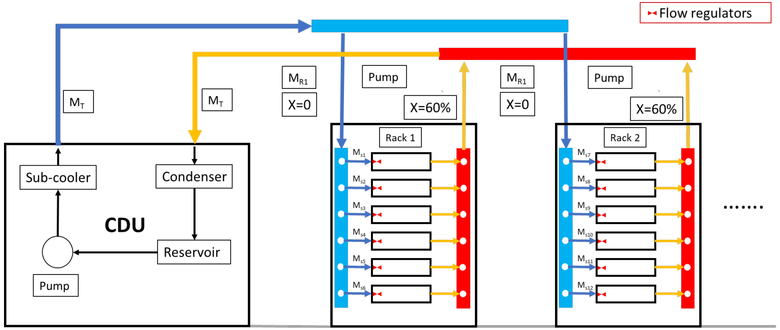
Rack Level Deployment of Refrigerant Cooling

Cooling Design Challenges

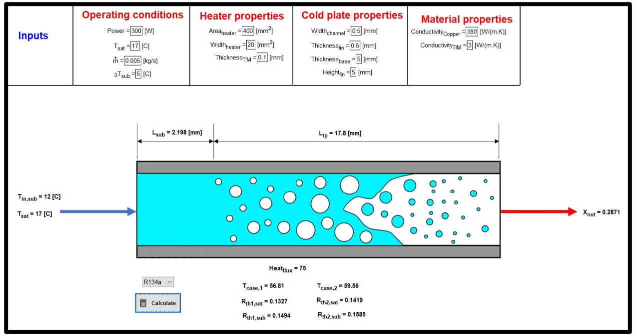
- Two Phase CDUs
- Two Phase Cooling Loops
- Rack & Row Manifolds Design
- Parallel and Serial Flows
- Two Phase Quality Control
- Choice of Refrigerants

Potential Choices of Refrigerants

- R134a (A1, MP, GWP=1430)
- R1233zd (A1, LP, GWP=1)
- R513a (A1, MP, GWP=631)
- R515b (A1, MP, GWP=293)
- R1234yf (A2L, GWP=4)



Cold Plate Simulating Tool (No Tools Currently Available)



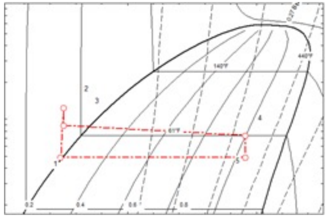
Experimental Results Post Processing Tool

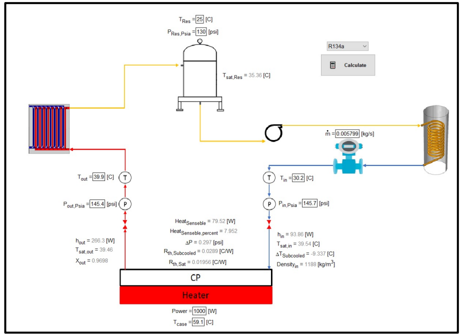
Tools Needs to be Developed for:

- Analyzing the experimental results
- Simulating refrigerant cold plates
- Analyzing system performance

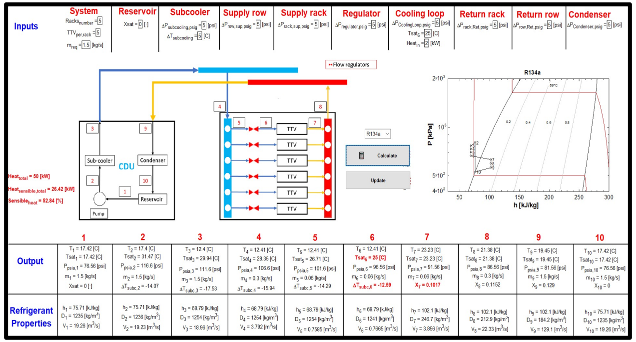
Developmental Tools:

