MEBS7014 Advanced HVAC applications

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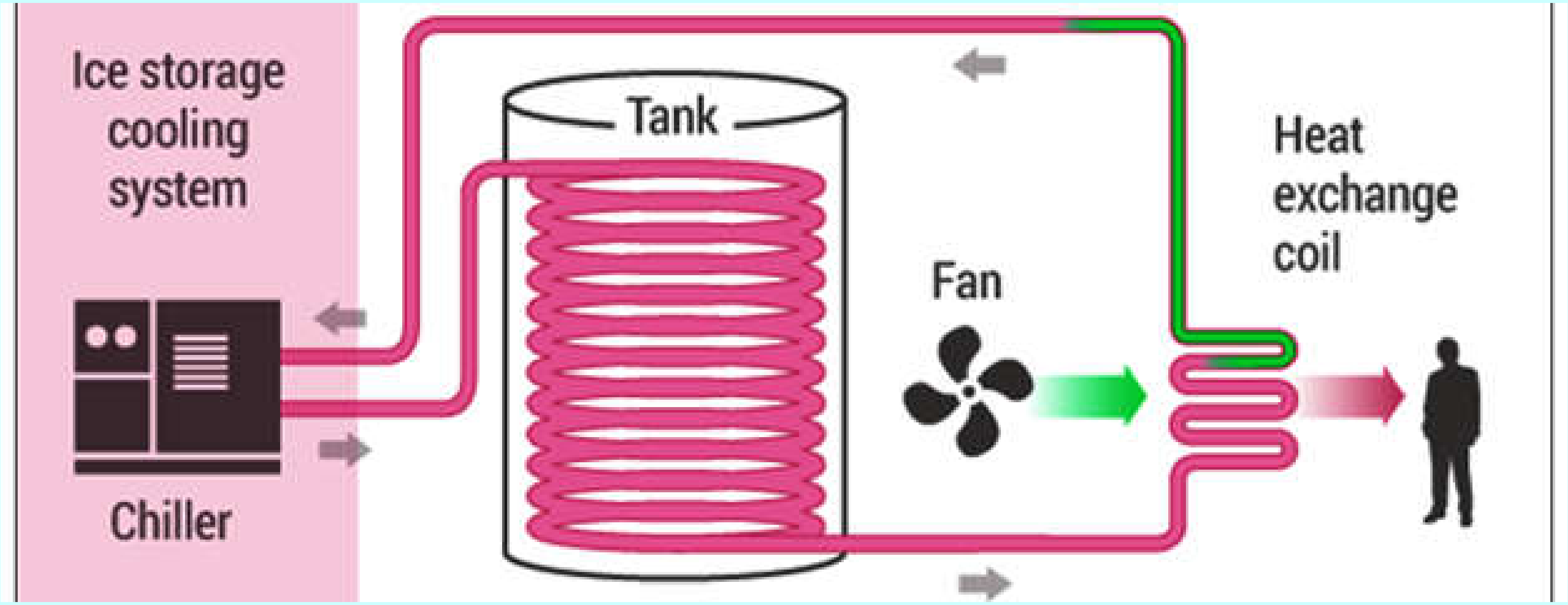

Thermal Storage Systems II

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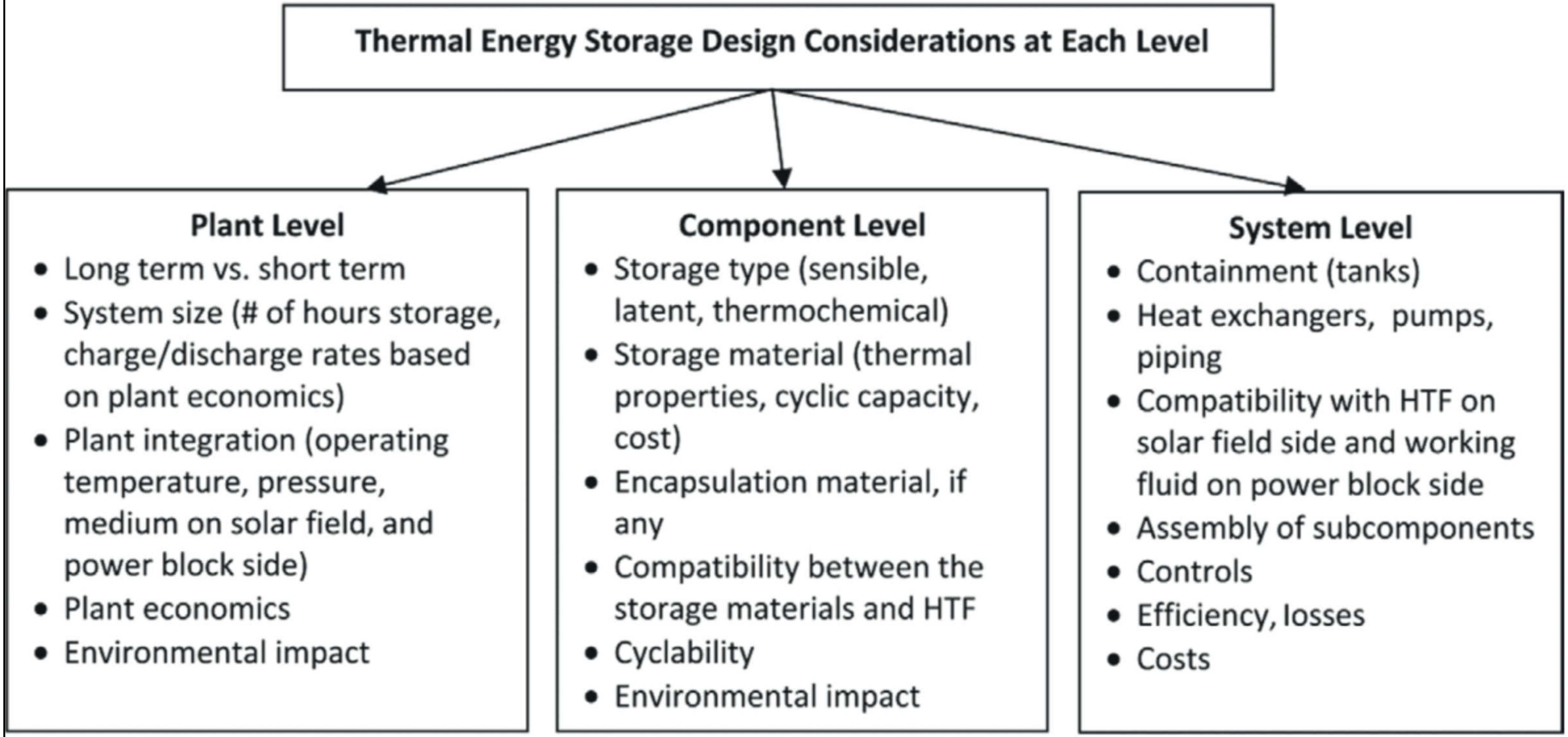
Contents

- System design & planning
- Cool thermal storage
- Chilled-water storage
- Ice thermal storage
- Design of ice storage system

System design & planning

- Design thermal energy storage (TES) systems
  - 1. Characterization of the thermal application
  - 2. Specification for the TES system
  - 3. Characterization of the TES technology
  - 4. Determination of the TES design
- Three levels of design considerations:
  - (a) Plant
  - (b) Component
  - (c) System

Thermal energy storage design considerations at each level



Thermal Energy Storage Design Considerations at Each Level

Plant Level

- Long term vs. short term
- System size (# of hours storage, charge/discharge rates based on plant economics)
- Plant integration (operating temperature, pressure, medium on solar field, and power block side)
- Plant economics
- Environmental impact

Component Level

- Storage type (sensible, latent, thermochemical)
- Storage material (thermal properties, cyclic capacity, cost)
- Encapsulation material, if any
- Compatibility between the storage materials and HTF
- Cyclability
- Environmental impact

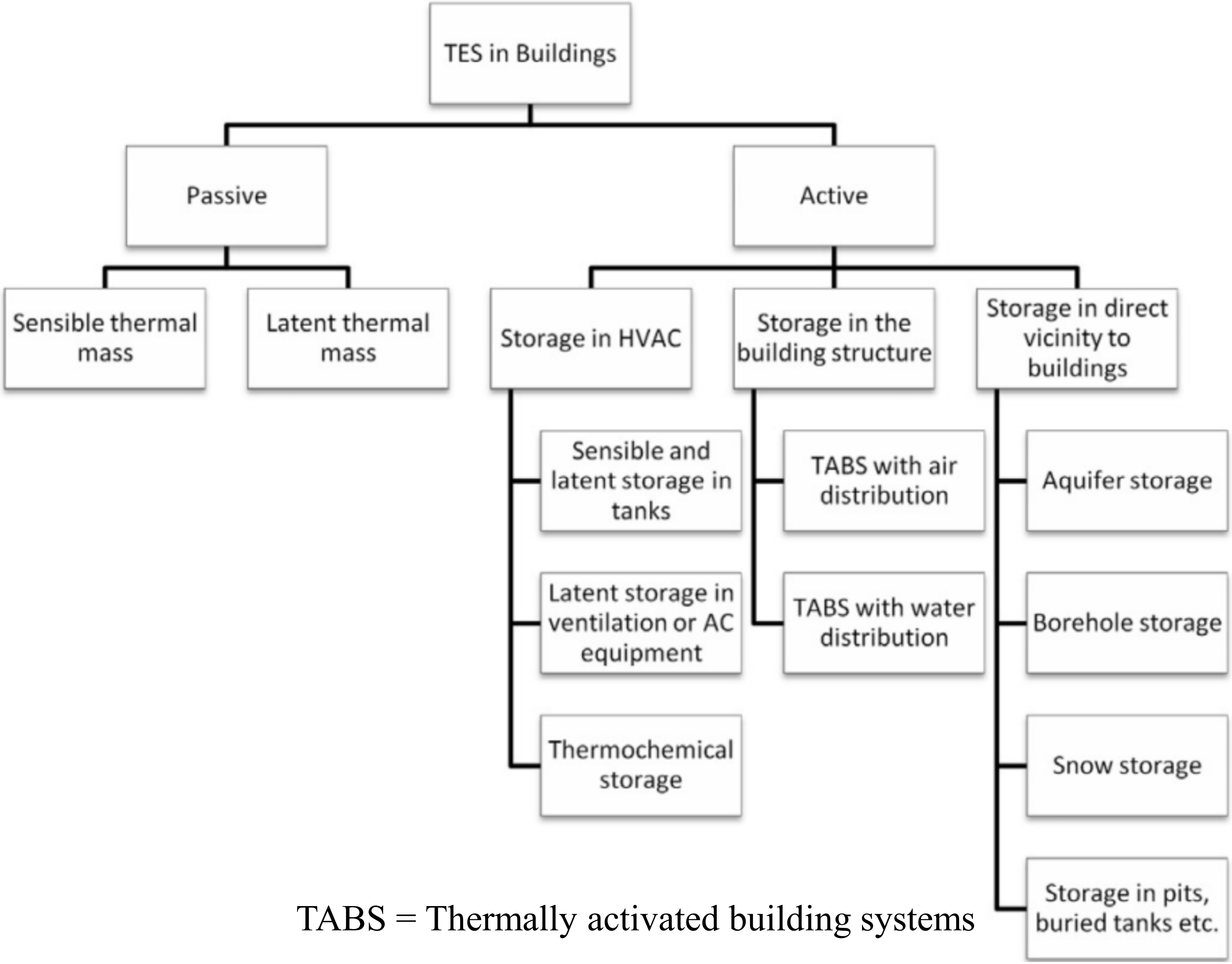
System Level

- Containment (tanks)
- Heat exchangers, pumps, piping
- Compatibility with HTF on solar field side and working fluid on power block side
- Assembly of subcomponents
- Controls
- Efficiency, losses
- Costs

HTF = Heat transfer fluid

(Source: Kalaiselvam S. & Parameshwaran R., 2014. *Thermal Energy Storage Technologies for Sustainability: Systems Design, Assessment and Applications*, Academic Press. https://doi.org/10.1016/C2013-0-09744-7)

Thermal energy storage (TES) in buildings



- TES in Buildings
  - Passive
    - Sensible thermal mass
    - Latent thermal mass
  - Active
    - Storage in HVAC
      - Sensible and latent storage in tanks
      - Latent storage in ventilation or AC equipment
      - Thermochemical storage
    - Storage in the building structure
      - TABS with air distribution
      - TABS with water distribution
    - Storage in direct vicinity to buildings
      - Aquifer storage
      - Borehole storage
      - Snow storage
      - Storage in pits, buried tanks etc.

TABS = Thermally activated building systems

(Source: Heier J., Bales C. & Martin V., 2015. Combining thermal energy storage with buildings – a review, *Renewable and Sustainable Energy Reviews*, 42: 1305-1325. https://doi.org/10.1016/j.rser.2014.11.031)

Technical comparison of sensible heat storage technologies

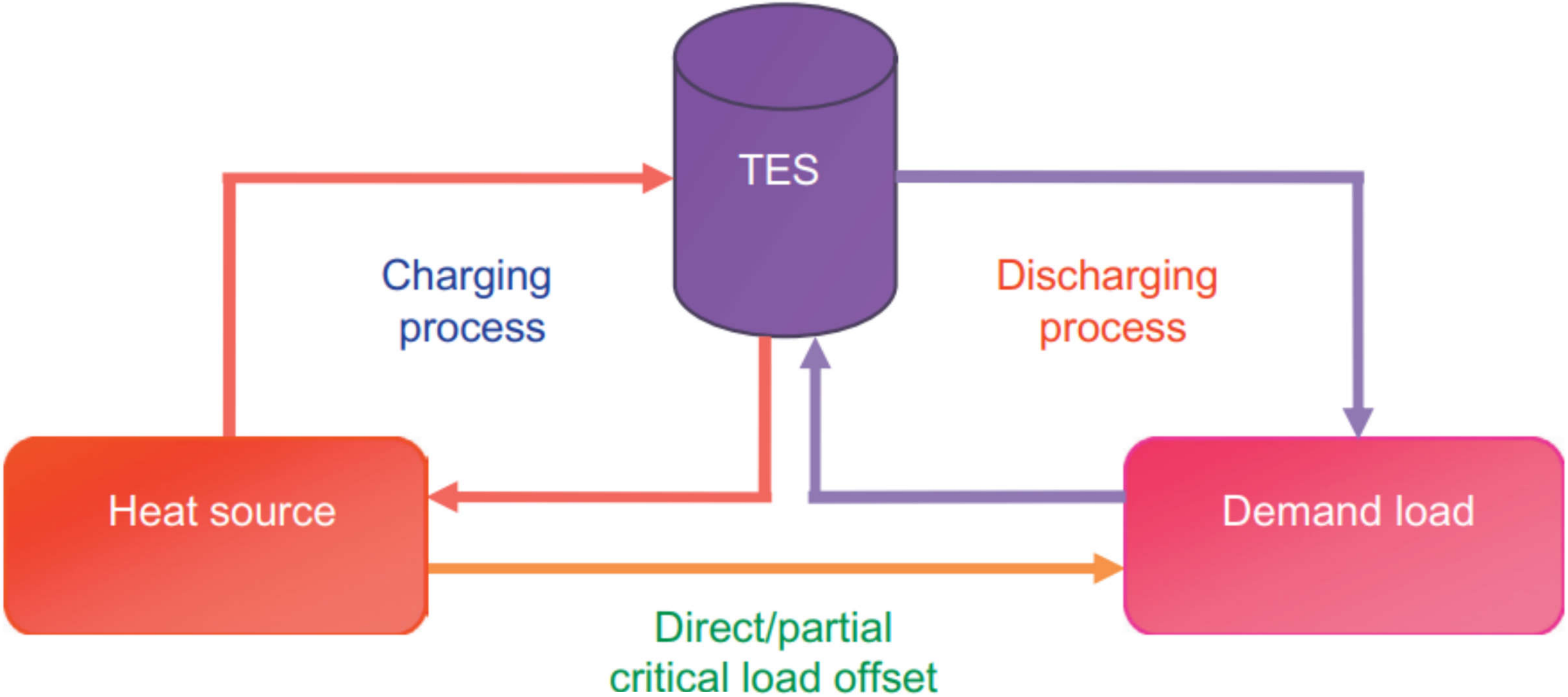
Tank	**Pit**	**Borehole**	**Aquifer**
Advantages: • No particular geological condition is required • Most mature technology • High stratification and heat capacity • Simple installation	Advantages: • No particular geological condition is required • Leaving natural aquifer untouched	Advantages: • Applied for both heating and cooling • Less sensitive to outdoor climate • Used for very large and very small applications • Requires less area for vertical borehole	Advantages: • Applied for both heating and cooling • Capability of generating direct cooling standalone • More effective heat transfer than borehole
Limitations: • High heat loss • Possible corrosion • Possible leakage	Limitations: • Lower stratification than tank • Possible leakage	Limitations: • Particular geological condition required • High heat loss and low energy density • Start-up process is needed	Limitations: • Particular geological condition required • High heat loss and low energy density • Long initial process for geological investigation

(Source: Behzadi A., *et al.*, 2022. Smart design and control of thermal energy storage in low-temperature heating and high-temperature cooling systems: A comprehensive review, *Renewable & Sustainable Energy Reviews*, 166: 112625. https://doi.org/10.1016/j.rser.2022.112625)

System design & planning

- Major design factors:
  - Building usage and future plans
  - Cooling load profiles (e.g. for design day)
  - Thermal storage system types
  - Equipment (chillers, storage tanks, controls)
  - Operating & control strategies
  - Interface with building systems
  - Sizing of cooling plants & storage
  - Redundancy & emergency cooling
  - Economic evaluation (including utility rates)

Thermal energy storage (TES) integration and operation



TES

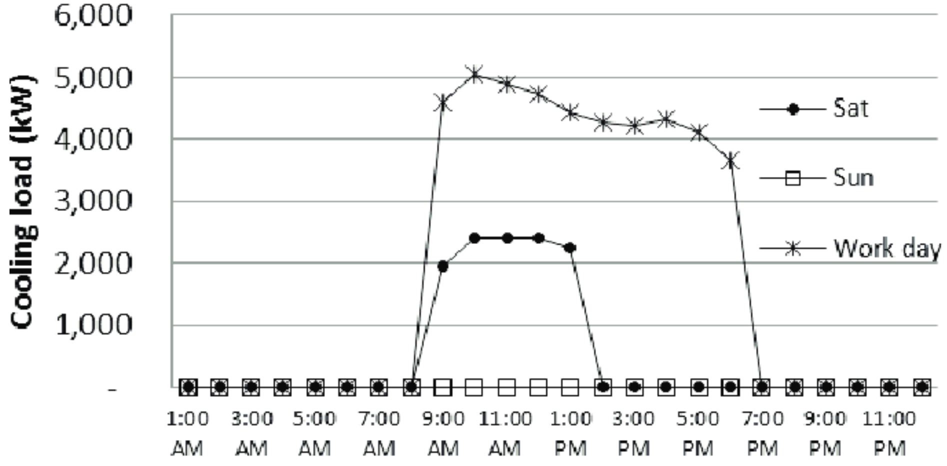
Charging process

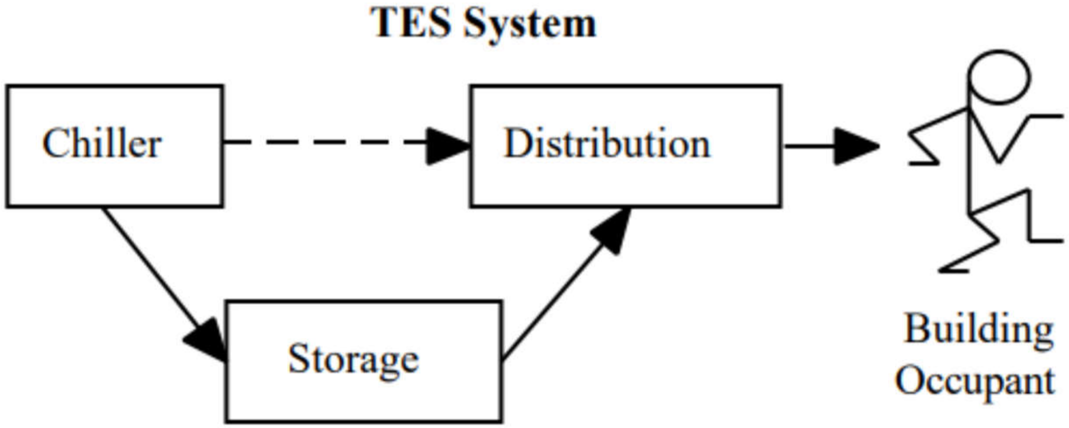
Discharging process

Heat source

Demand load

Direct/partial critical load offset





TES System

Chiller

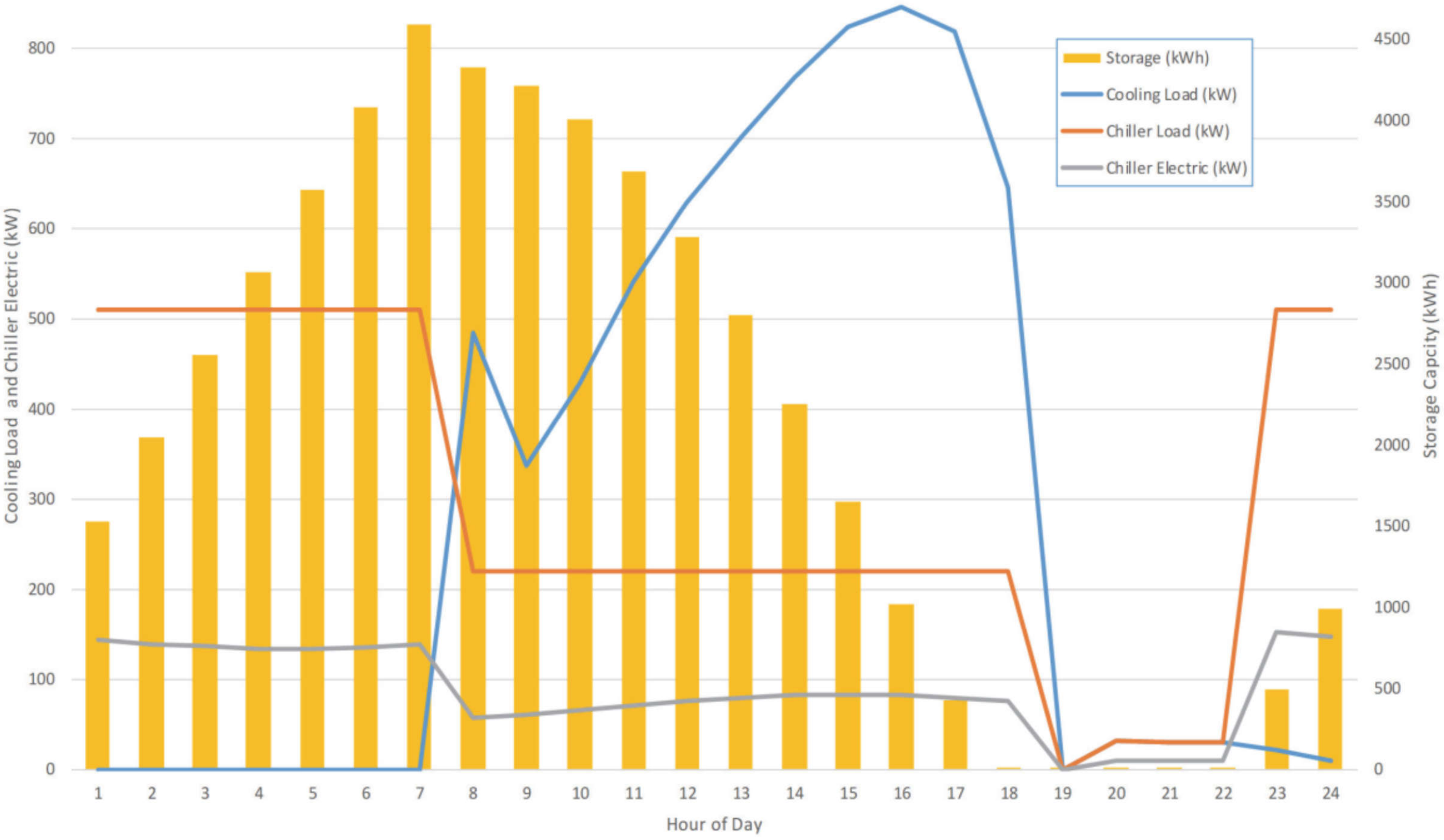
Distribution

Storage

Building Occupant

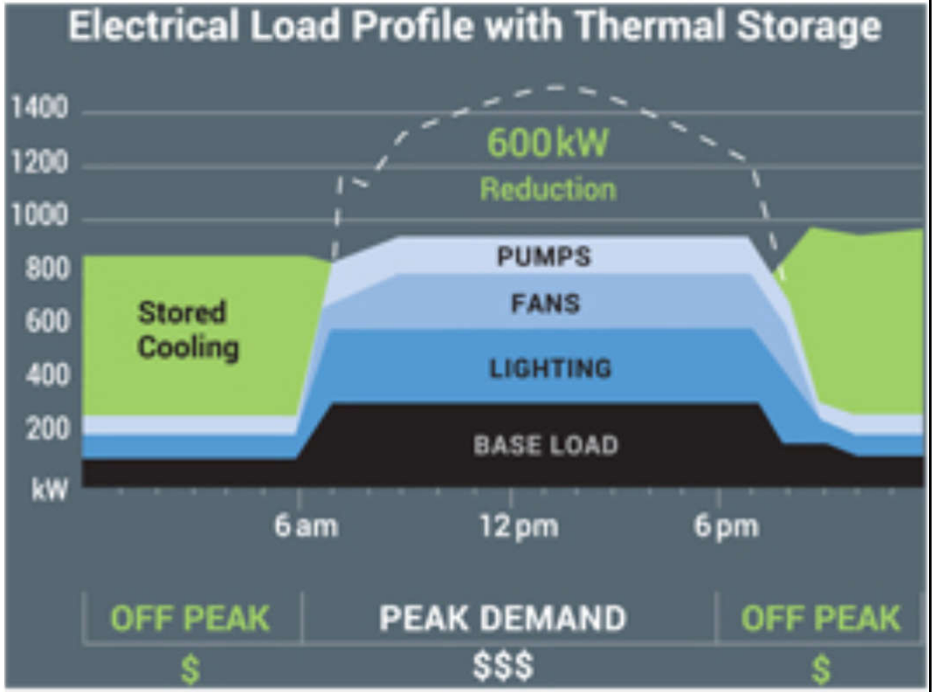
(Source: Li P.-W. & Chan C. L., 2017. *Thermal Energy Storage Analyses and Designs*, Academic Press. https://doi.org/10.1016/C2015-0-04678-0)

