AI-Native Data Center Pod - 10 MW Reference Architecture (PoC)

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2026-02-11

Contents

Authority Model

- **BoD** is the single normative source of requirements and evidence gates.
- **Appendices** are the single source of derivations and worked examples.
- **Reference Architecture** instantiates a topology that satisfies the BoD by reference only.
- **Witness excerpt** is a pointer and reconciliation summary; the authoritative witness lives in Appendix F.

Engineering Basis of Design

Physics-First, Vendor-Agnostic

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0. Executive Snapshot

Purpose:
Define a facility capable of sustaining ~10 MW IT load for large-scale AI training with liquid-cooled racks, while remaining safe, observable, and operable across its lifecycle.

What this document is

- A set of **engineering contracts** between IT and facility
- A definition of **envelopes** (power, heat, water, telemetry)
- A framework for **commissioning and evidence**

What this document is not

- A vendor selection
- A construction drawing pack
- A detailed controls implementation

System Chain (intent)

`Workload → Electrical Power → Heat Capture → Fluid Transport → Heat Rejection → Monitoring → Operations`

Key Envelopes

Domain	Target
IT load	10 MW nominal
Rack cooling	Direct liquid to chip + CDU
ΔT liquid	8–12 K initial assumption
Redundancy	N+1 at critical layers
Observability	Second-level telemetry

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1. Scope, Audience, Definitions

1.1 Audience

- Electrical & mechanical engineering
- Controls & BMS teams
- Safety/compliance
- Operations

1.2 Boundary Definitions

- **IT boundary:** rack manifolds and CDU interface
- **Facility boundary:** power delivery, fluid loops, heat rejection, controls
- **Responsibility split** defined at CDU inlet/outlet and rack PDU

1.3 Terminology

- FW – facility water loop
- TC – technical coolant to racks

- CDU – coolant distribution unit
- HIL – hardware-in-loop testing
- KPI – sustainability & performance metric

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2. Architecture Contracts (Normative Core)

A. Electrical Contract

The facility shall:

1. Deliver up to **10 MW IT power** with defined ramp limits
2. Support dynamic AI workloads with bounded inrush
3. Provide:
    - N+1 at MV/LV transformation
    - Selective coordination
    - Power quality monitoring

Evidence

- FAT/SAT under staged load banks
- Ramp tests 0→100% and 100→0%
- Harmonics and THD reports

B. Thermal Contract

1. Capture $\geq$ 95% of IT heat via liquid path
2. Maintain rack inlet temperature within OEM envelope
3. Provide:
    - Dual-loop separation (FW / TC)
    - Leak containment and detection
    - Minimum ΔT target 8 K

Evidence

- Calibrated heat balance
- Flow vs load linearity
- CDU failover test

C. Water Contract

1. Water quality per OEM specification
2. Treatment for corrosion/biological control
3. Leak detection at:
    - rack
    - CDU
    - header

Evidence

- Lab analysis
- Pressure decay tests
- Containment verification

D. Observability Contract

1. All critical paths instrumented
2. Time-synchronized telemetry
3. Alarms classified:
    - Safety
    - Service
    - Advisory

Evidence

- Telemetry acceptance
- Alarm storm testing
- Loss-of-signal scenarios

E. Sustainability Contract

1. Measure PUE, WUE, CUE boundaries
2. Reportable metering at:
    - utility entry
    - IT PDUs
    - cooling plant

Evidence

- KPI reconciliation
- Sensor calibration records

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3. Reference Architecture Overview (Non-Normative Orientation)

3.1 Electrical

- Utility → MV → LV
- Static transfer where required
- Rack PDUs with branch monitoring
- Grounding and bonding strategy

3.2 Mechanical

- FW loop to dry coolers
- CDU layer with TC distribution
- Residual air path for ancillaries

3.3 Controls

- BMS + DCIM integration
- State machines for:
    - ramp
    - fault isolation
    - maintenance modes

3.4 Safety

- EPO logic
- Leak isolation

- Fire strategy compatible with liquid cooling

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4. Sizing Envelopes (Outputs)

4.1 Thermal

Item	Value (initial)
Heat to liquid	9.5–10 MW
ΔT design	10 K
Estimated flow	derived in Appendix B
CDU capacity	N+1

4.2 Electrical

Item	Value
IT power	10 MW
Ancillary	~8–12%
Diversity	workload dependent

4.3 Water

- Header sizing per hydraulic model
- Treatment plant sized for volume turnover

4.4 Observability

- 1 s resolution for critical paths
- 10 s for secondary
- Retention $\geq$ 24 months

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5. Commissioning & Evidence Plan

For each contract:

1. **Method**
   - FAT
   - SAT
   - IST
   - HIL
2. **Instrumentation**
   - Calibrated meters
   - Flow/temperature pairs
   - Power analyzers
3. **Acceptance**
   - Numeric criteria
   - Stability windows
   - Negative tests
4. **Artifacts**
   - Reports
   - Traces

- As-built configs

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6. Operational Model

- Change governance
- Maintenance schedules
- Alarm philosophy
- Training requirements
- Failure drills

Document Status

- Version: Draft 1.0
- Nature: Engineering Basis of Design
- Ownership: Multidisciplinary

Appendix Index (authoritative derivations and evidence mapping)
- Appendix A — Workload → Boundary Projection
- Appendix B — Thermal Physics and Digital Twin Basis
- Appendix C — Hydraulics, Piping, and ΔP Budgets
- Appendix D — Sustainability Model and KPI Closure
- Appendix E — Cross-Domain FMEA and Commissioning Mapping
- Appendix F — CausalCompute Alignment (Witness Workload Closure) # Appendix A — Workload → Boundary Projection

A.1 Purpose

This appendix translates **arbitrary AI training objectives** into the **electrical and thermal quantities visible at the facility boundary**.