- Refrigerants' properties
- Thermodynamics laws
- Experimental results
- Empirical correlations





Data Center Facility Simulating Tool (Engineering Equation Solver)



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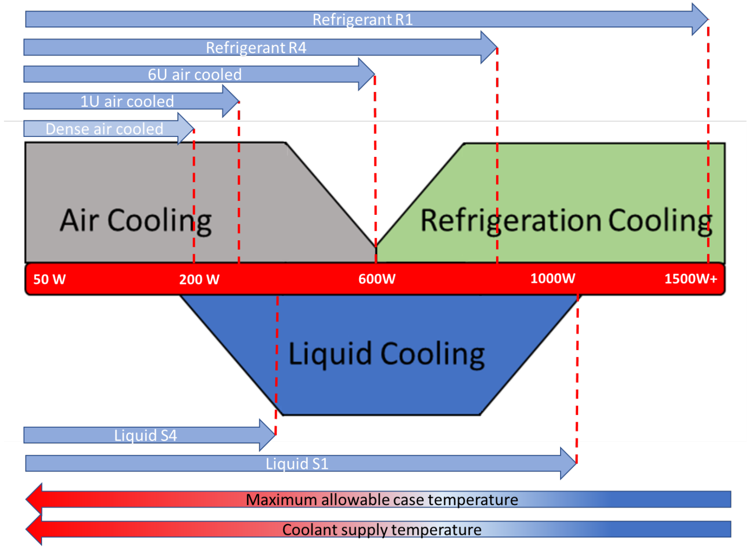
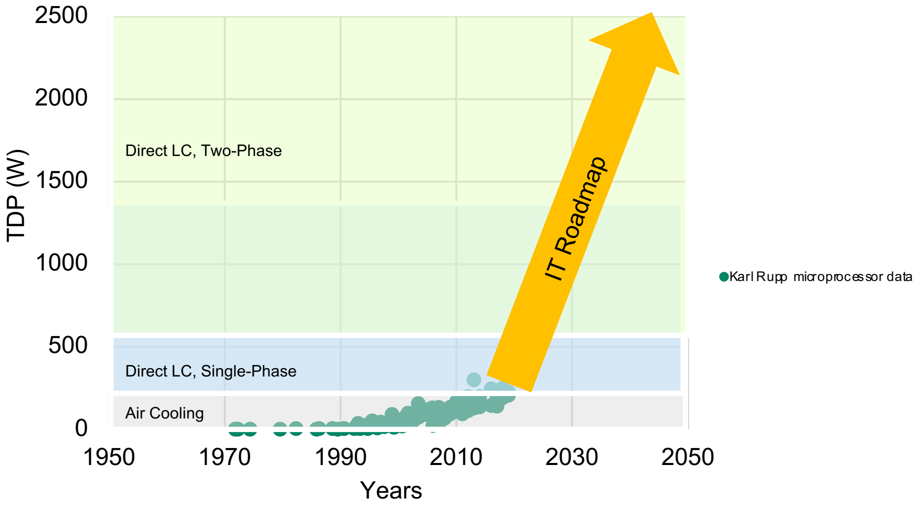
AIR TO SINGLE-PHASE LIQUID TO TWO-PHASE REFRIGERATION ROADMAP





Summary and Conclusions

- Data Center industry is greatly challenged due to substantial increase in chip heat density and power dissipation
- Majority of data center will go through a transition from 100% air cooled to hybrid of air and liquid cooling
- Direct to chip liquid cooling design using cold plates, cooling loops, rack/row manifolds and CDUs using treated water (DI, PG25) are going to be dominant design
- Transition from single phase to two phase liquid cooling will happen much sooner than air to single phase liquid cooling transition
- Currently challenges with two-phase data center refrigeration design;
  - ❖ Lack of two-phase detailed simulation tools
  - ❖ Difficulty in serial vs parallel flow distribution
  - ❖ Two phase CDUs availability
  - ❖ Phasing out of R134a due to high GWP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