Analysis of chiller electrical demand and storage use during design day



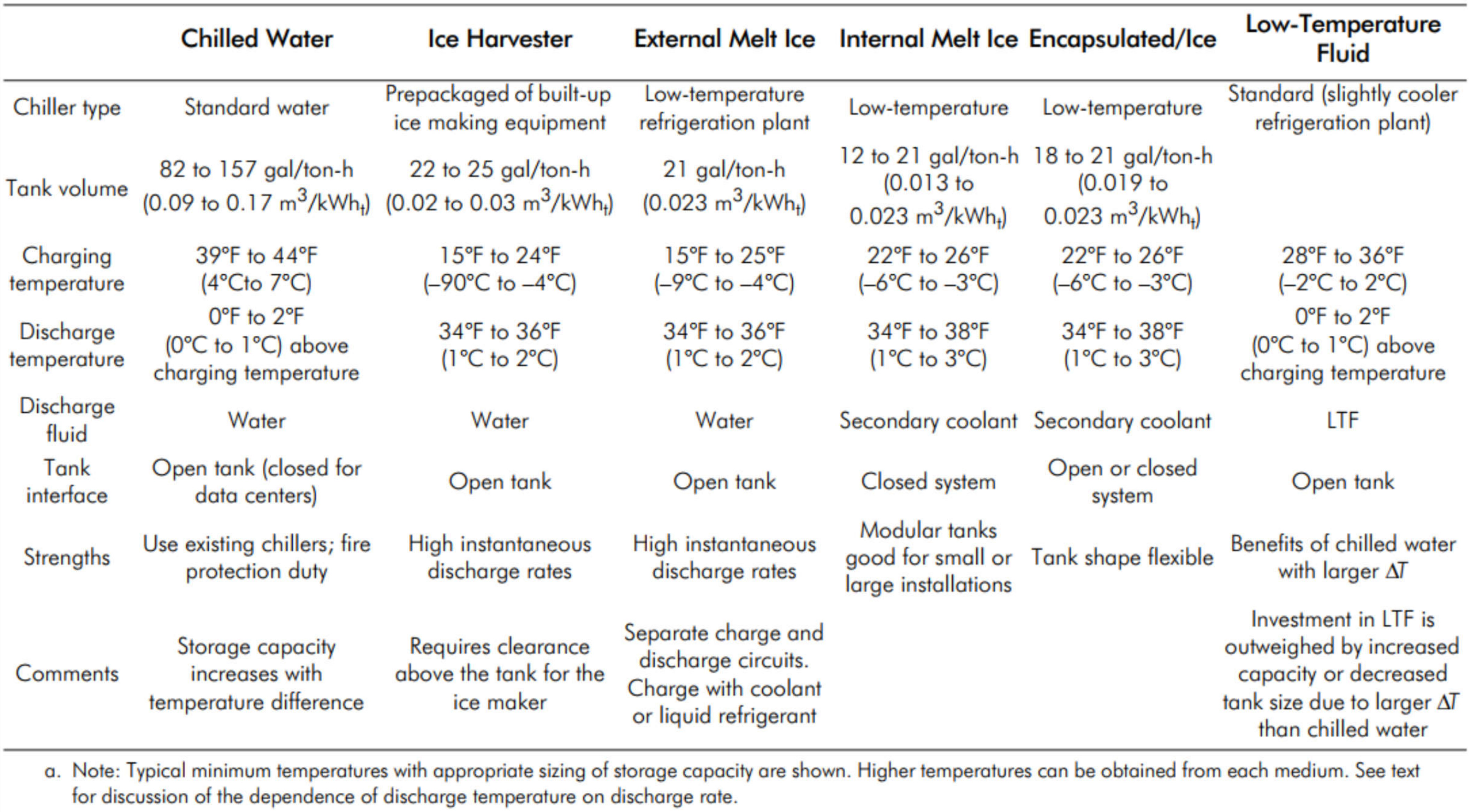
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

System design & planning



- Cooling load profiles
  - Design day hourly profile
    - Tall peak?
    - Low and flat?
    - Off peak usage?
  - Acquire from…
    - Cooling load calculation program
    - Chiller or building management system (BMS) logs
  - Night loads
    - If > 20% consider night chiller

Comparison of cool storage systems



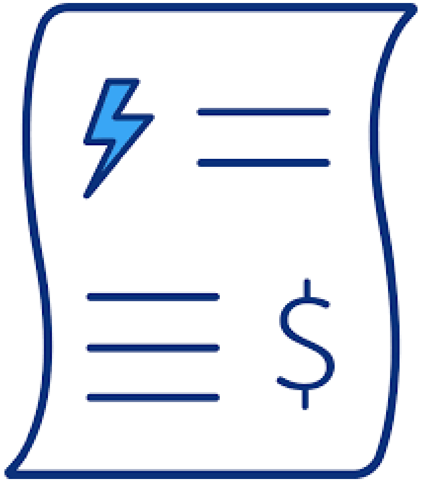
	Chilled Water	Ice Harvester	External Melt Ice	Internal Melt Ice	Encapsulated/Ice	Low-Temperature Fluid
Chiller type	Standard water	Prepackaged of built-up ice making equipment	Low-temperature refrigeration plant	Low-temperature	Low-temperature	Standard (slightly cooler refrigeration plant)
Tank volume	82 to 157 gal/ton-h (0.09 to 0.17 m^3/kWh_t)	22 to 25 gal/ton-h (0.02 to 0.03 m^3/kWh_t)	21 gal/ton-h (0.023 m^3/kWh_t)	12 to 21 gal/ton-h (0.013 to 0.023 m^3/kWh_t)	18 to 21 gal/ton-h (0.019 to 0.023 m^3/kWh_t)	
Charging temperature	39°F to 44°F (4°Cto 7°C)	15°F to 24°F (–90°C to –4°C)	15°F to 25°F (–9°C to –4°C)	22°F to 26°F (–6°C to –3°C)	22°F to 26°F (–6°C to –3°C)	28°F to 36°F (–2°C to 2°C)
Discharge temperature	0°F to 2°F (0°C to 1°C) above charging temperature	34°F to 36°F (1°C to 2°C)	34°F to 36°F (1°C to 2°C)	34°F to 38°F (1°C to 3°C)	34°F to 38°F (1°C to 3°C)	0°F to 2°F (0°C to 1°C) above charging temperature
Discharge fluid	Water	Water	Water	Secondary coolant	Secondary coolant	LTF
Tank interface	Open tank (closed for data centers)	Open tank	Open tank	Closed system	Open or closed system	Open tank
Strengths	Use existing chillers; fire protection duty	High instantaneous discharge rates	High instantaneous discharge rates	Modular tanks good for small or large installations	Tank shape flexible	Benefits of chilled water with larger ΔT
Comments	Storage capacity increases with temperature difference	Requires clearance above the tank for the ice maker	Separate charge and discharge circuits. Charge with coolant or liquid refrigerant			Investment in LTF is outweighed by increased capacity or decreased tank size due to larger ΔT than chilled water

a. Note: Typical minimum temperatures with appropriate sizing of storage capacity are shown. Higher temperatures can be obtained from each medium. See text for discussion of the dependence of discharge temperature on discharge rate.

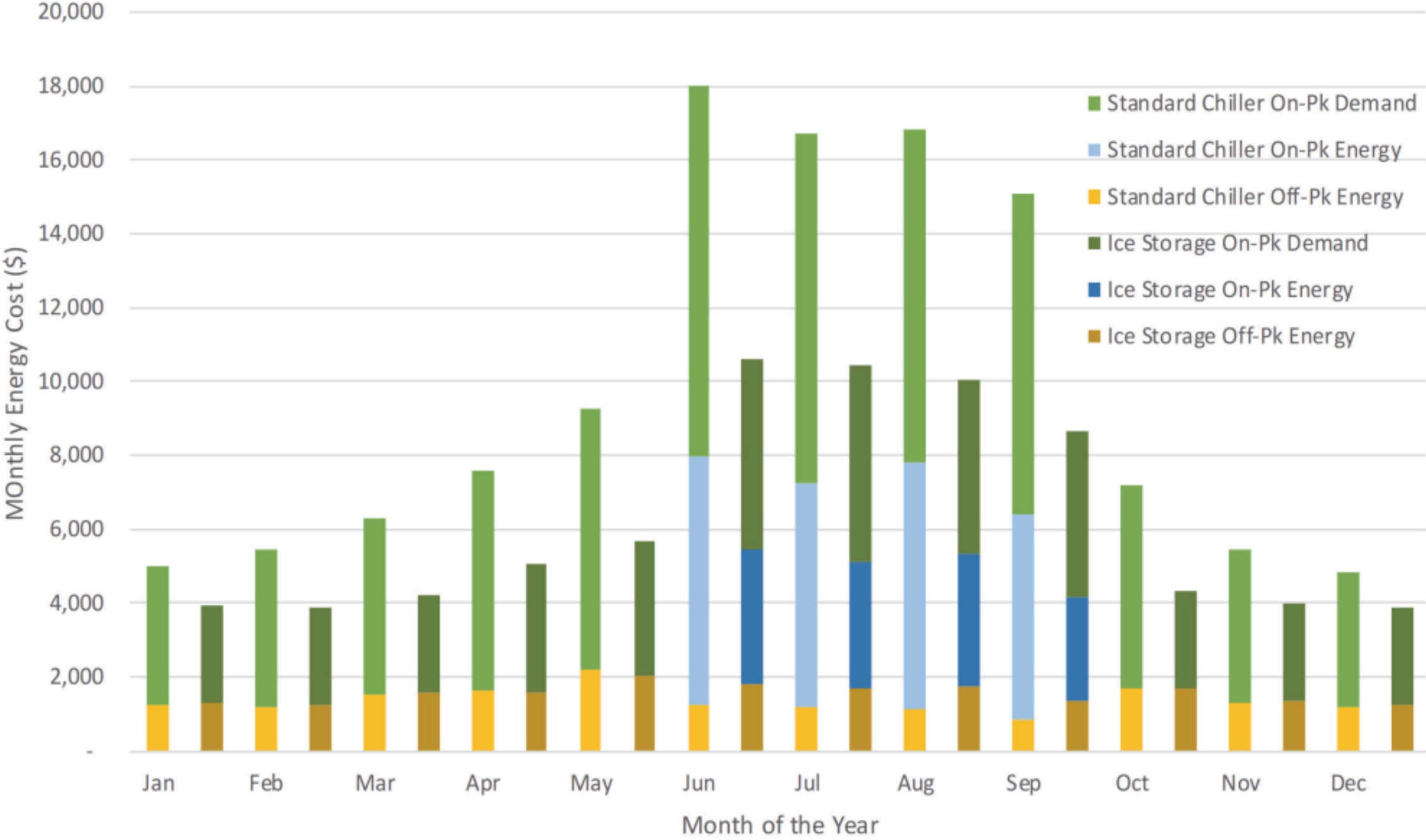
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

System design & planning

- Utility rates:
    - kW charge
        - Ratcheted? Time of day (TOD)? Stepped rate?
    - On-peak/Off-peak -- kW and/or kWh
    - Real time pricing
    - Up front or on-going incentives
- Utility rate coordination:
    - Direct measurement of building demand
    - Demand response signal from utility
    - Monitoring of real-time pricing

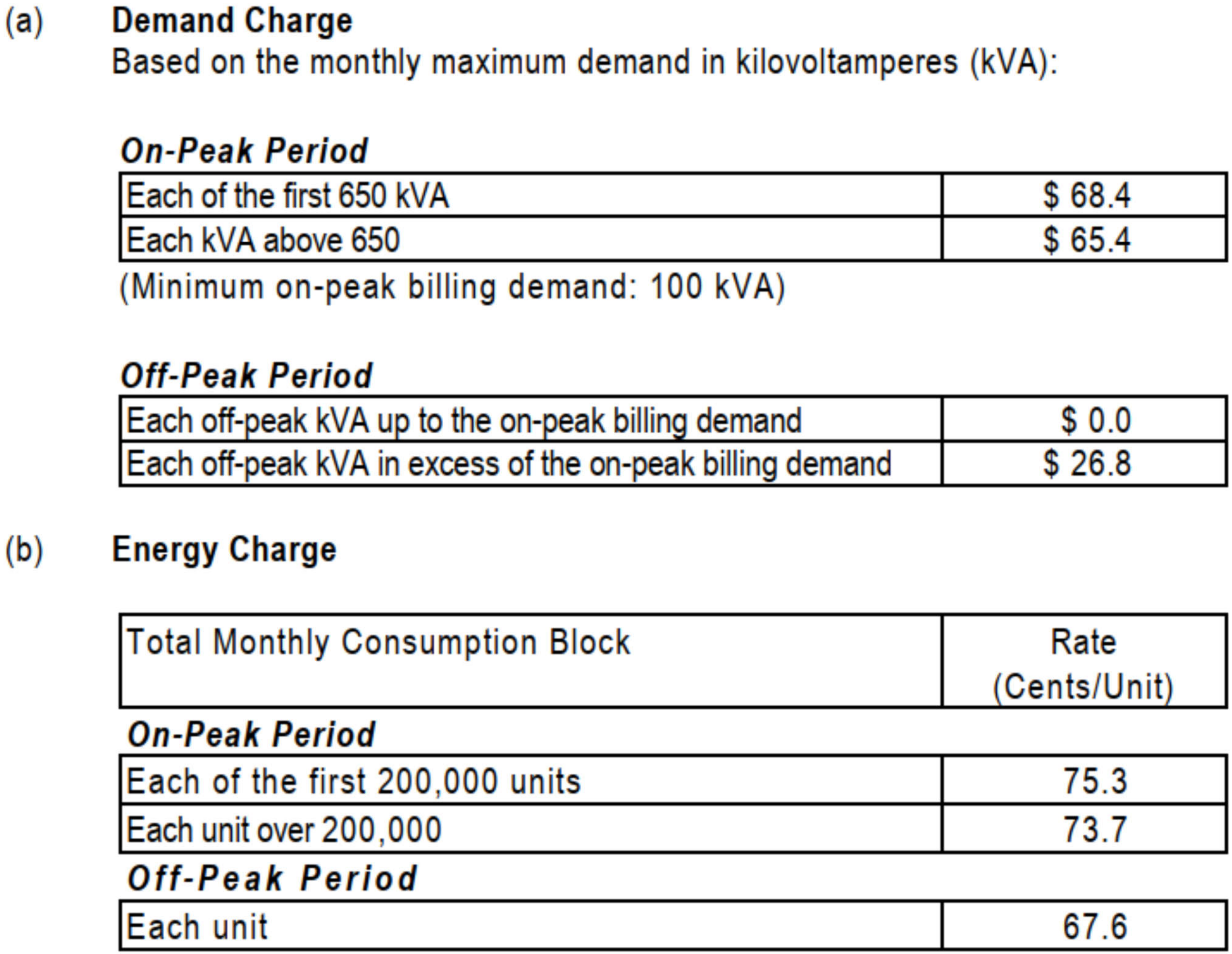


Estimated monthly electric bills



(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

CLP electricity tariff for 2023: Bulk tariff



(a) **Demand Charge**

Based on the monthly maximum demand in kilovoltamperes (kVA):

On-Peak Period

Each of the first 650 kVA	$ 68.4
Each kVA above 650	$ 65.4

(Minimum on-peak billing demand: 100 kVA)

Off-Peak Period

Each off-peak kVA up to the on-peak billing demand	$ 0.0
Each off-peak kVA in excess of the on-peak billing demand	$ 26.8

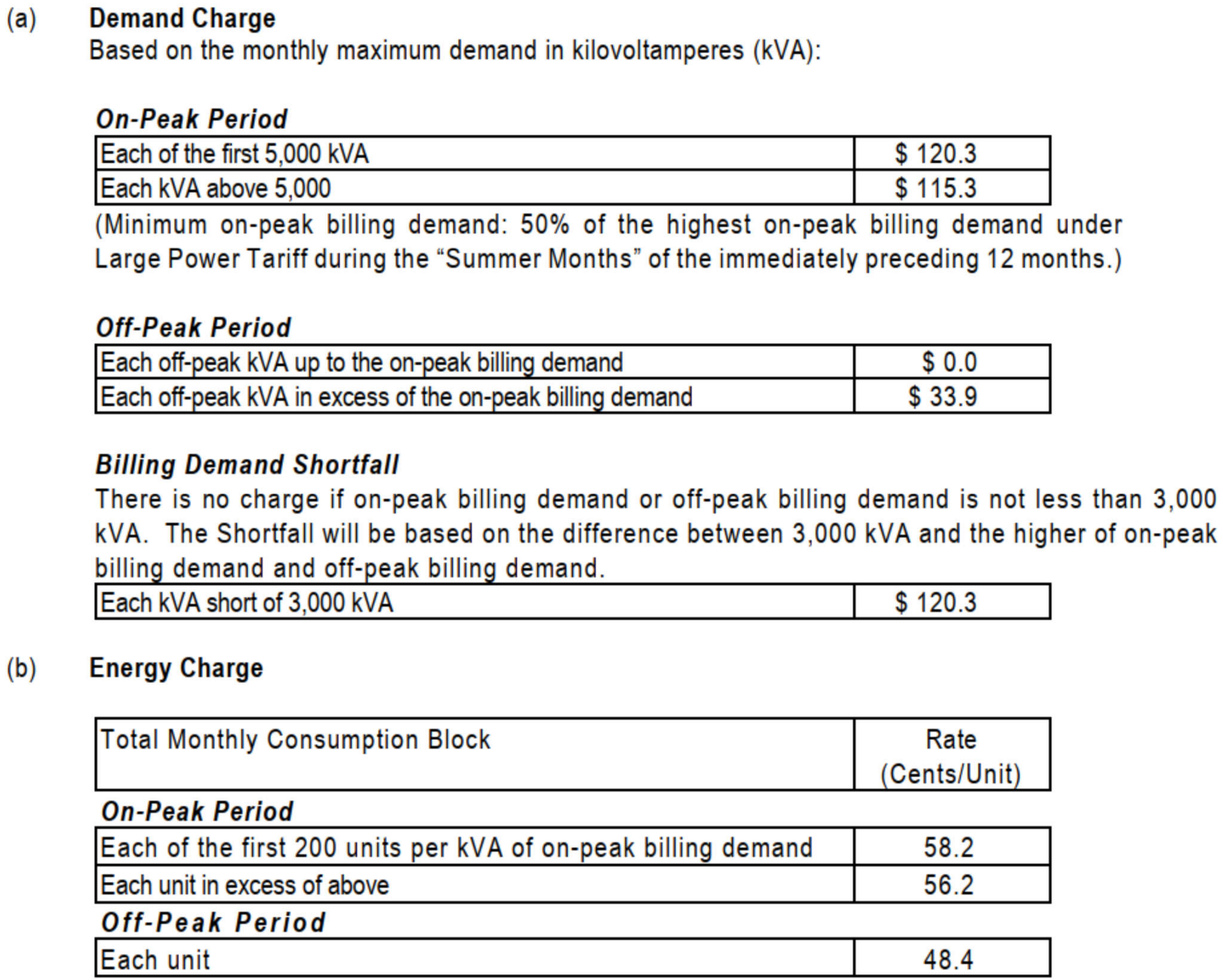
(b) **Energy Charge**

Total Monthly Consumption Block	Rate (Cents/Unit)
On-Peak Period	
Each of the first 200,000 units	75.3
Each unit over 200,000	73.7
Off-Peak Period	
Each unit	67.6

"Off-peak Period" is the daily period between 2100 hours and 0900 hours and all day Sundays and Public Holidays

(Source: CLP https://www.clp.com.hk/)

CLP electricity tariff for 2023: Large power tariff



(a) **Demand Charge**

Based on the monthly maximum demand in kilovoltamperes (kVA):

On-Peak Period

Each of the first 5,000 kVA	$ 120.3
Each kVA above 5,000	$ 115.3

(Minimum on-peak billing demand: 50% of the highest on-peak billing demand under Large Power Tariff during the “Summer Months” of the immediately preceding 12 months.)

Off-Peak Period

Each off-peak kVA up to the on-peak billing demand	$ 0.0
Each off-peak kVA in excess of the on-peak billing demand	$ 33.9

Billing Demand Shortfall

There is no charge if on-peak billing demand or off-peak billing demand is not less than 3,000 kVA. The Shortfall will be based on the difference between 3,000 kVA and the higher of on-peak billing demand and off-peak billing demand.

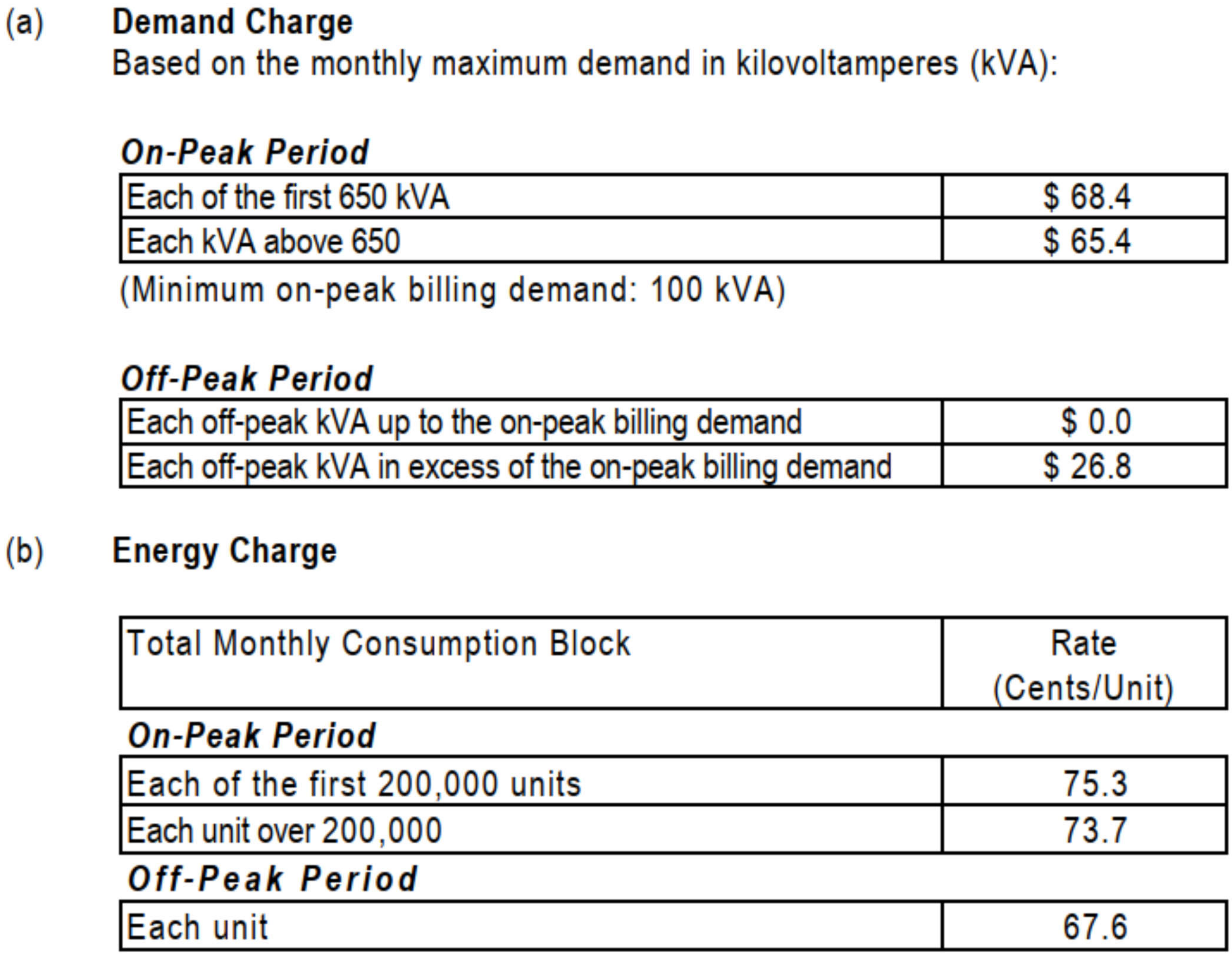
Each kVA short of 3,000 kVA	$ 120.3

(b) **Energy Charge**

Total Monthly Consumption Block	Rate (Cents/Unit)
On-Peak Period	
Each of the first 200 units per kVA of on-peak billing demand	58.2
Each unit in excess of above	56.2
Off-Peak Period	
Each unit	48.4

(Source: CLP https://www.clp.com.hk/)

CLP electricity tariff for 2023: Ice-storage air-conditoning tariff



(a) **Demand Charge**

Based on the monthly maximum demand in kilovoltamperes (kVA):

On-Peak Period

Each of the first 650 kVA	$ 68.4
Each kVA above 650	$ 65.4

(Minimum on-peak billing demand: 100 kVA)

Off-Peak Period

Each off-peak kVA up to the on-peak billing demand	$ 0.0
Each off-peak kVA in excess of the on-peak billing demand	$ 26.8

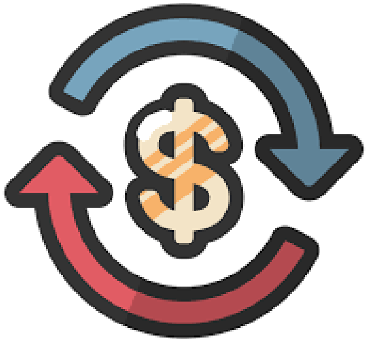
(b) **Energy Charge**

Total Monthly Consumption Block	Rate (Cents/Unit)
On-Peak Period	
Each of the first 200,000 units	75.3
Each unit over 200,000	73.7
Off-Peak Period	
Each unit	67.6

(Source: CLP https://www.clp.com.hk/)

System design & planning

- Making the economics work
  - Use actual utility rate for life cycle costs if possible
  - Use storage for the safety factor
  - Use actual load profile for equipment selection
  - Take credit for smaller electrical and mechanical ancillary equipment (e.g. downsizing chillers)
  - Take advantage of any utility rebates
  - Use low flow high ΔT energy distribution
  - Use low temperature air distribution



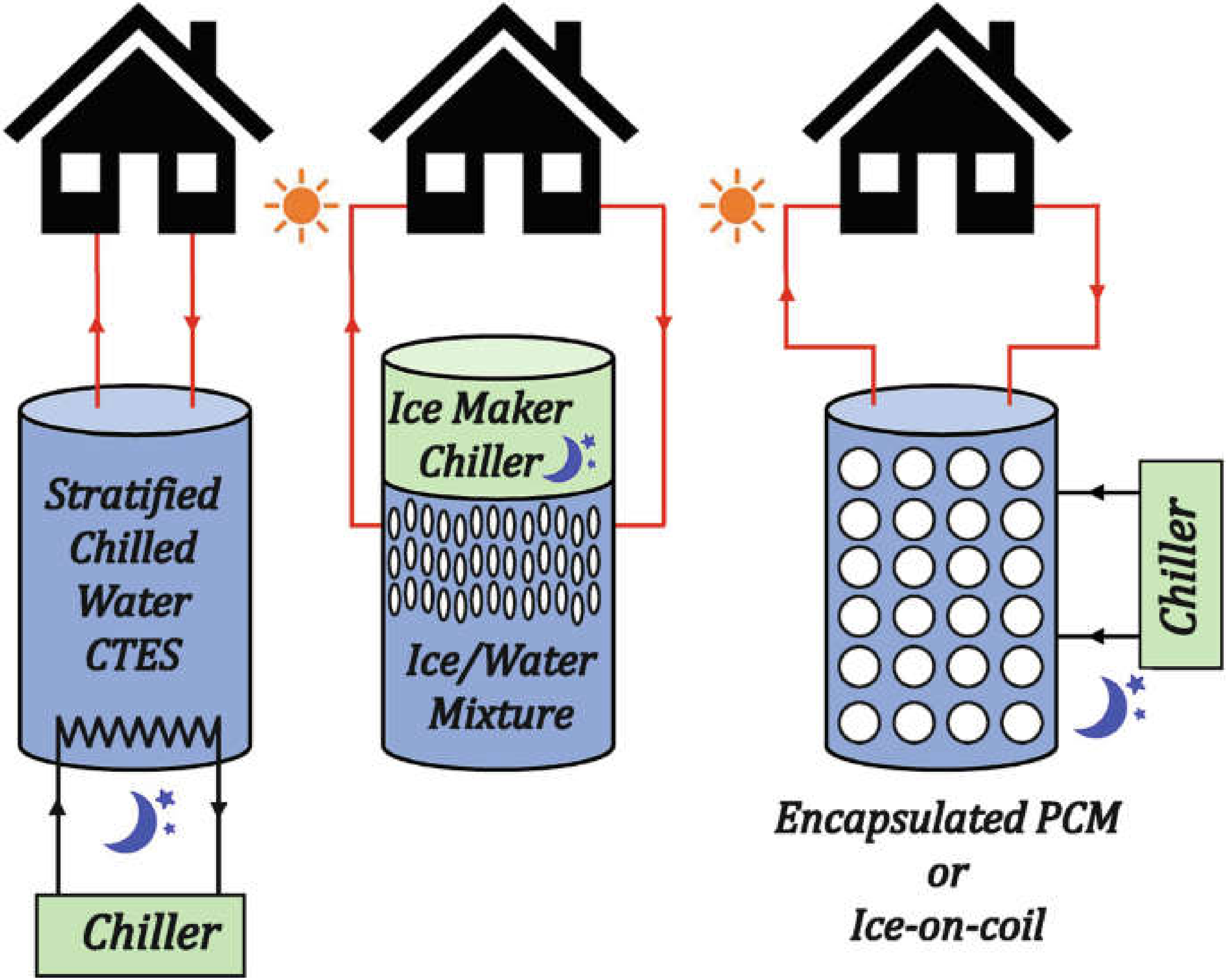
System design & planning

- Special applications:
  - Mission critical and emergency cooling (e.g. data centres)
  - Demand response (for electric utility)
  - Fire protection (for chilled water storage)
  - Underground thermal energy storage
  - District cooling & heating
- Other related issues:
  - Cold-air distribution, pumping, water treatment, retrofit projects, redundancy, codes & standards

Cool thermal storage

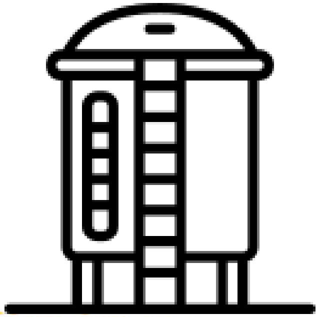
- Cool thermal energy storage systems remove heat from a thermal energy storage medium during periods of low cooling demand or when surplus renewable energy is available
  - The stored cooling capacity is later used to meet an air-conditioning or process cooling load
- For many utilities, the peak system demand is driven by the air-conditioning load on the hottest days of the year
  - Encourage customers to shift their loads

Cool thermal storage using chilled water, ice and encapsulated phase change materials (PCM)



(Source: Dincer I. & Ezan M. A., 2018. Thermal energy storage applications, In: *Heat Storage: A Unique Solution For Energy Systems, Green Energy and Technology*, Springer, Cham. https://doi.org/10.1007/978-3-319-91893-8_4)

Cool thermal storage

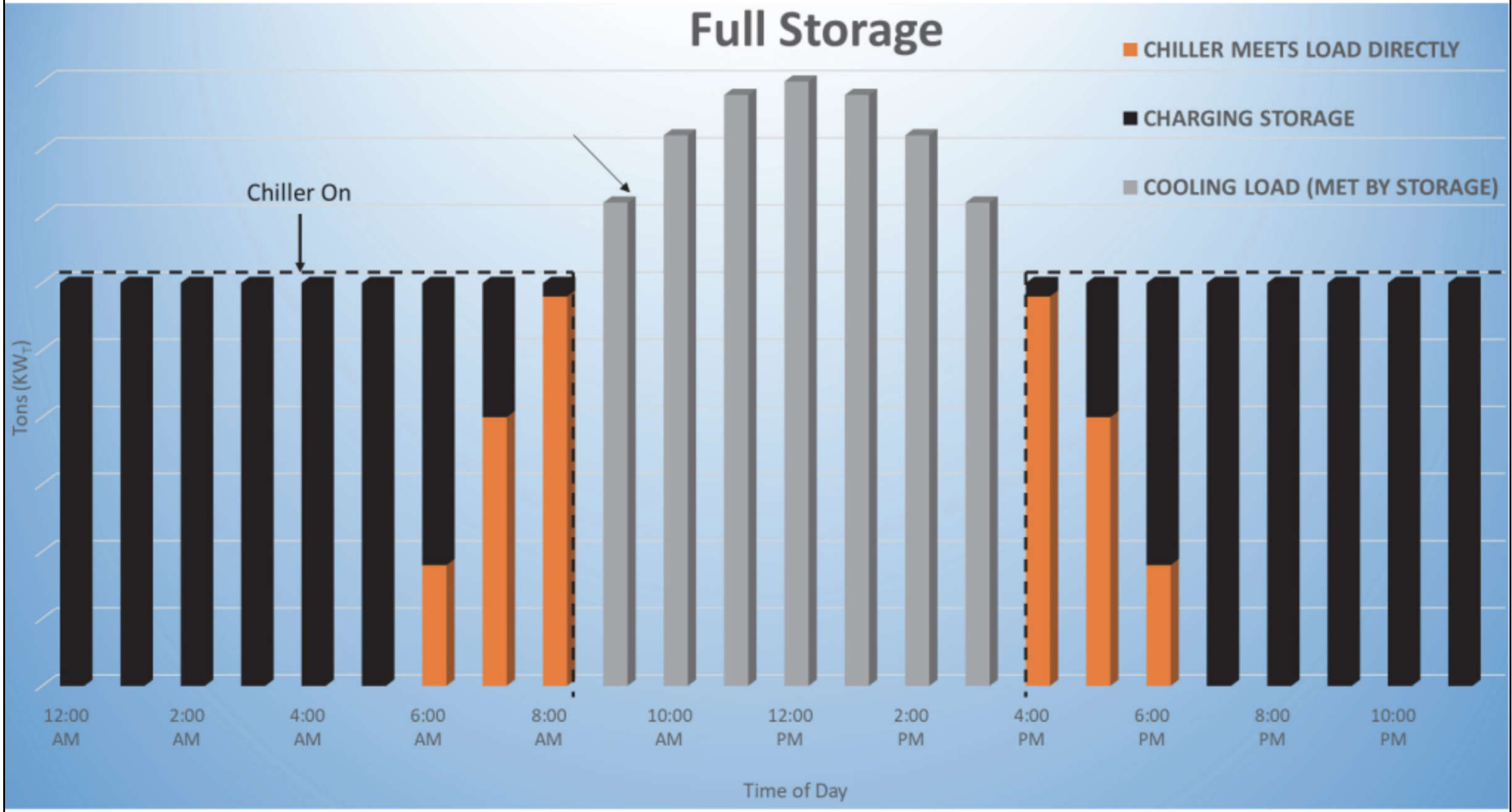


- Typical operating & control strategies for cool thermal storage:

- Full storage
- Partial storage, load levelling
- Partial storage, demand limiting
- Baseloading of chillers
- Sequencing of chillers
- Daily charging cycles
- Weekly or other charging cycles

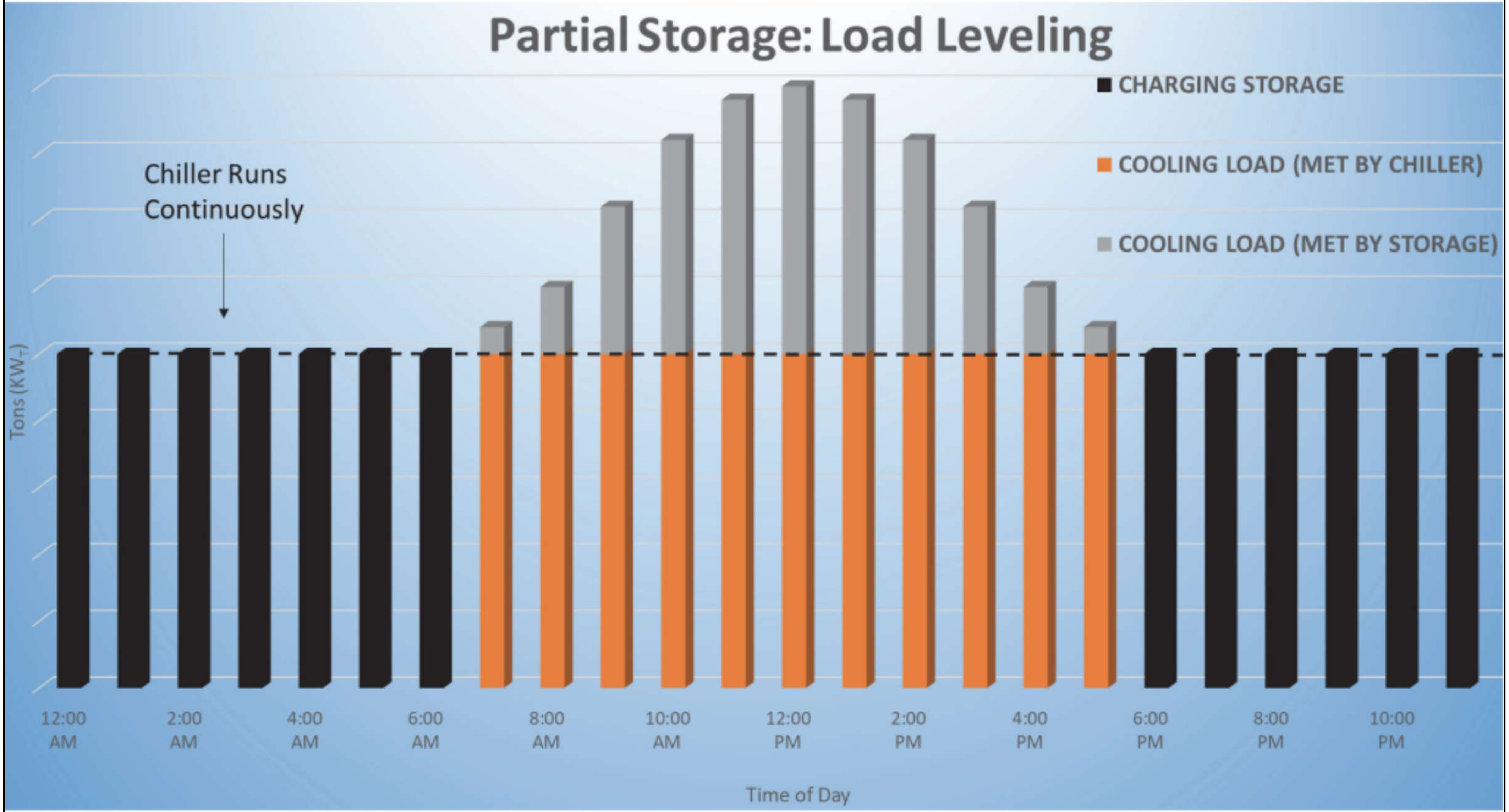
- Identifying demand-shift period
- Chiller priority
- Storage priority
- Charging rate control
- Load prediction
- Renewable energy source priority

Full-storage operating strategy



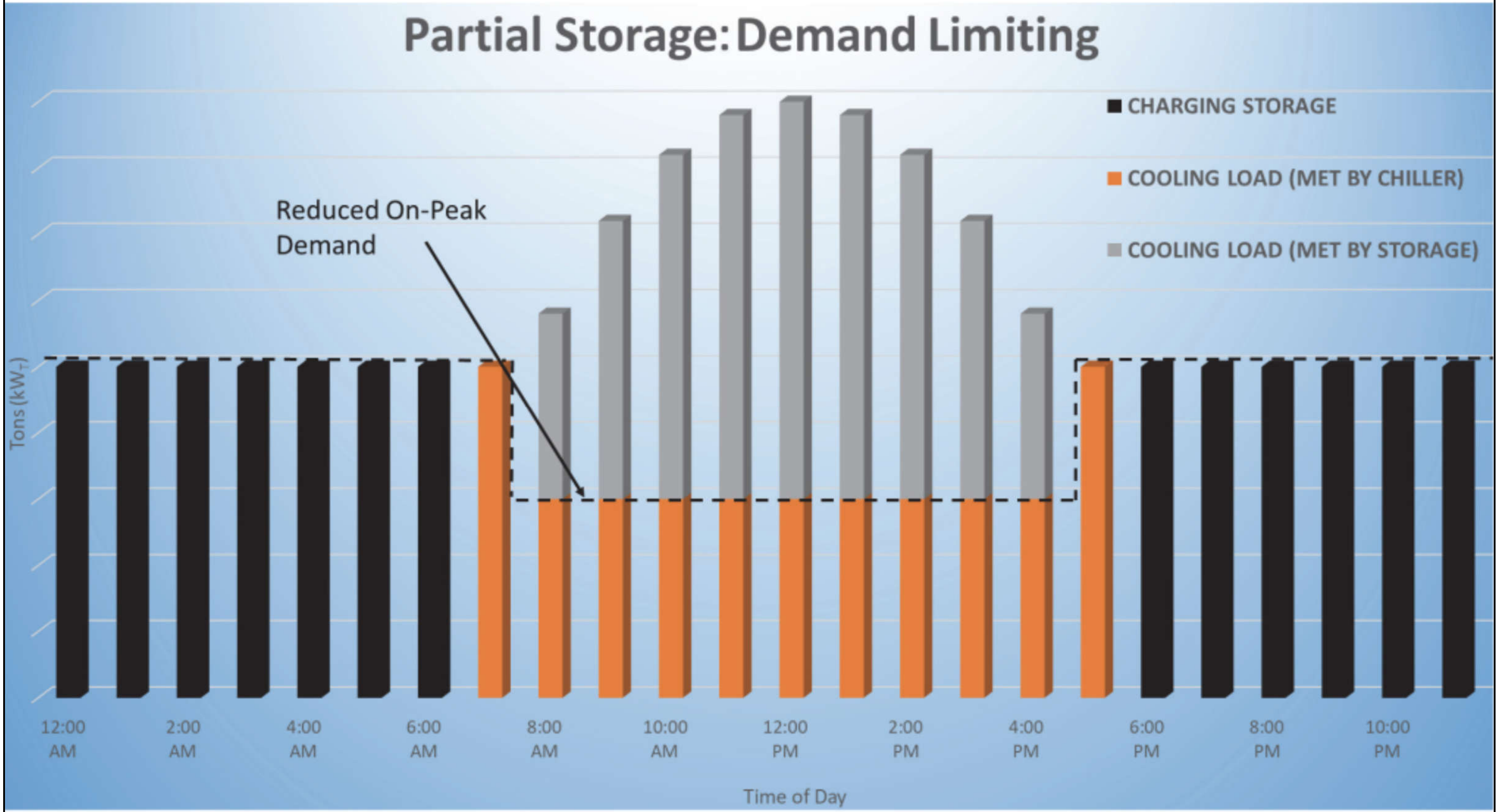
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Partial-storage load leveling operating strategy



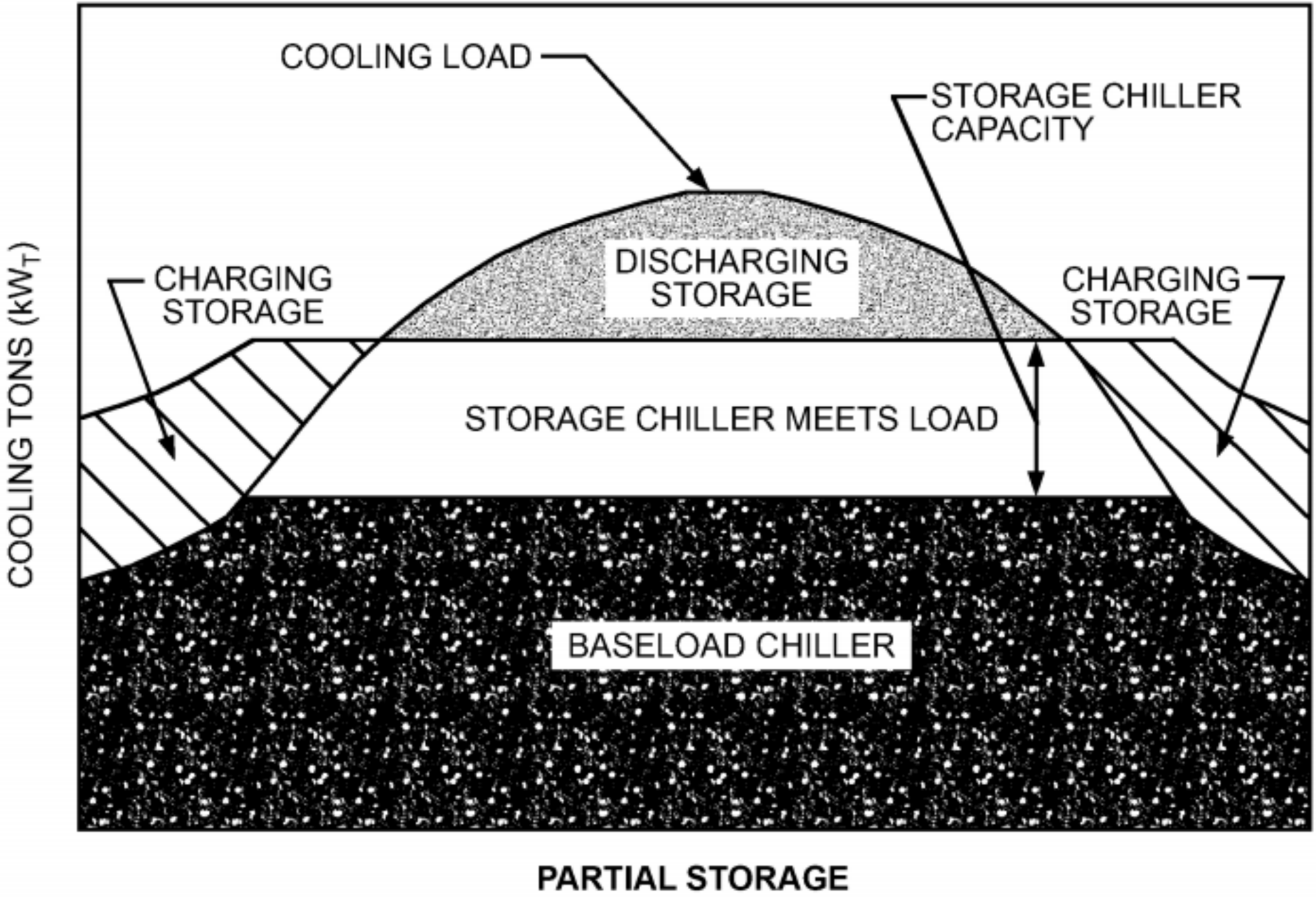
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Partial-storage demand limiting operating strategy



(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Baseloading operation with partial cool storage



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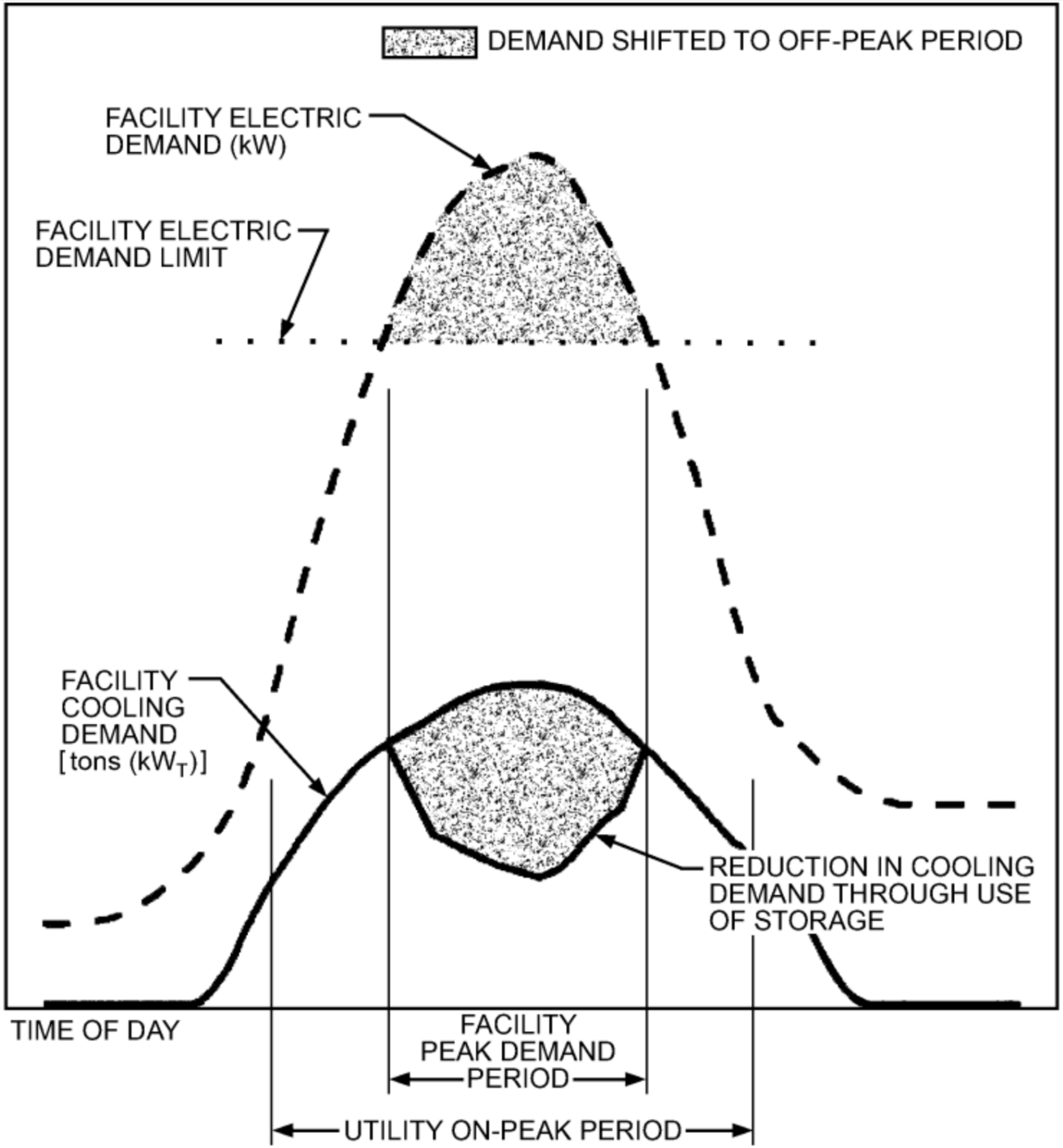
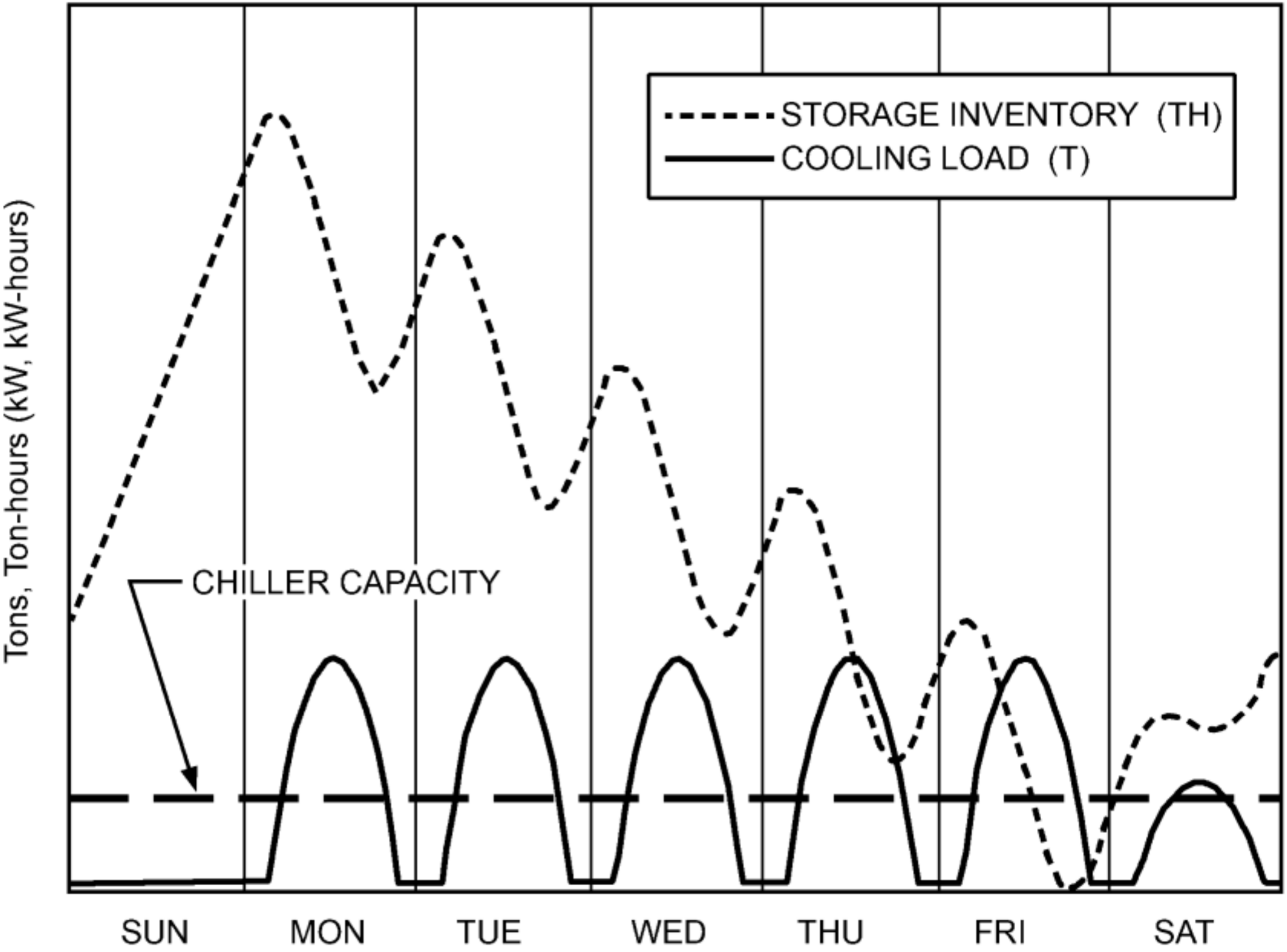


Demand limiting operational strategy for electric and cooling demand

(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

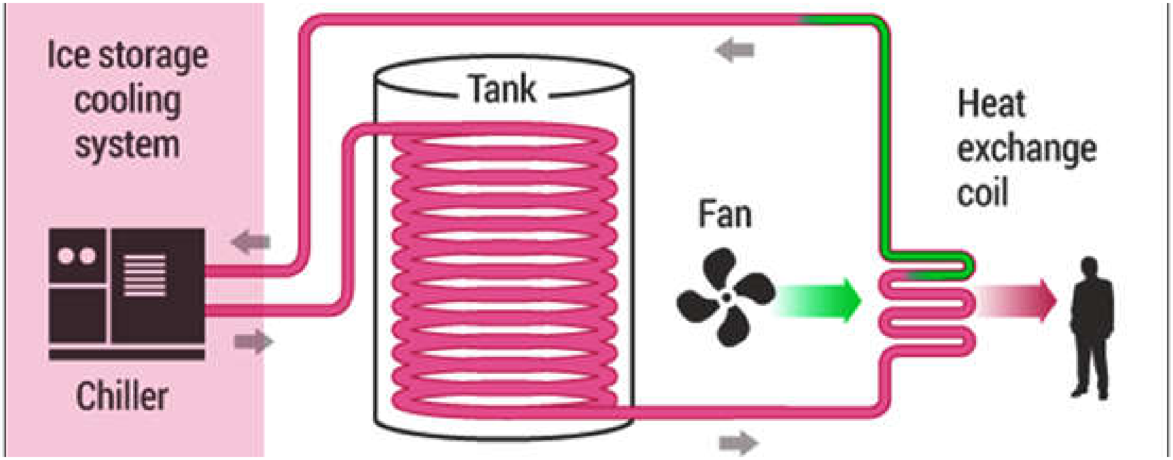
Weekly storage cycle



(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Common thermal energy storage operating modes

Operating Mode	Cool Thermal Energy Storage
Charging storage	Operating cooling equipment to remove heat from storage
Charging storage while meeting loads	Operating cooling equipment to remove heat from storage and meet loads
Meeting loads from storage only	Discharging (adding heat to) storage to meet loads without operating cooling equipment
Meeting loads from storage and direct equipment operation	Discharging (adding heat to) storage and operating cooling equipment to meet loads
Meeting loads from direct equipment operation only	Operating cooling equipment to meet loads (no fluid flow to or from storage)



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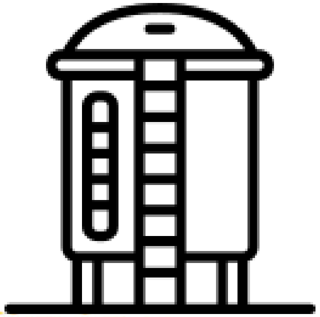
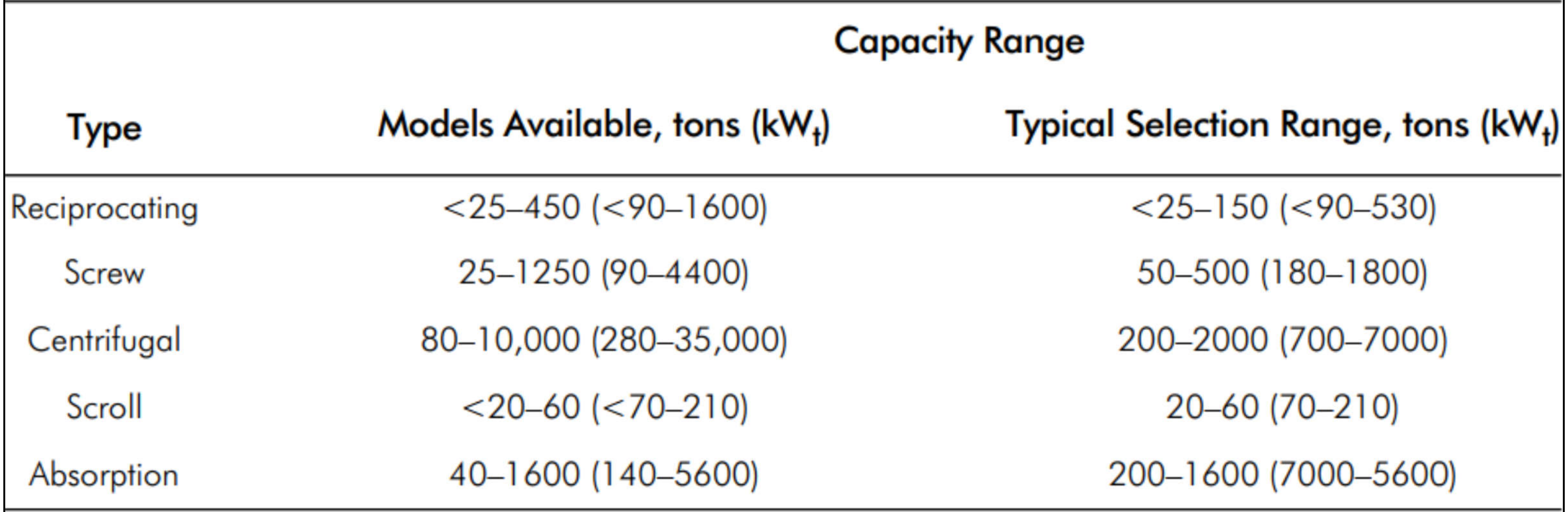
Cool thermal storage



- Sizing of cooling plants & storage:
  - Determine the building or system load profile
  - Select the design day system operating strategy
  - Select the appropriate storage technology
  - Calculate the initial chiller size and initial storage capacity
  - Refine and finalize the chiller and storage equipment selection

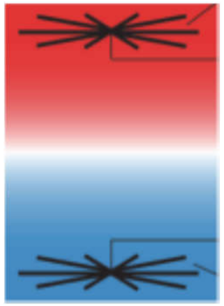
Capacity ranges for various chiller types



Type	Capacity Range Models Available, tons (kW_t)	 Typical Selection Range, tons (kW_t)
Reciprocating	<25–450 (<90–1600)	<25–150 (<90–530)
Screw	25–1250 (90–4400)	50–500 (180–1800)
Centrifugal	80–10,000 (280–35,000)	200–2000 (700–7000)
Scroll	<20–60 (<70–210)	20–60 (70–210)
Absorption	40–1600 (140–5600)	200–1600 (7000–5600)

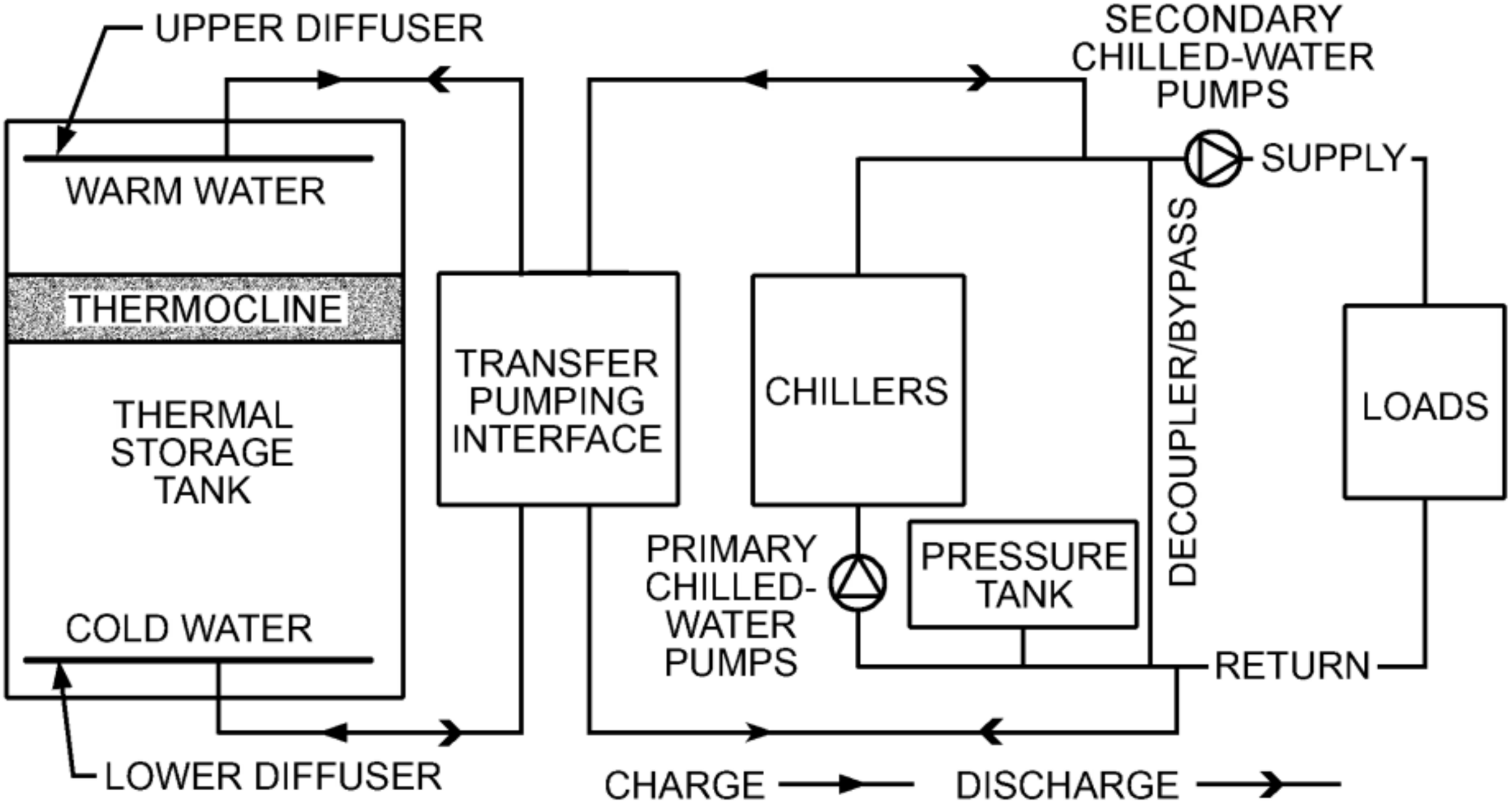
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Chilled-water storage



- Major characteristics:
    - Uses standard chillers operating at high rates of efficiency with no need for special equipment
    - Is ideal for increasing capacity of existing conventional systems
    - Becomes increasingly economical with larger tank sizes
    - Competitive first cost at approximately 2000 ton-h
    - Can serve double duty by providing a water reservoir for fire protection
    - Is proven, reliable and has a long history of successful installations
    - Can be configured to store both warm and chilled water

Basic stratified chilled-water configuration



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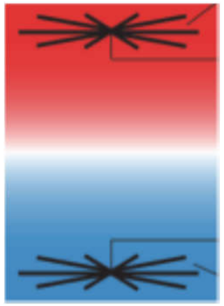
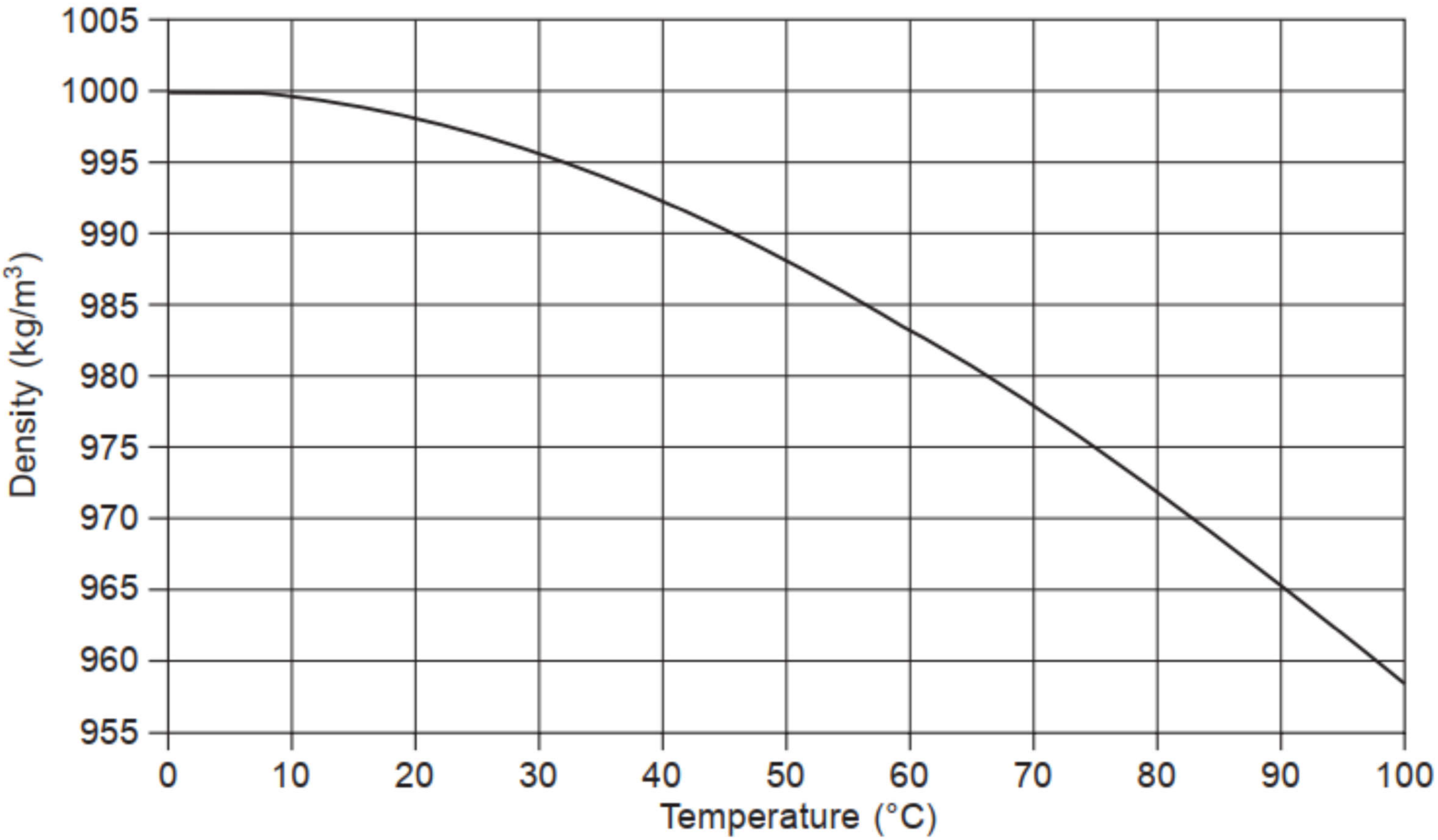
Chilled-water storage



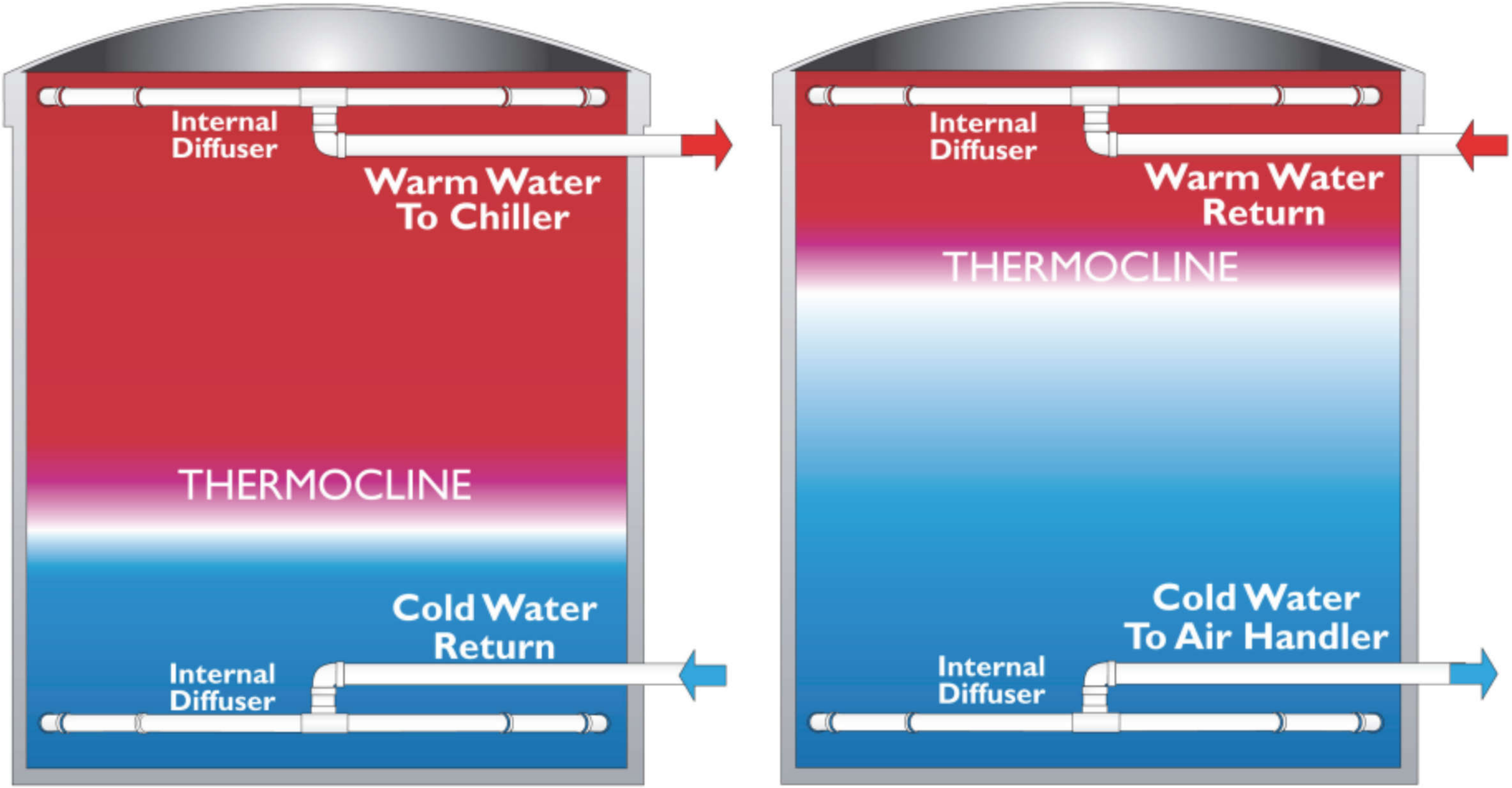
- Stratification:
  - Separation between warmer and cooler water
    - Tendency of water to form horizontal layers of uniform temperature due to its temperature dependent density
    - Warmer, less dense water lies above cooler, denser chilled water due to buoyancy forces
  - Well-designed stratified chilled water storage tanks can deliver 90% to 95% of the stored energy as useful cooling
  - A thermocline or transition layer between the warm upper zone and the cool lower zone

Water density as a function of temperature



(Source: Cabeza L. F. (ed.), 2015. *Advances in Thermal Energy Storage Systems: Methods and Applications*, Woodhead Publishing. https://doi.org/10.1016/C2013-0-16453-7)

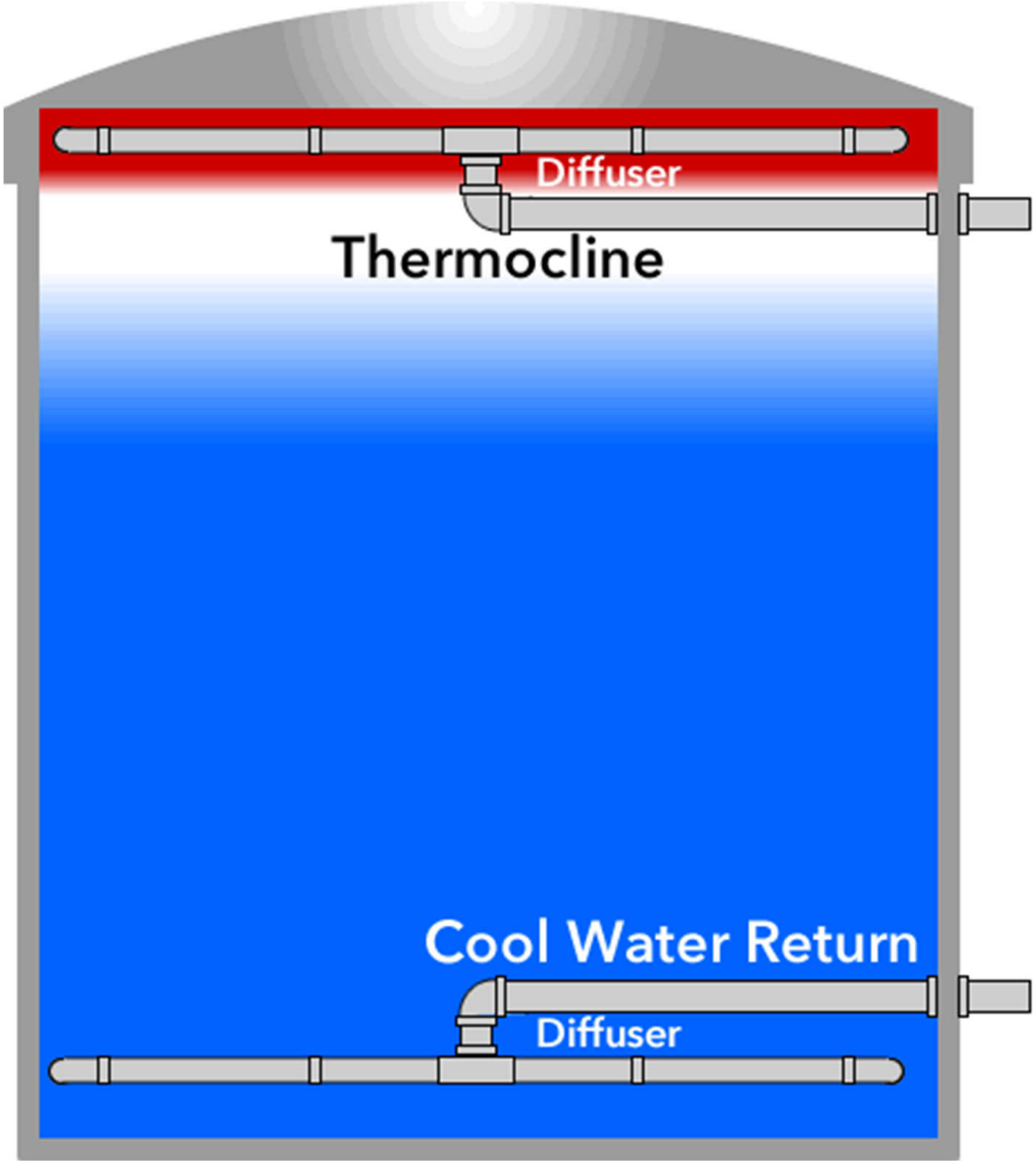
Stratified chilled-water tank during (a) recharge and (b) discharge



(a) recharge (b) discharge

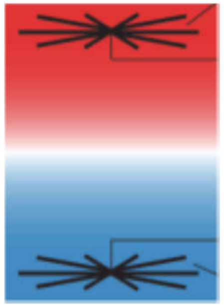
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Chilled water thermal storage stratified tank



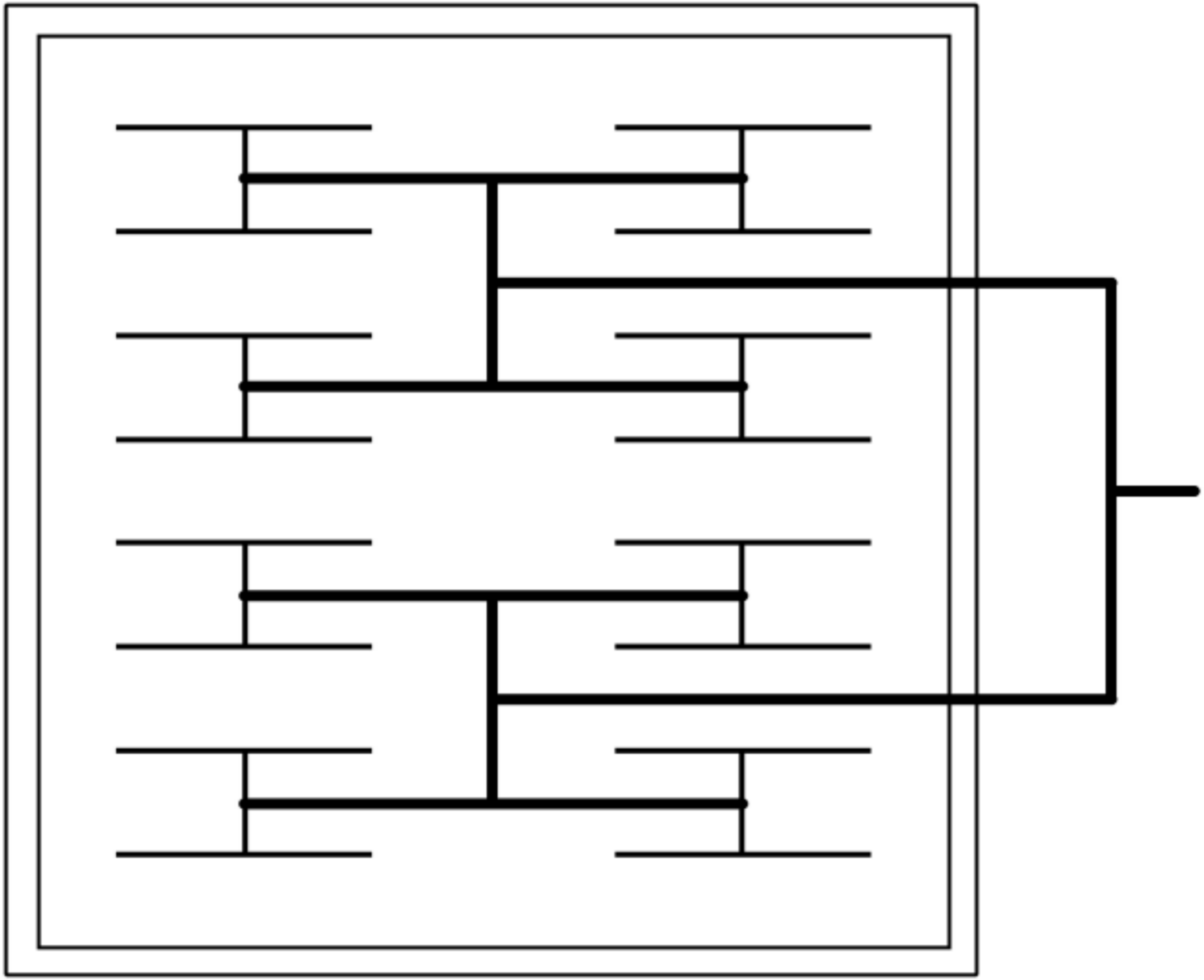
(Source: https://www.pacifictank.net/tes-tanks/)

Chilled-water storage



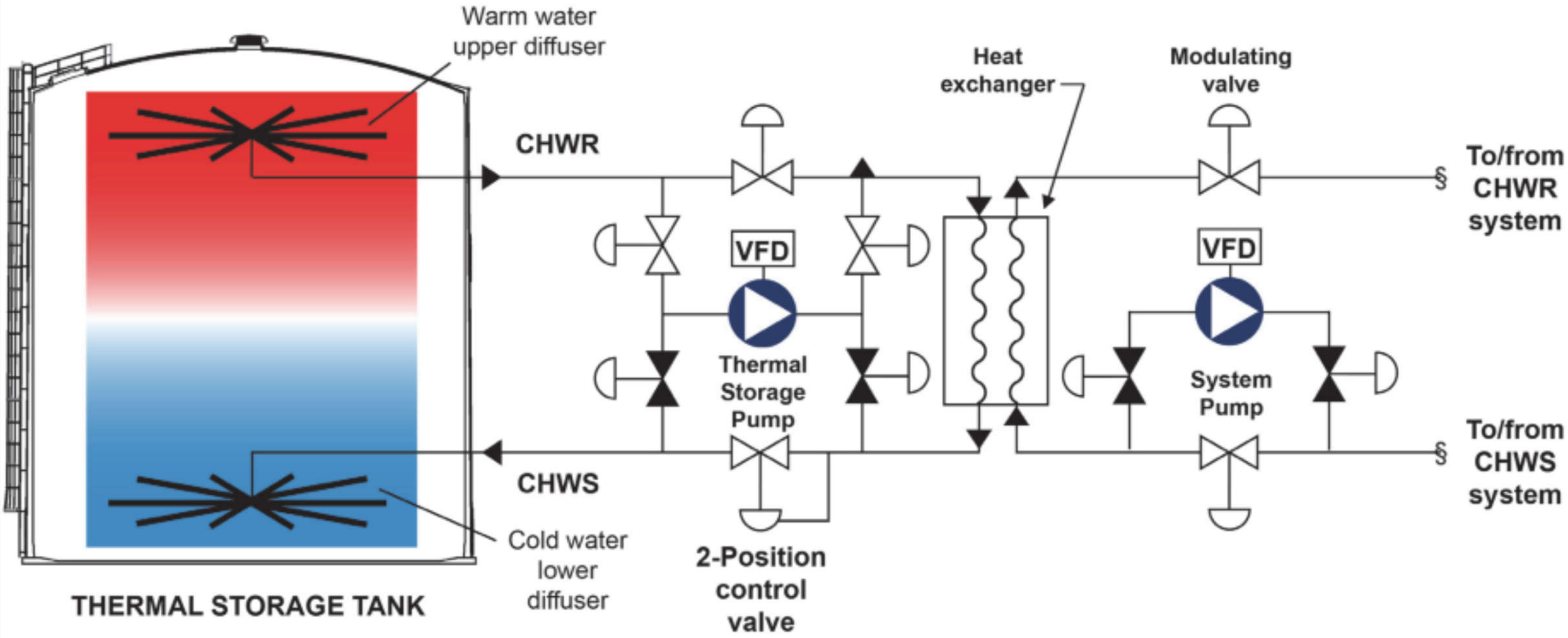
- Design of chilled-water storage tanks:
  - Shape, location, construction factors, material of construction, insulation and diffuser design
- Controls and instrumentation:
  - Temperature sensors, pressure sensors, flow meters and water level sensors
  - Monitor the levels of warm and cold water
  - Multiple tanks require extra valving and controls
- Interface with building systems
  - Temperature differential & distribution pressure

H-style diffuser in a chilled water storage tank



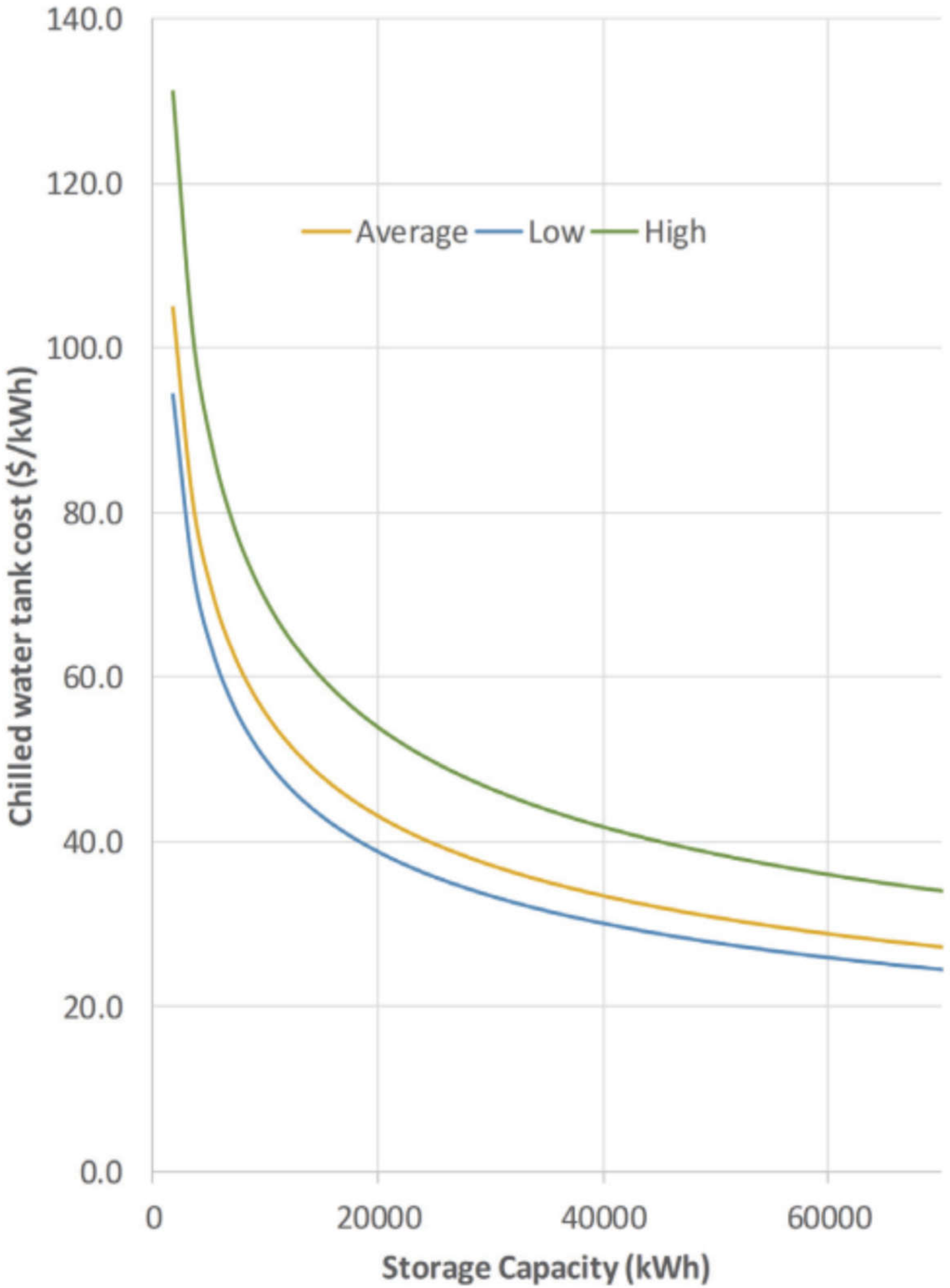
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Chilled-water storage with pressure break heat exchanger



(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Costs for chilled-water storage tanks



Factors affecting the costs:

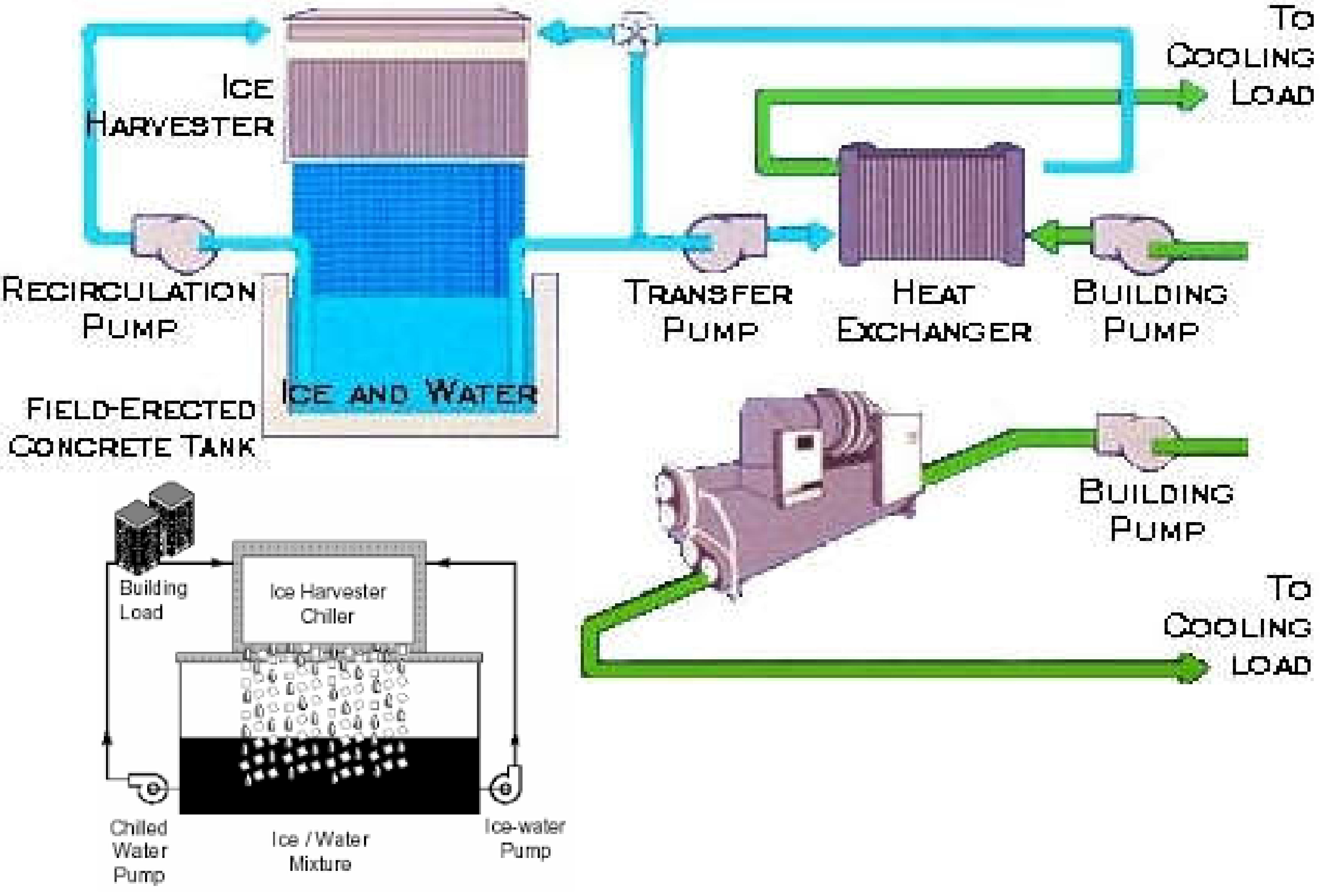
- Chilled-water ΔT (between supply and return)
- Material
- Shape
- Size
- Existing soil type and capacity
- Local conditions affecting ease of construction
- Local labour requirements
- Coatings
- Insulation
- Foundation

(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Ice thermal storage

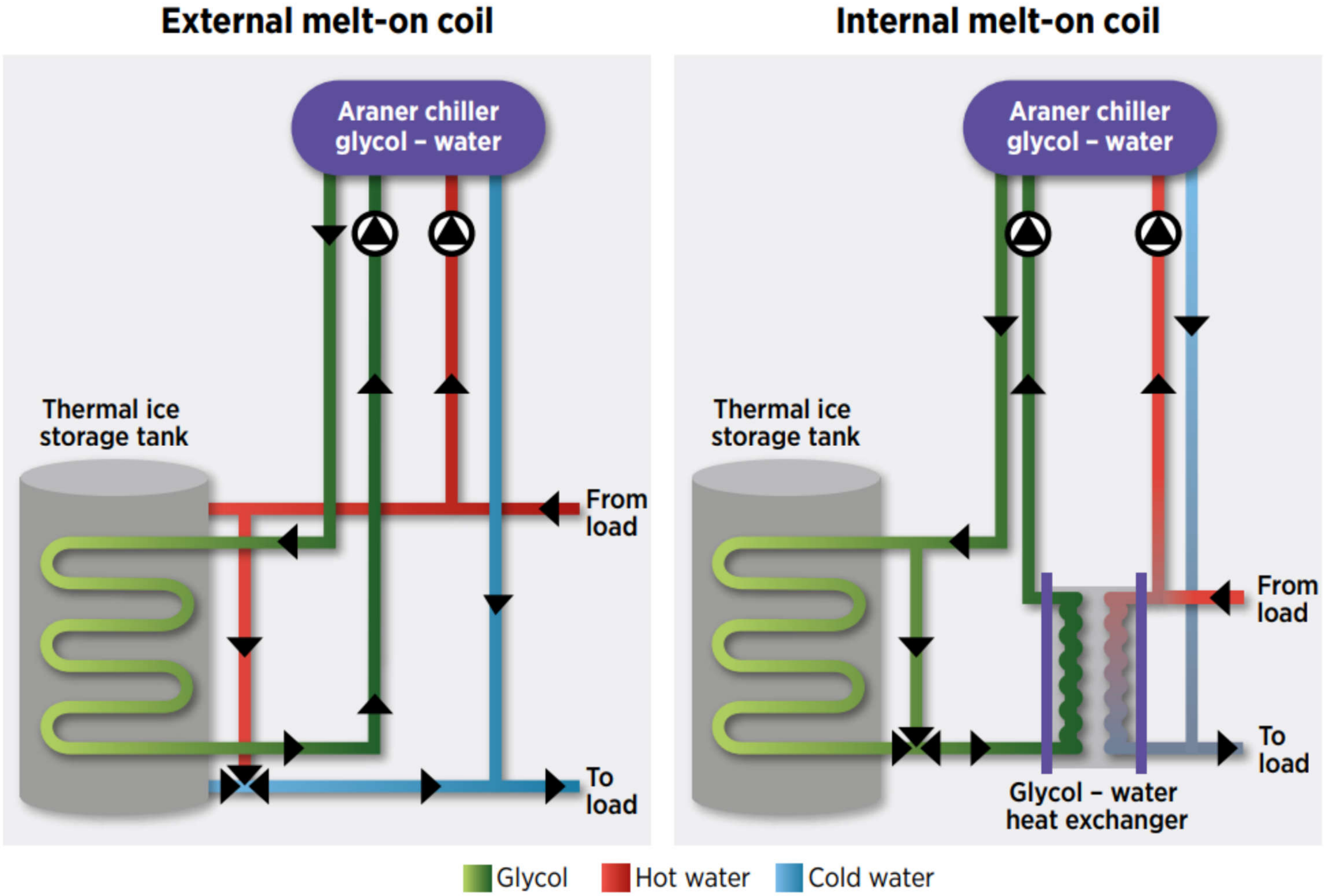
- The most prevalent ice storage technologies:
  - 1. Ice maker systems (ice harvester including spray-slush ice)
  - 2. Ice-on-coil in an open water side system (requires some periodic water treatment)
  - 3. Ice-on-coil using brine in a closed (pressurized) water side system
  - 4. Ice slurry systems (pump the ice slurry)
  - 5. Other system types (such as encapsulated ice, ice balls, eutectic salt storage) are variations being developed and commercialized

Ice maker (ice harvester) system



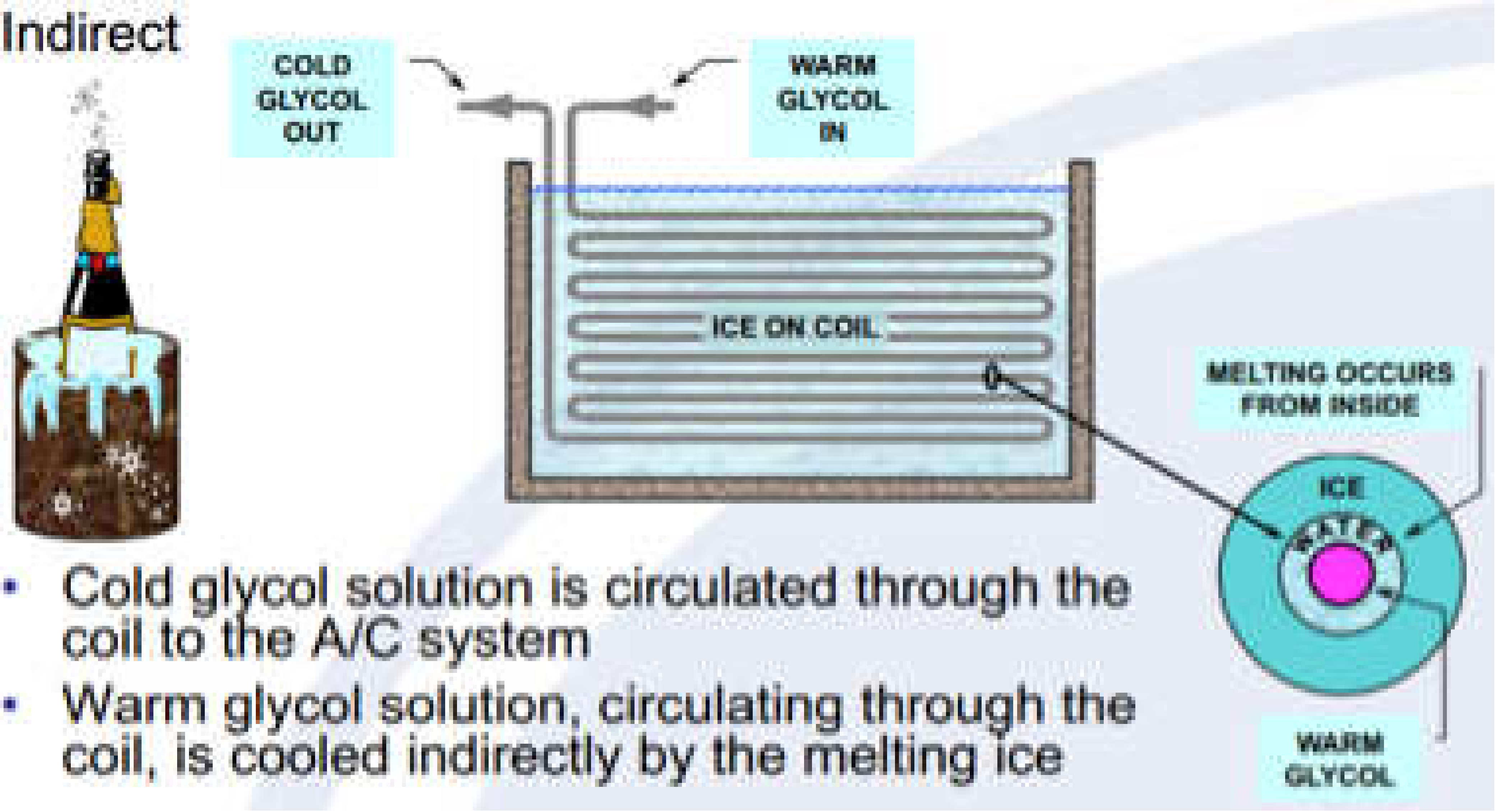
(Source: Trane)

Ice-on-coil system



(Source: IRENA, 2020. *Innovation Outlook: Thermal Energy Storage*, International Renewable Energy Agency (IRENA), Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf)

Internal-melt ice storage tank

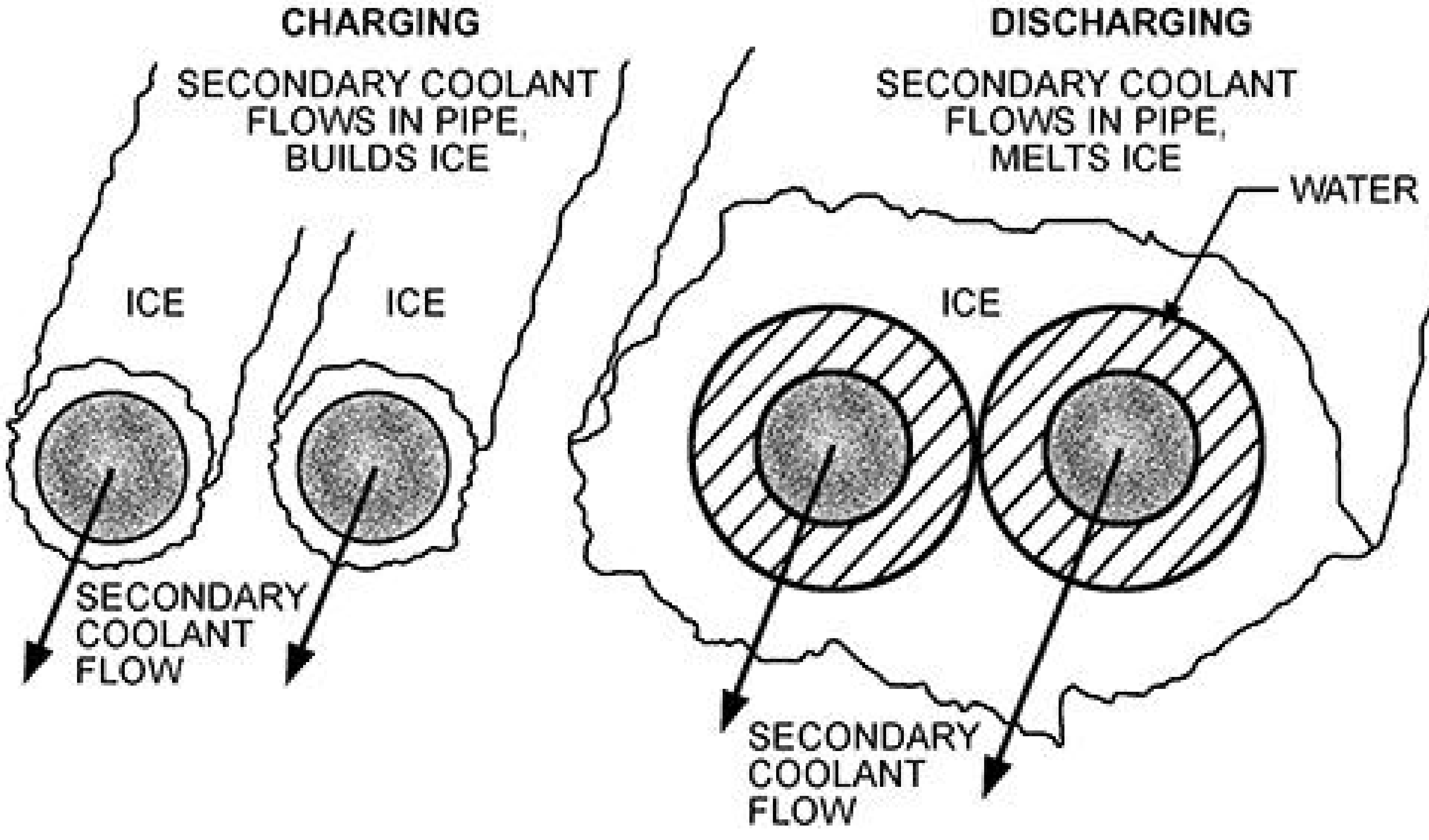


Indirect

- Cold glycol solution is circulated through the coil to the A/C system
- Warm glycol solution, circulating through the coil, is cooled indirectly by the melting ice

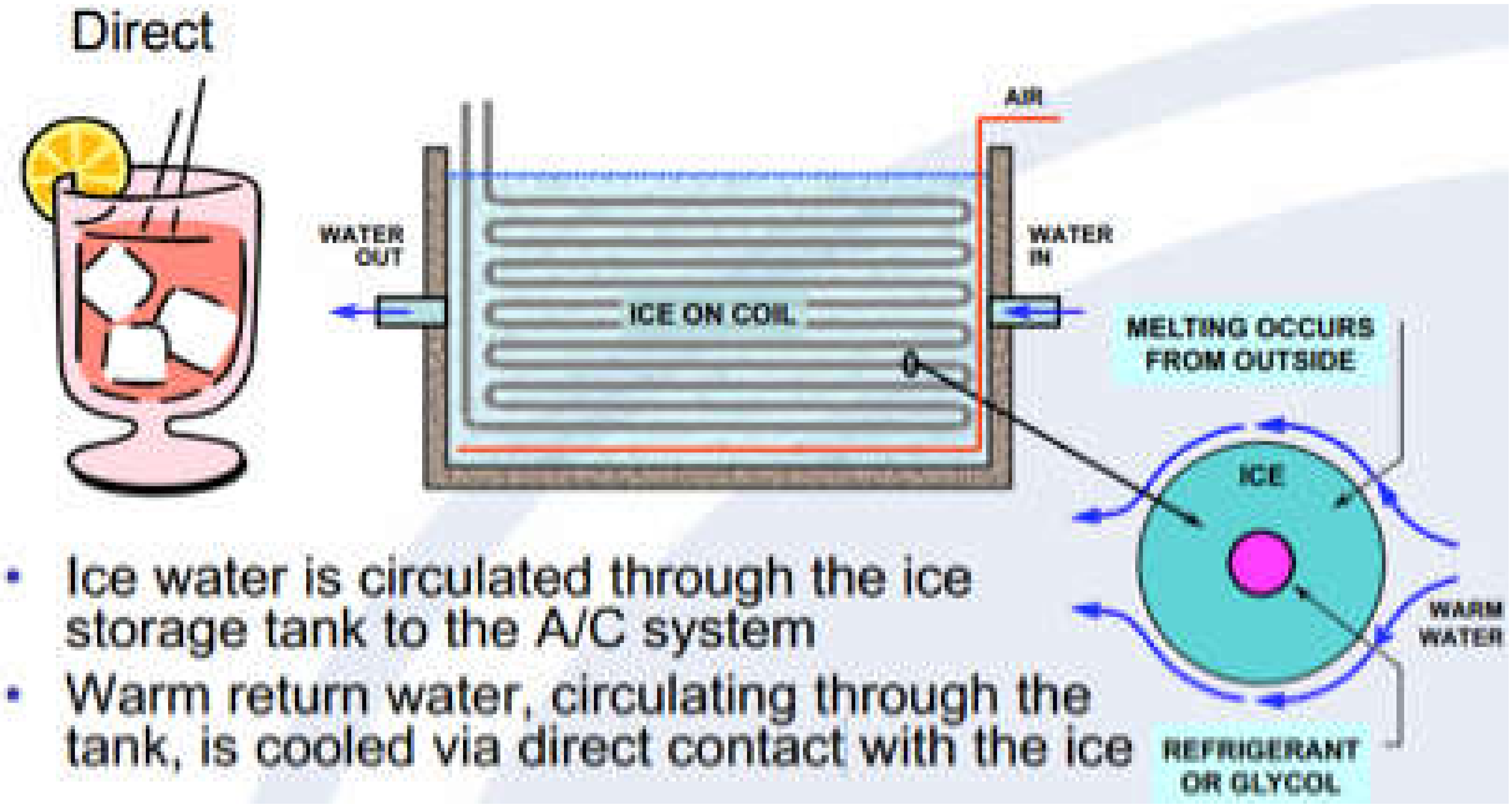
(Source: http://www.danielrdgz.com/development-of-a-three-ton-source-of-cool-air.html)

Charge and discharge of internal-melt ice storage



(Source: *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, Chp. 50 Thermal Storage)

External-melt ice storage tank

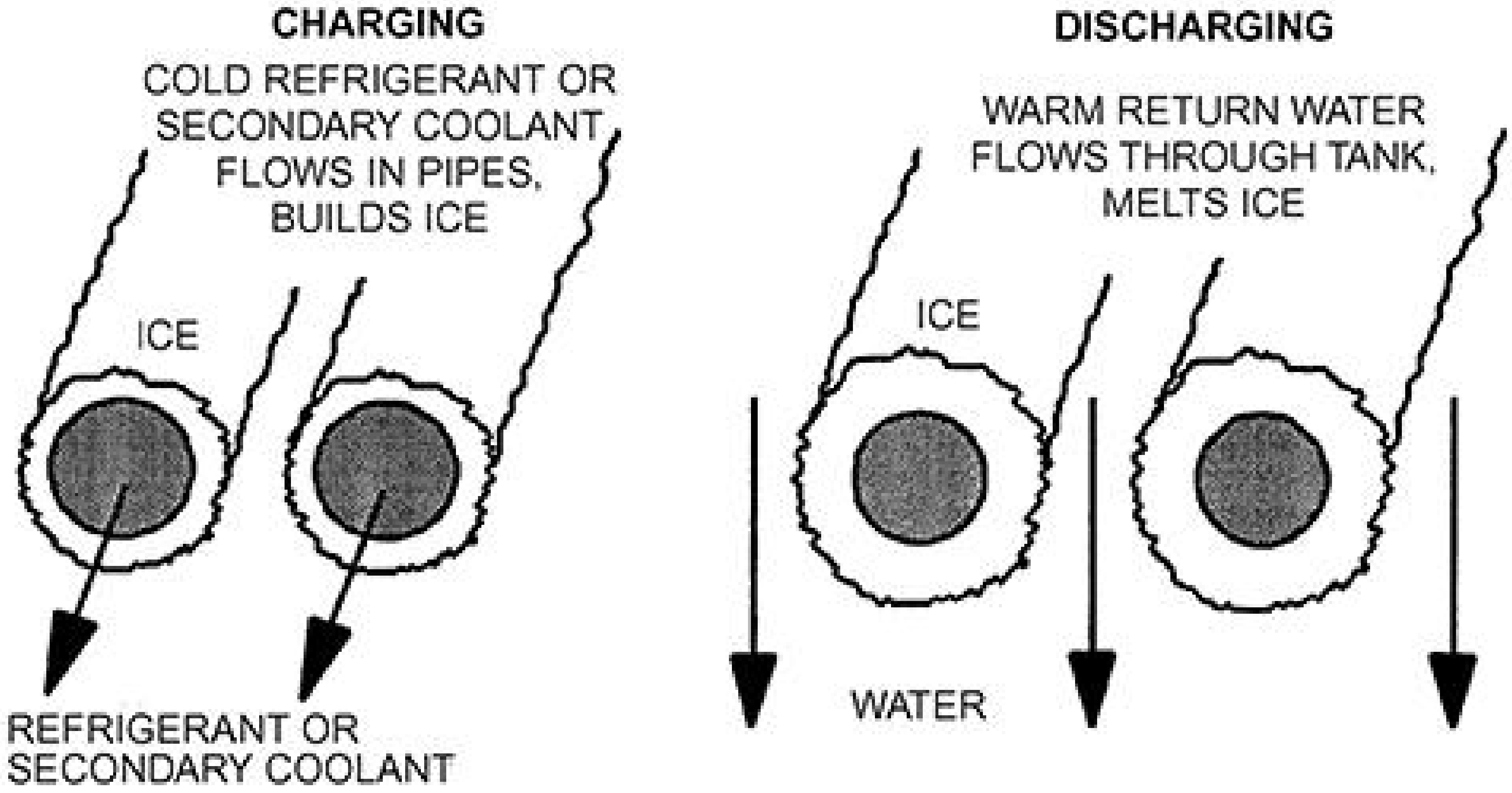


Direct

- Ice water is circulated through the ice storage tank to the A/C system
- Warm return water, circulating through the tank, is cooled via direct contact with the ice

(Source: http://www.danielrdgz.com/development-of-a-three-ton-source-of-cool-air.html)

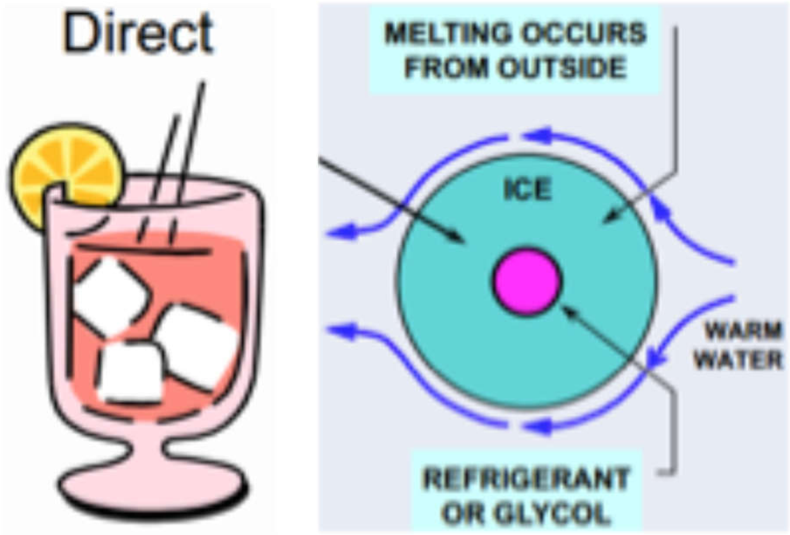
Charge and discharge of external-melt ice storage

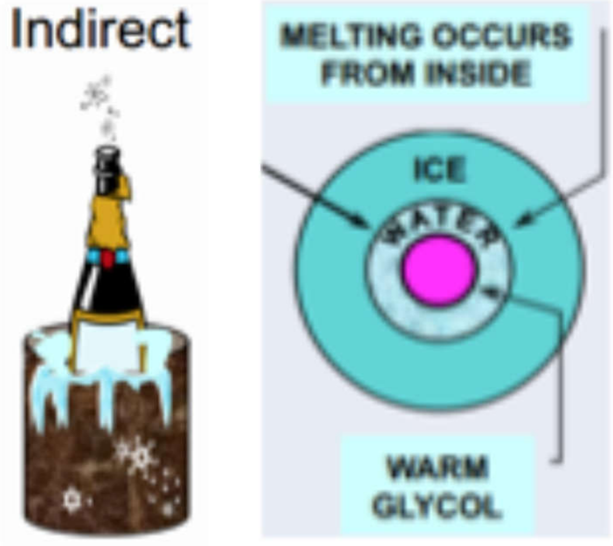


(Source: *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, Chp. 50 Thermal Storage)

Comparison of external-melt and internal-melt ice storage system

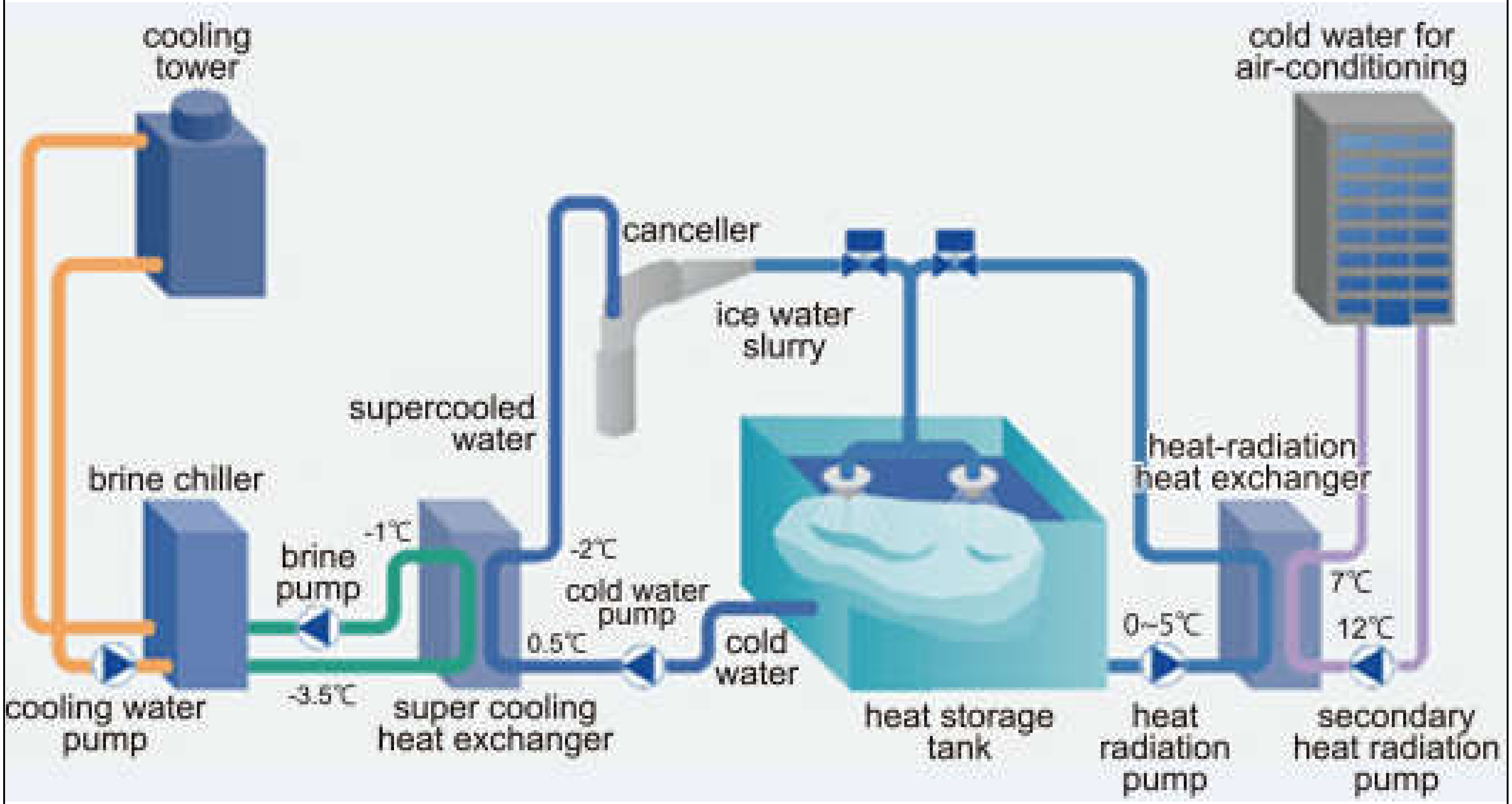
External-melt	**Internal-melt**
• Project requires constant, cold supply water temperature of about 1 °C or quick discharge periods • Trained operating staff • Savings in distribution piping system • Highest energy efficiency	• Projects does not require coldest possible supply temperature • Simpler design and operation • Individual buildings • Energy efficiency is less critical (extra heat transfer required)





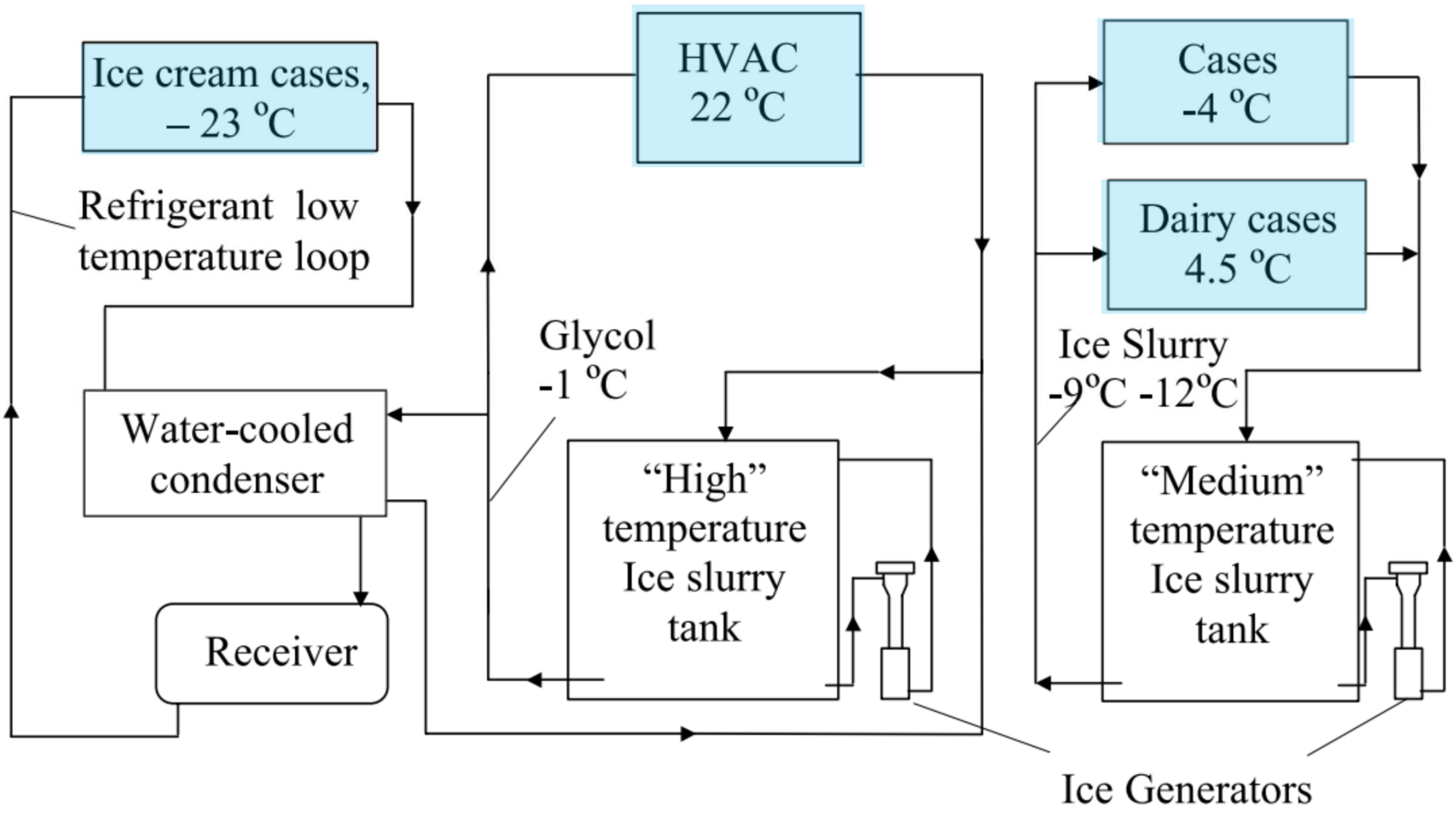
(Source: http://www.danielrdgz.com/development-of-a-three-ton-source-of-cool-air.html)

Schematic of a thermal storage system using ice water slurry



(Source: https://www.taikisha-group.com/service/heat-storage/stratherm/)

Schematic diagram of a supermarket ice slurry system

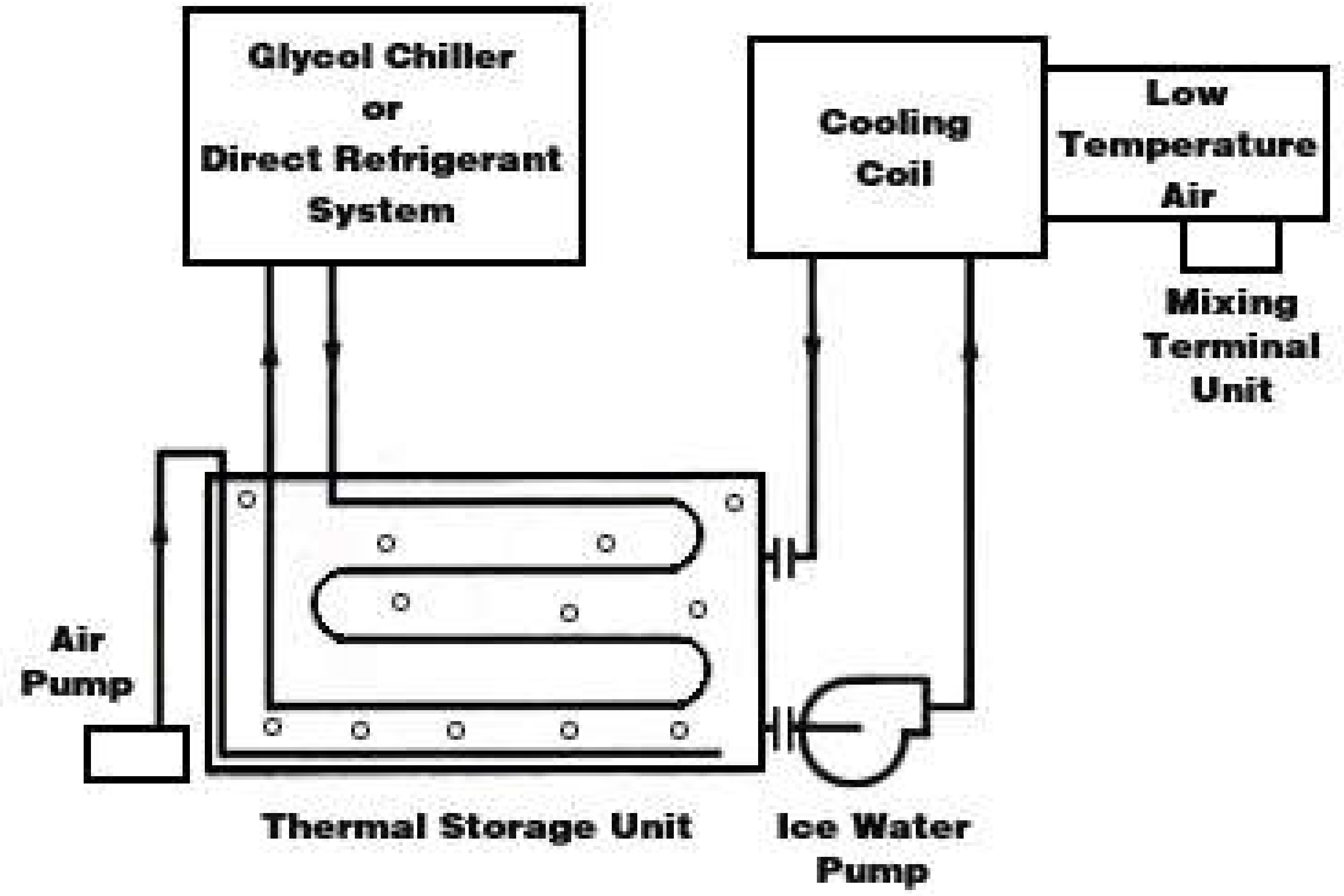


(Source: Bellas I. & Tassou S. A., 2005. Present and future applications of ice slurries, *International Journal of Refrigeration*, 28 (1) 115-121. https://doi.org/10.1016/j.ijrefrig.2004.07.009)

Ice thermal storage

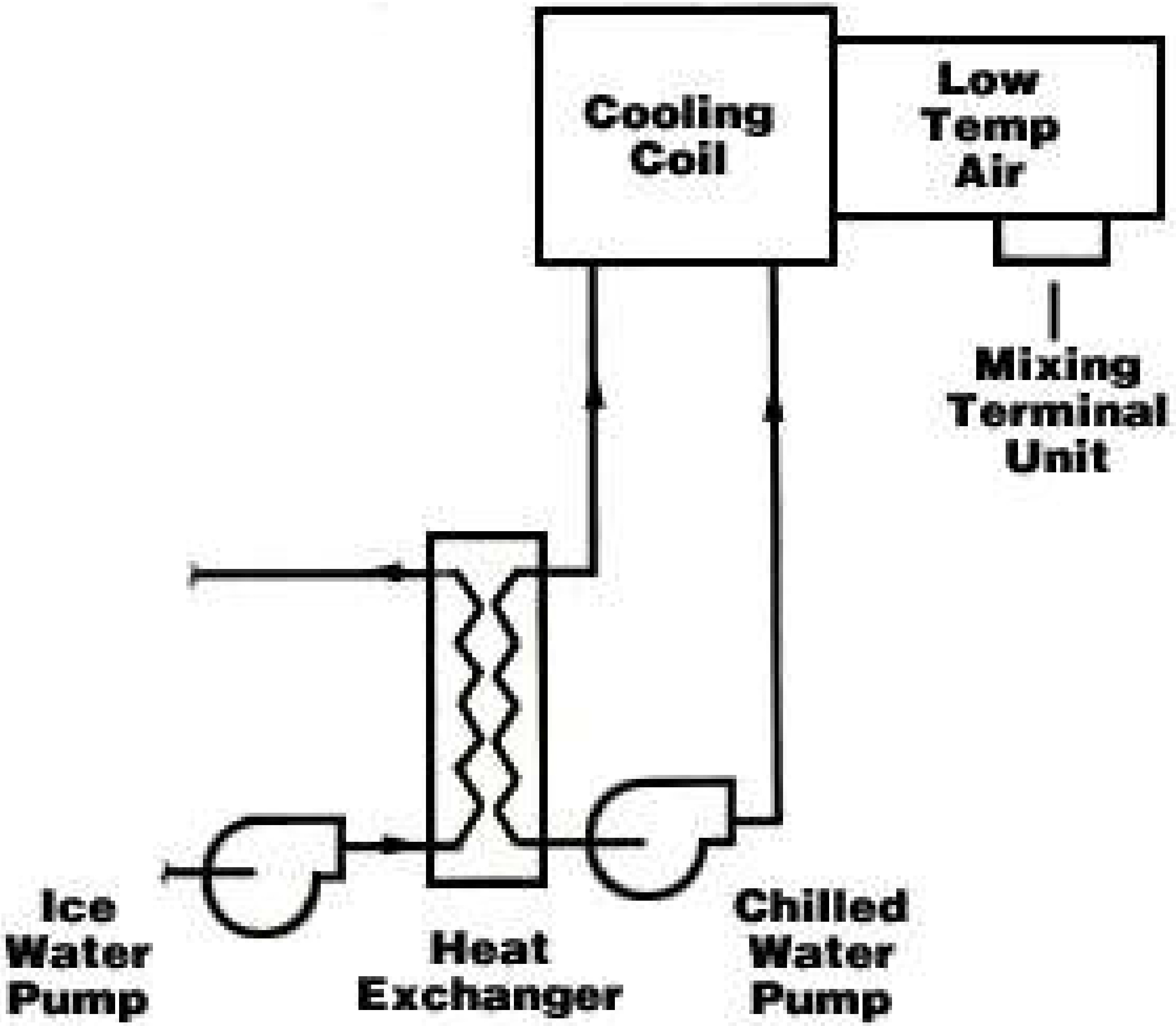
- System arrangements of ice storage systems:
  - 1. Open system (cold refrigerant or a brine solution is circulated through pipe coils submerged in an open water tank)
  - 2. Closed system (a heat exchanger is used between the circulating ice water and building chilled water)
  - 3. Modular ice storage systems using glycol brine (Chilled brine is circulated through a series of heat exchange tubes to freeze most of the liquid in the tank to ice)

Open system arrangement of ice storage systems



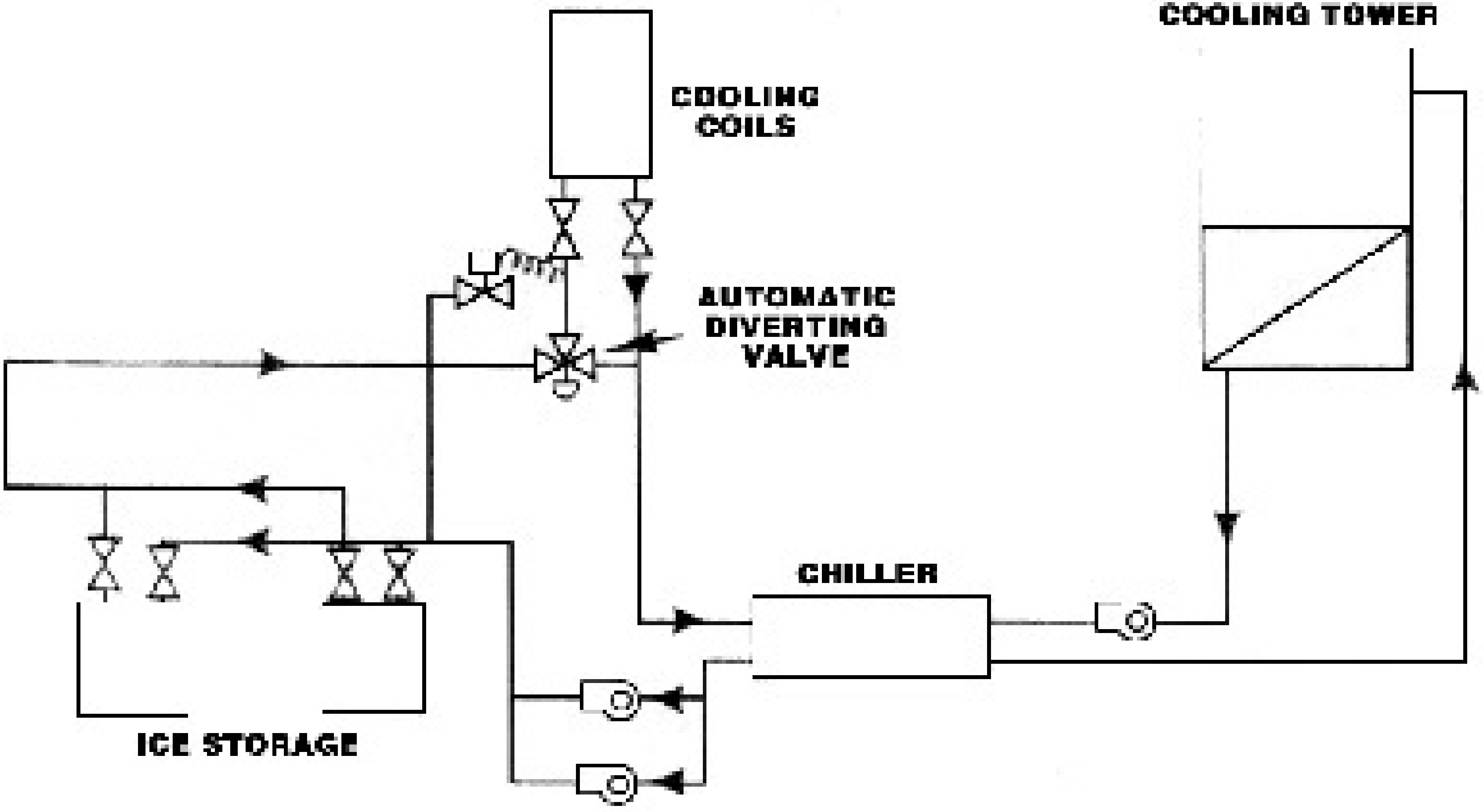
(Source: https://pdhonline.com/courses/m145/m145content.pdf)

Closed system arrangement of ice storage systems



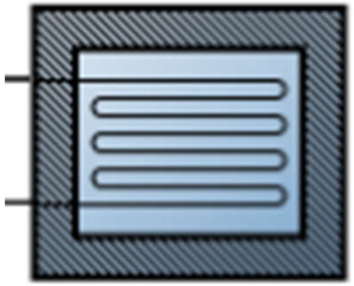
(Source: https://pdhonline.com/courses/m145/m145content.pdf)

Modular ice storage system using brine



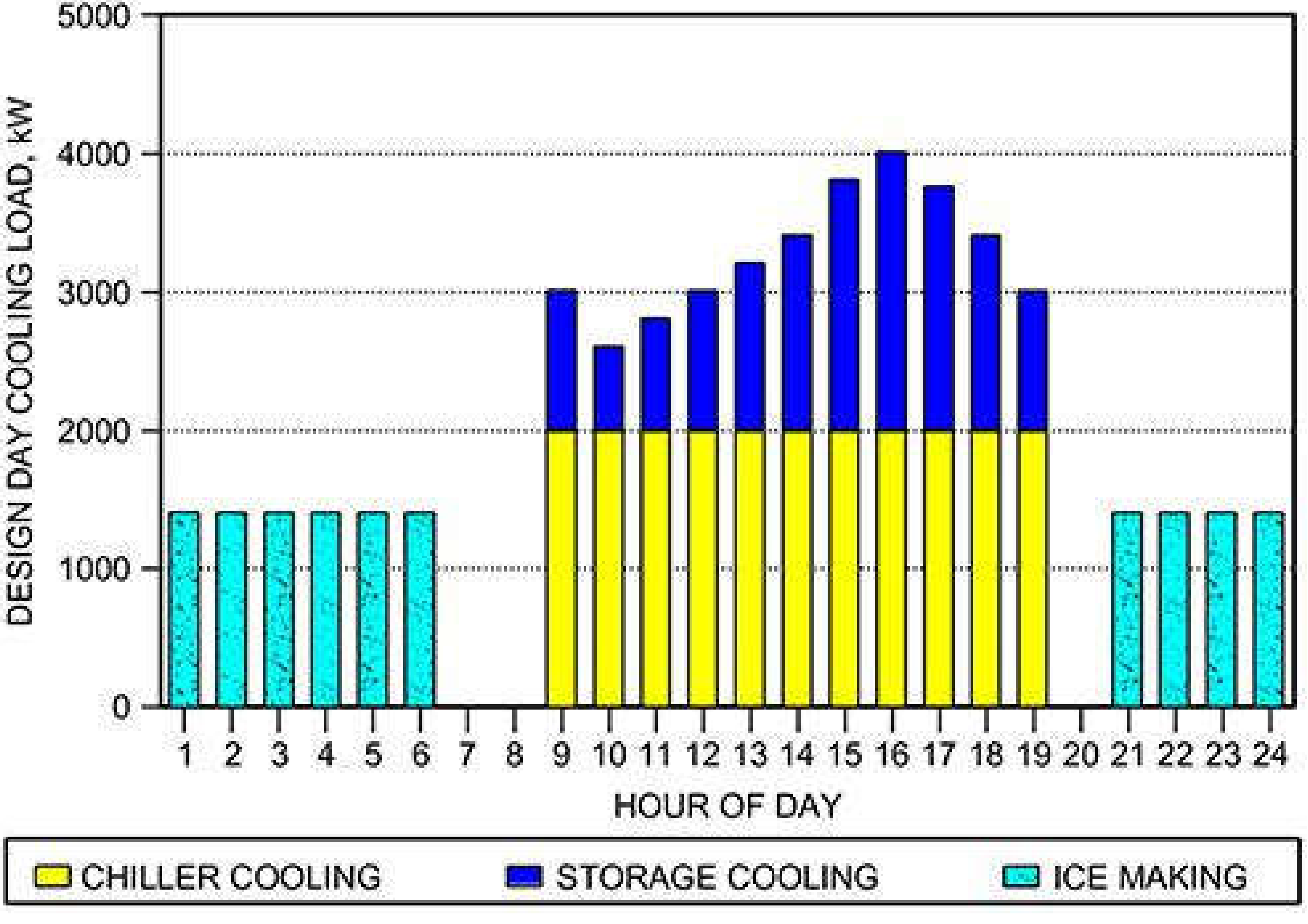
(Source: https://pdhonline.com/courses/m145/m145content.pdf)

Design of ice storage system



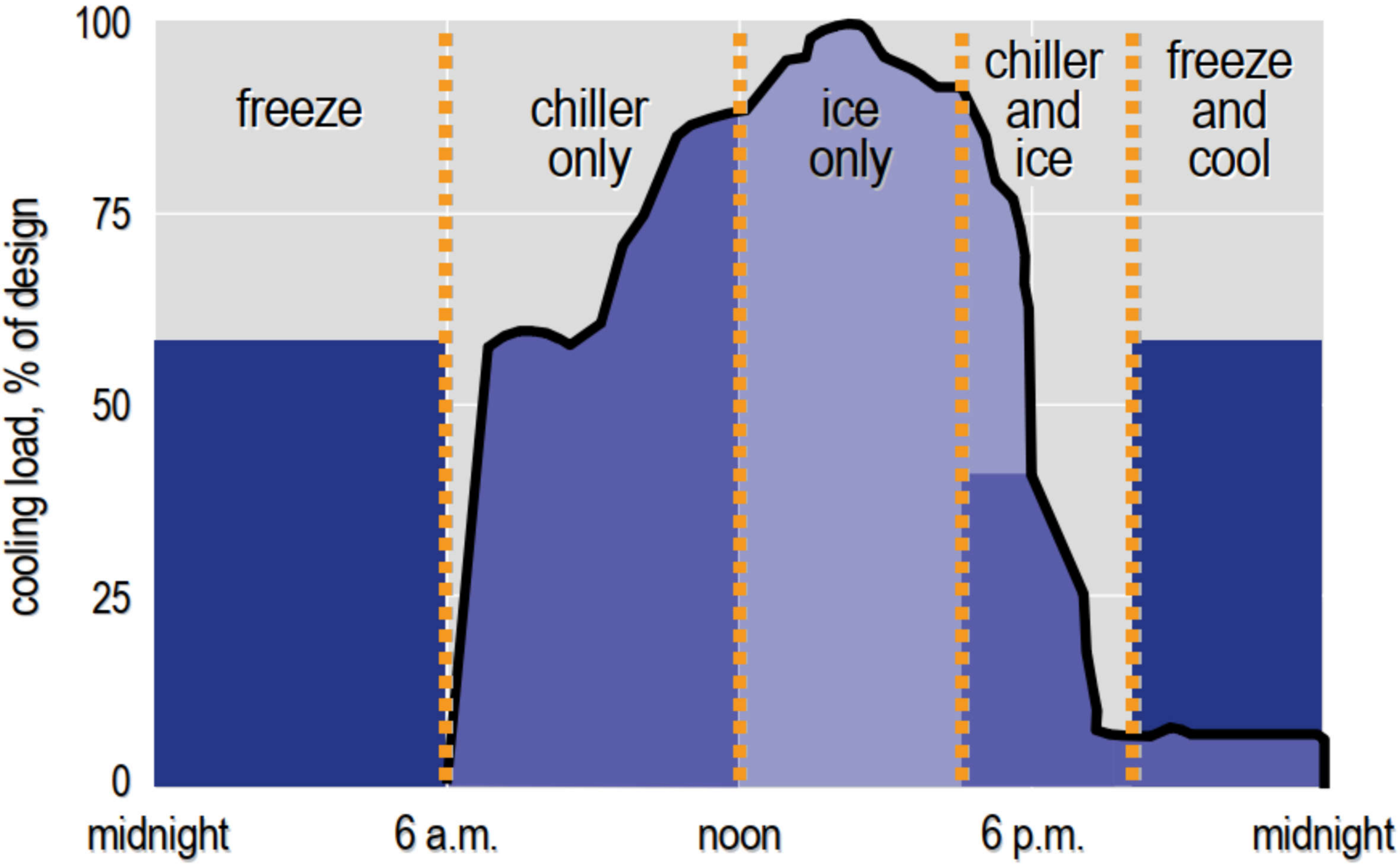
- Typical design process of ice storage systems:
  - 1. Define the mission
    - Which of the potential benefits of ice storage are more important for the project?
    - Priority of these benefits will dictate how the system is designed and controlled
  - 2. Determine ice storage capacity
    - Available space
    - Economics (installed cost & life-cycle cost)
    - Hourly cooling load & energy analysis
  - 3. Select the storage tanks and chillers

Minimum-sized chilled and storage contribution to cooling load



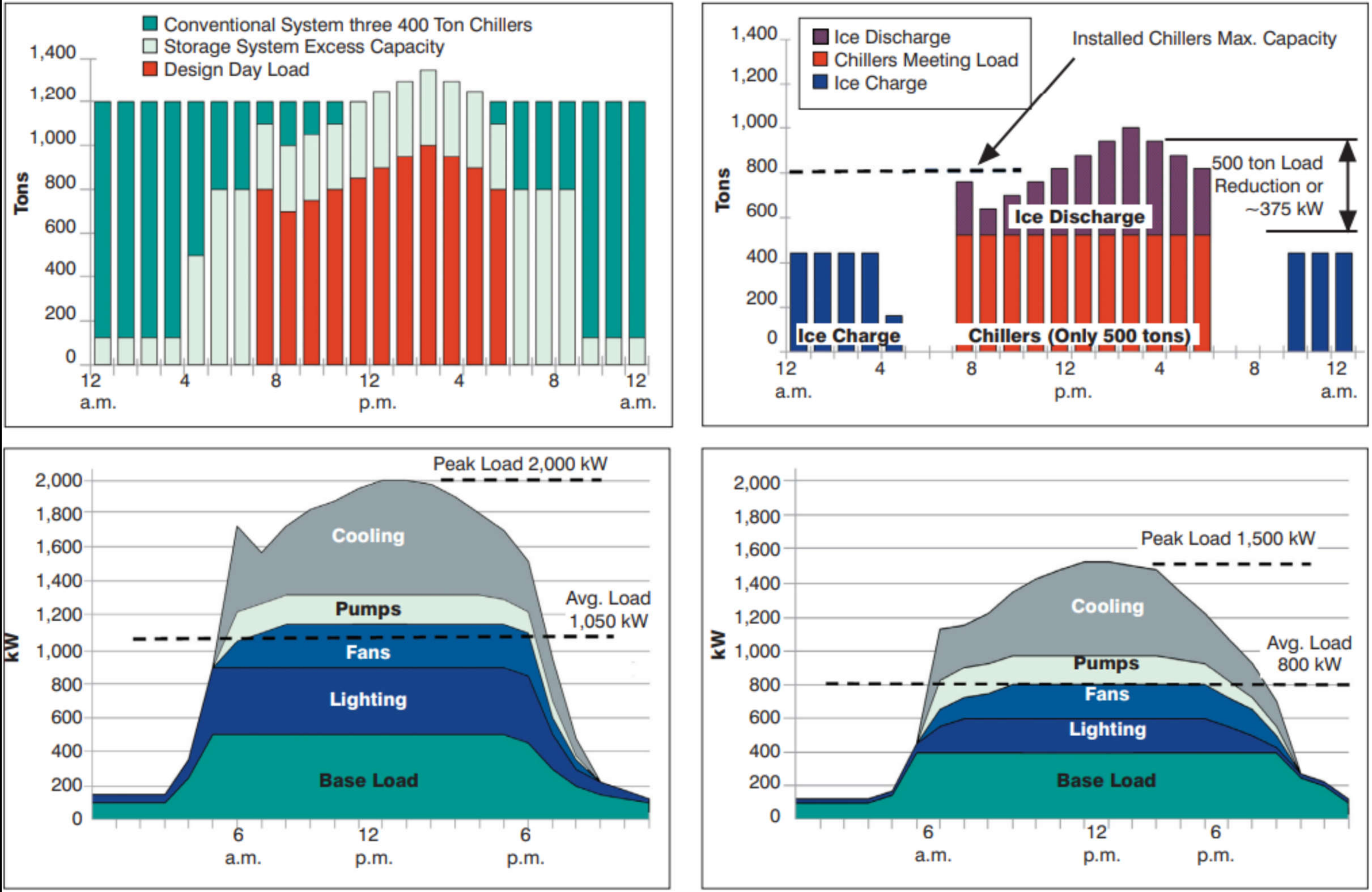
(Source: *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, Chp. 50 Thermal Storage)

Tactical and strategic control of ice thermal storage system



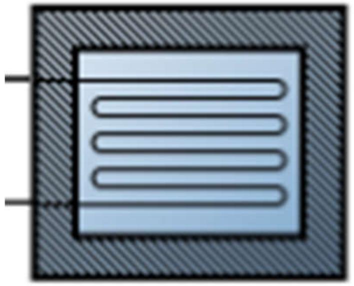
(Source: Trane)

Analysis of cooling load for ice thermal storage



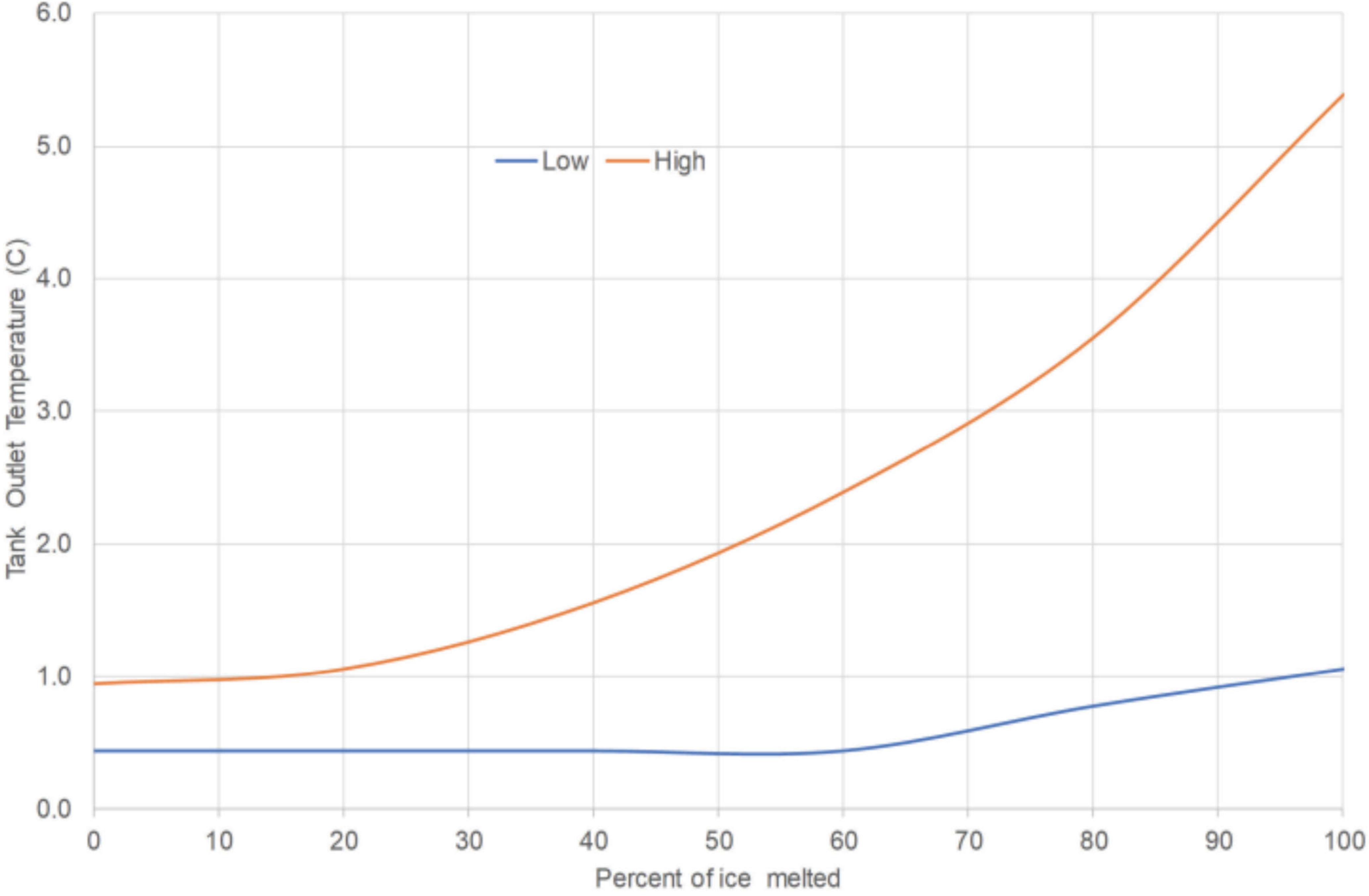
(Source: MacCracken M., 2004. Thermal energy storage in sustainable buildings, *ASHRAE Journal*, 46 (9) S39-S41.)

Design of ice storage system



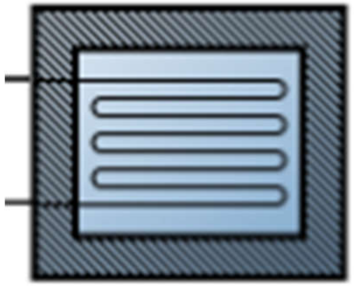
- Design considerations:
  - Sizing basis (full/partial storage, demand limiting)
  - Chiller capacity and storage capacity, and required supply temperature
  - Design operating profile (load, chiller output, and amount added to or taken from storage)
  - Chiller operating conditions while charging storage when meeting the load directly
  - Chiller efficiency under each operating condition
  - System control strategy (design-day and part-load)

Typical ice harvester storage discharge temperature range



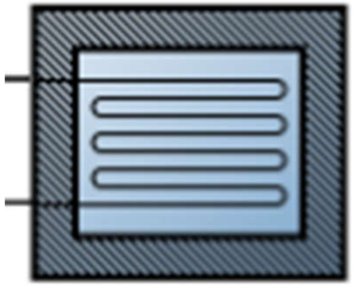
(Source: Glazer J., 2019. *ASHRAE Design Guide for Cool Thermal Storage*, 2nd Edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.)

Design of ice storage system



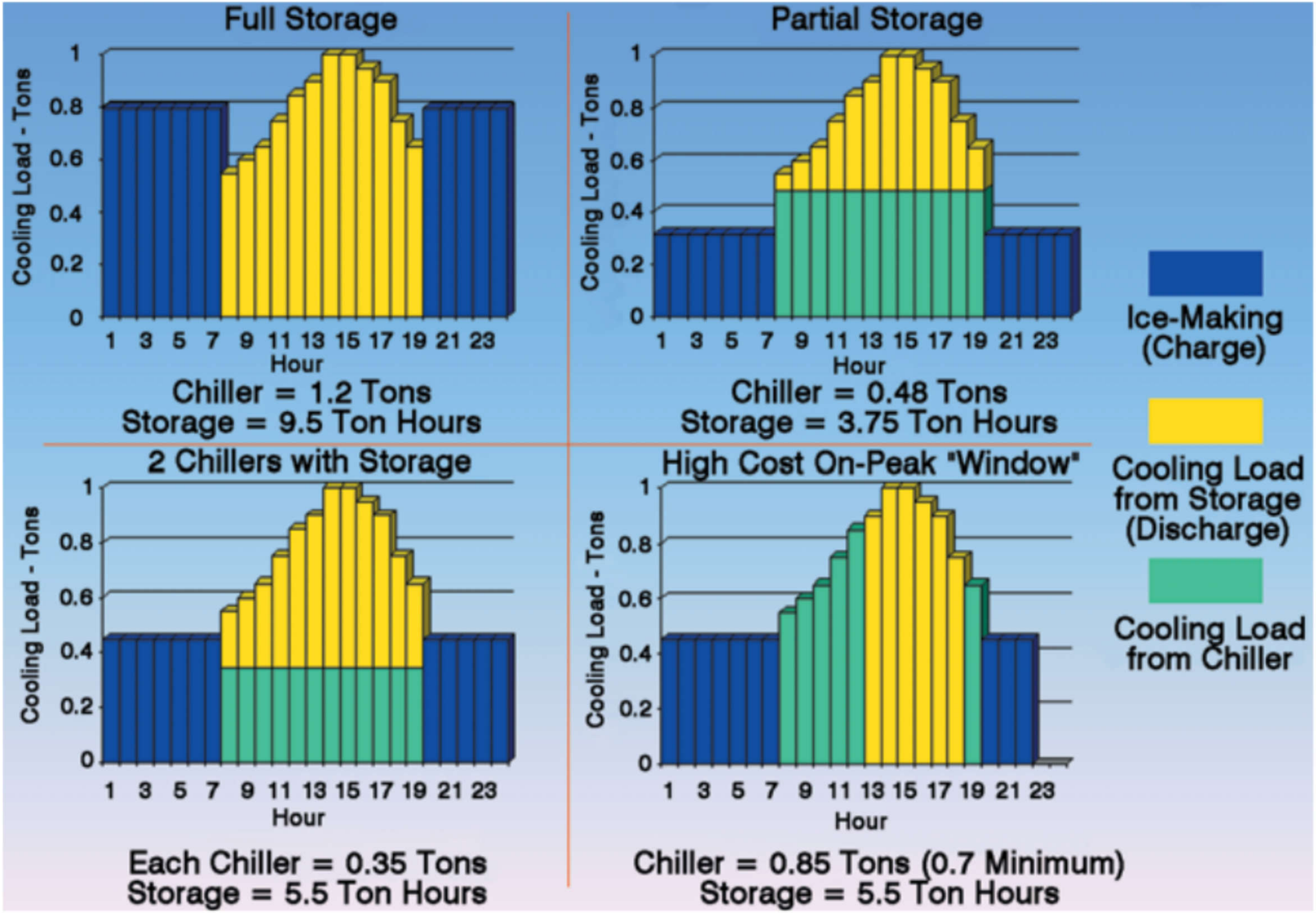
- Component sizing
  - Total ton hours = chiller [day + night] capacity
  - Chiller day capacity = chiller tons x day hours
  - Chiller night capacity = chiller tons x derating x night hours
  - Total ton hours = chiller tons (day hours + derating x night hours)
  - Chiller tons = (total ton hours) / (days hours + derating x night hours)
  - Storage ton hours = total ton hours – chiller tons x day hours

Design of ice storage system



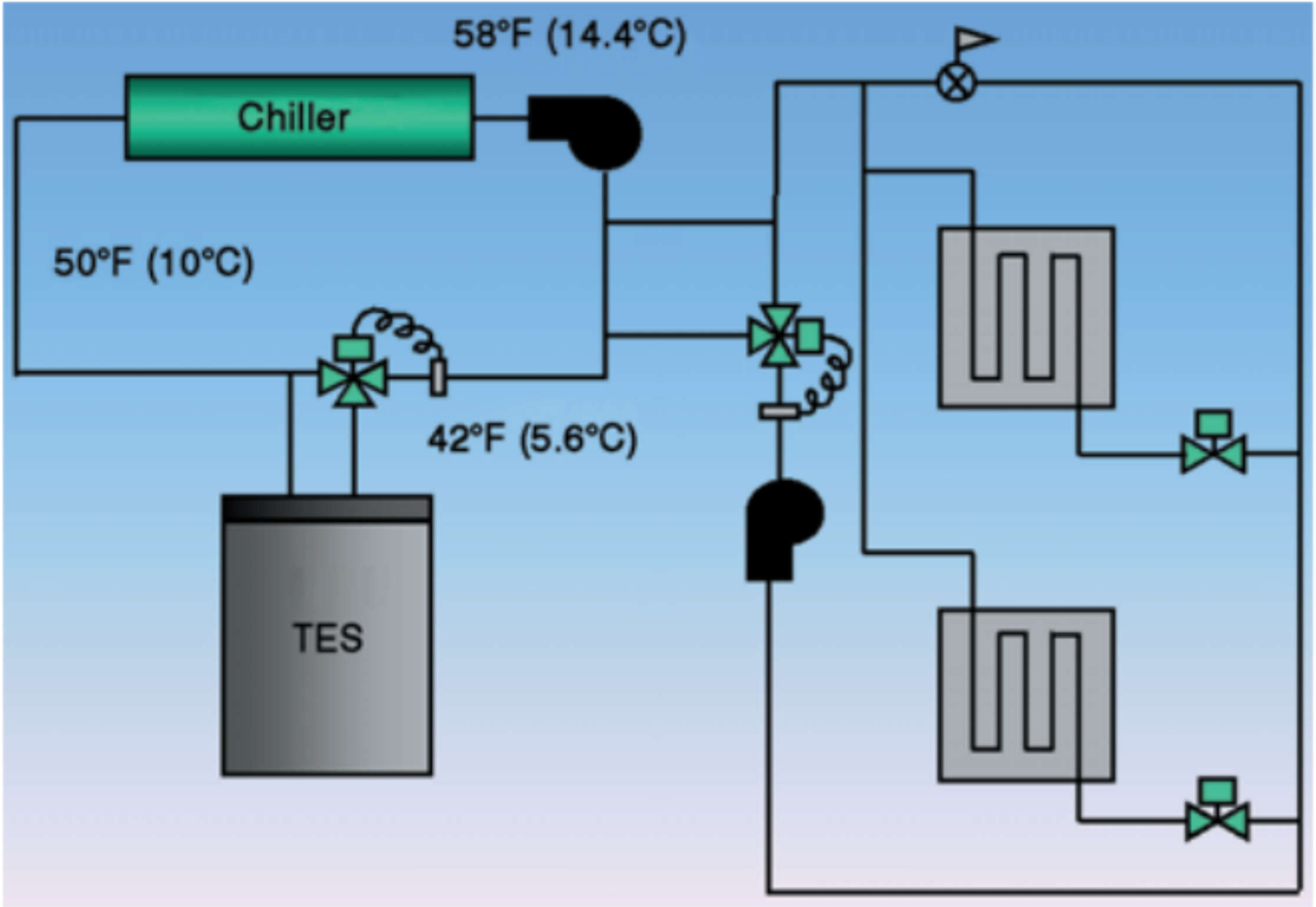
- Equipment selection criteria
  - Heat transfer fluid type & concentration
  - Ice tank model
  - Chiller daytime contribution as a % of nominal
  - Chiller charging capacity as a % of nominal
  - Supply and return delta T
  - 24 hour load profile
    - Full or partial storage

Chiller/storage selection (1 ton peak load, 9.5 total ton hours)



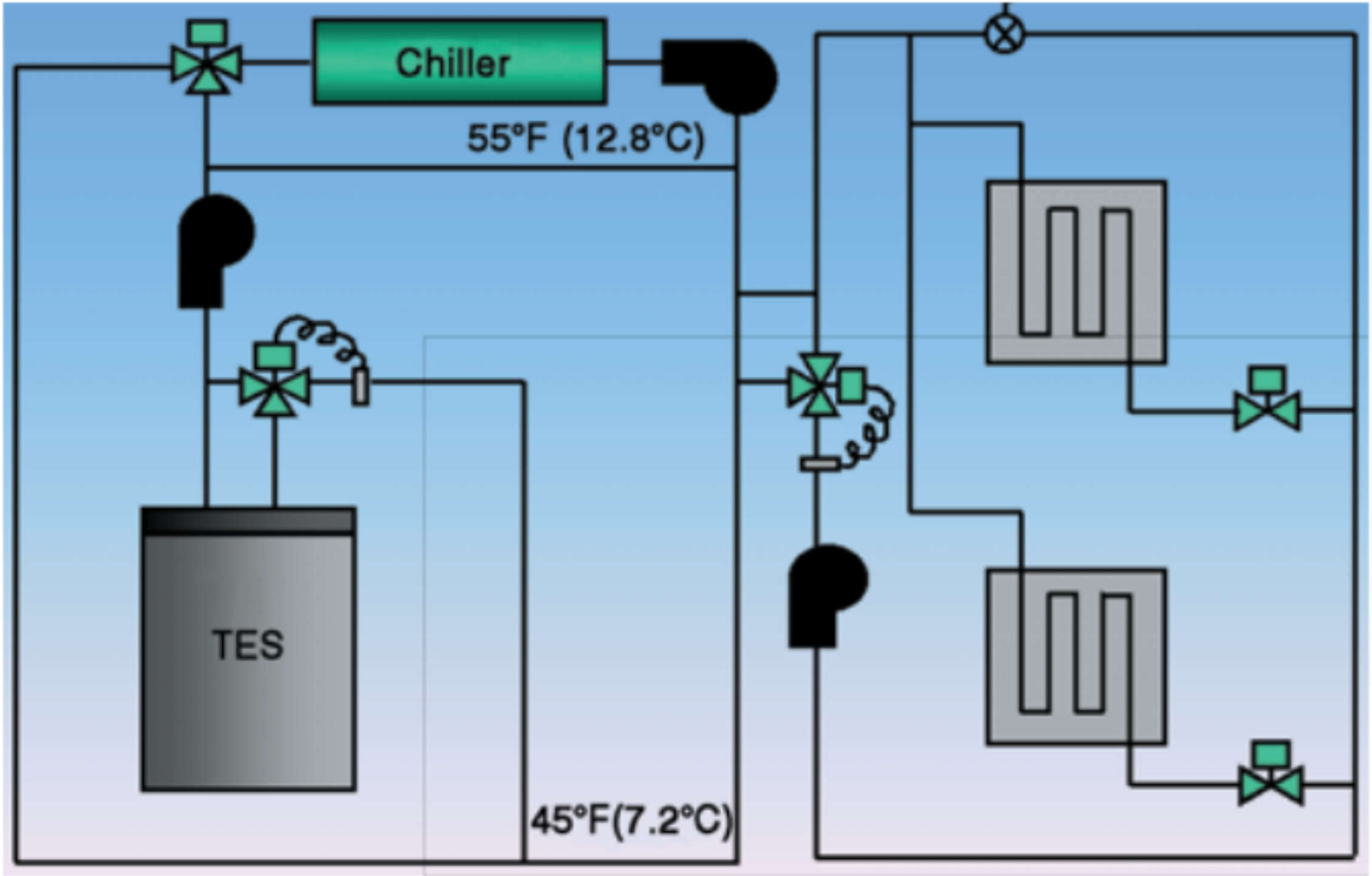
(Source: Silvetti B., 2002. Application fundamentals of ice-based thermal storage, *ASHRAE Journal*, 44 (2) 30-35.)

Ice thermal storage system in series flow with chiller upstream



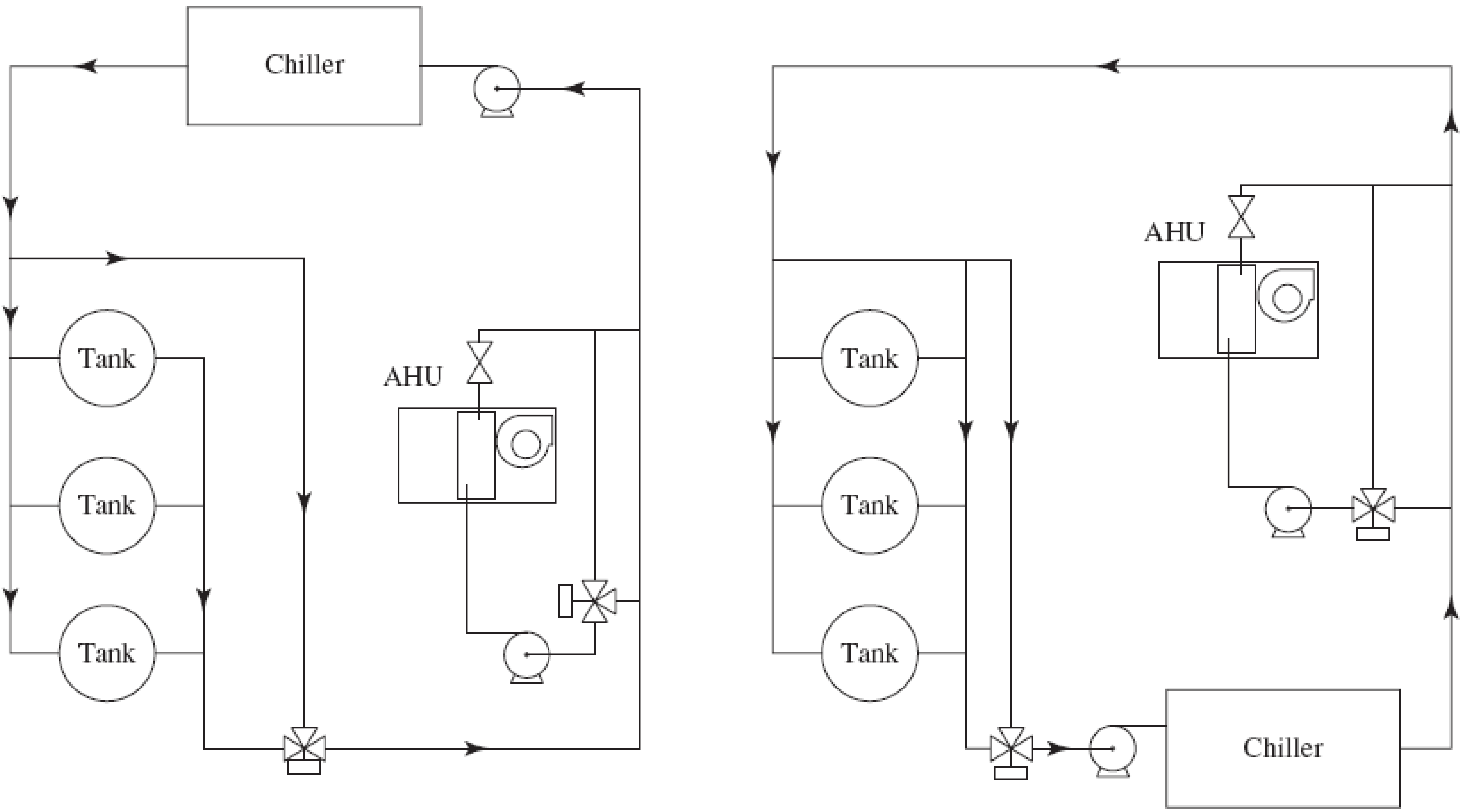
(Source: Silvetti B., 2002. Application fundamentals of ice-based thermal storage, *ASHRAE Journal*, 44 (2) 30-35.)

Ice thermal storage system in parallel flow



(Source: Silvetti B., 2002. Application fundamentals of ice-based thermal storage, *ASHRAE Journal*, 44 (2) 30-35.)

Ice thermal storage systems with chiller upstream and downstream



(a) Chiller upstream

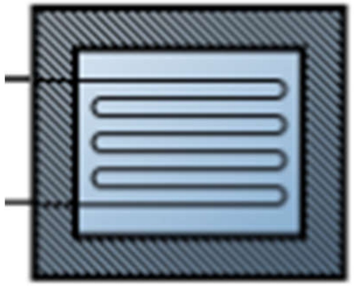
(b) Chiller downstream

Arrangement of ice and chillers in series

Chiller in upstream position	**Chiller in downstream position**
• Increases chiller efficiency • Increases chiller capacity • Decreases ice capacity • Simplifies system layout • Tank capacity loss doesn't exceed chiller efficiency and capacity benefits • Smaller system, screw or scroll -- tanks downstream	• Decreases chiller efficiency • Decreases chiller capacity • Increases ice capacity (reduced number of tanks?) • Tank capacity benefit is substantial • Larger system, centrifugals -- tanks upstream

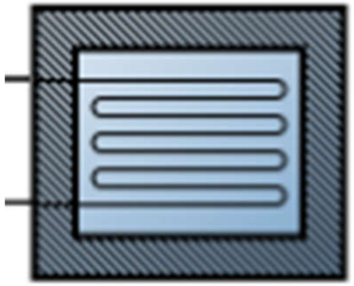
(Source: Trane)

Design of ice storage system



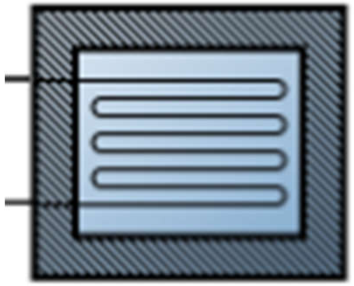
- Air-cooled or water-cooled chillers?
  - Not that much design difference
  - Air-cooled:
    - Reduces initial investment for efficient system
    - Fewer components to select
  - Water-cooled:
    - Large chiller capacities (>500 tons)
    - May require multiple stages of compression
    - Expanded economizer cycle
      - Ice extends the hours for water economizer free cooling cycle
      - Reduces cooling tower energy by charging tanks at night with fans unloaded

Design of ice storage system



- Chilled water piping arrangement
  - Constant volume (3-way valves on AHU coils)
    - Wider ΔTs reduce pumping horsepower
      - Larger system justified
    - Better for small systems
  - Constant primary/variable secondary
  - Variable primary flow
    - Can save more energy than primary/secondary
    - Controls more complicated
- Direction of flow during charge & discharge
  - Same direction for best operation

Design of ice storage system

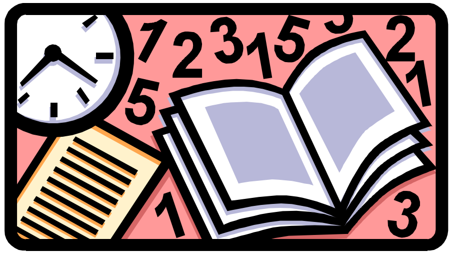


- System operating modes
  - 1. Cool building with chiller only
  - 2. Cool building with ice only
  - 3. Cool building with chiller & ice
  - 4. Make ice
  - 5. Make ice & cool building
  - 6. Off
- Energy saving goals
  - Peak shaving (kW reduction), load shifting (kWh deferral), real-time pricing response

Further Reading

- MacCracken M., 2004. Thermal energy storage in sustainable buildings, *ASHRAE Journal*, 46 (9) S39-S41.
  - http://www.calmac.com/stuff/contentmgr/files/0/4aae3ff72cfe5654e367936685f20f87/pdf/thermal_energy_storage_in_sustainable_buildings_unabridged.pdf
- Silvetti B., 2002. Application fundamentals of ice-based thermal storage, *ASHRAE Journal*, 44 (2) 30-35.
  - http://www.calmac.com/stuff/contentmgr/files/0/9ee1a79e74c076ff2adac9661e9ef80f/pdf/020311_emjas_emailablearticle_ashraejournalfeb02.pdf

References (books)



- ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, Chp. 50 Thermal Storage, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.
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