The facility is intentionally **workload-agnostic**.
Therefore the mathematics is used to generate:

- admissibility envelopes, not a single model instance
- power transients, not GPU counts
- boundary quantities (P_{IT}, ΔP, dP/dt)

A.2 Notation

Symbol	Meaning	Units
P	model parameters	params
Tok	total training tokens	tokens
T	wall-clock budget	s
c	FLOPs per param-token (dense ≈ 6)	FLOPs/(param · token)
η	sustained training efficiency	–
ε_{comp}	compute efficiency at IT boundary	FLOPs/s/W
P_{IT}	IT electrical power	W
ΔP	step change in power	W
dP/dt	ramp rate	W/s

A.3 Compute Demand

Total algorithmic work:

$$F_{total} = c \cdot P \cdot Tok$$

Required sustained throughput:

$$F_{req} = \frac{F_{total}}{T}$$

Mapping to electrical boundary:

$$P_{IT,derived} = \frac{F_{req}}{\eta \cdot \varepsilon_{comp}}$$

Admissibility condition

$$P_{IT,derived} \leq P_{IT,envelope}$$

For this pod:

$$P_{IT,envelope} = 10 \text{ MW}$$

This relation **does not size the facility to one model**;
it checks whether any proposed workload lies inside the envelope.

A.4 Transient Abstraction

AI training creates power transients through:

- job start/stop
- collective synchronizations
- checkpoint I/O
- failure recovery

Detailed behavior is reduced to enforceable limits:

$$|\Delta P| \leq \Delta P_{max}$$

$$\left|\frac{dP}{dt}\right| \leq (dP/dt)_{max}$$

PoC Envelope (per 2 MW block)

$$\Delta P_{block} \leq 0.2 \text{ MW in 1 s}$$

$$\left|\frac{dP_{block}}{dt}\right| \leq 0.1 \text{ MW/s}$$

Recovery objective:

$$t_{rec,block} \leq 10\text{–}30 \text{ s}$$

Per Rack (100 kW baseline)

$$\Delta P_{rack} \leq 10 \text{ kW in } 1 \text{ s}$$

$$\left| \frac{dP_{rack}}{dt} \right| \leq 5 \text{ kW/s}$$

A.5 Admissible Workload Set

The facility admits any workload whose boundary image lies in:

$$\mathcal{A} = \begin{cases} P(t) \leq 10 \text{ MW} \\ |\Delta P| \leq 0.2 \text{ MW/block} \\ |dP/dt| \leq 0.1 \text{ MW/s} \\ T_{TC} \in [T_{min}, T_{max}] \\ \dot{m} \geq \dot{m}_{min} \end{cases}$$

Workload mathematics therefore act as the **projection operator** into this admissible set.

A.6 Conceptual Shift

Locked design

$$(P, Tok, T) \rightarrow \text{exact GPU count} \rightarrow \text{facility}$$

Agnostic design

$$(P, Tok, T) \rightarrow (P_{IT},\ \Delta P,\ dP/dt) \rightarrow \text{facility envelopes}$$

A.7 Scheduler $\leftrightarrow$ Facility Interface

Enforcement Layers

1. **Primary – Scheduler Policy**
    - staged energization
    - anti-herd starts
    - block-local ramp sequencing
2. **Secondary – Power Capping**
    - per-rack limits
    - collective smoothing
3. **Tertiary – BESS/UPS**
    - grid event absorption
    - residual transient buffer

A.8 Verification Method

Acceptance requires replay of representative traces:

- voltage sag within limits
- UPS not overloaded
- CDU controls stable
- T_{out} within envelope

A.9 Definition

> In the agnostic formulation, workload mathematics serve to **map arbitrary ML objectives into boundary quantities** rather than prescribe a specific model instance.

A.10 Outputs to Facility Design

This appendix produces:

- IT power envelope (P_{IT})
- transient limits (ΔP, dP/dt)
- inputs to thermal sizing (Appendix B)
- acceptance tests for commissioning

A.11 Witness Reference

A single worked witness is maintained in Appendix F (CausalCompute alignment).
All numeric witness values used by Appendices B–E are sourced from Appendix F.

End of Appendix A # Appendix B — Thermal Physics and Digital Twin Basis (with Full Derivations)

B.1 Purpose

This appendix closes the thermodynamic and control loop for the **single witness workload** defined in Appendix F:

- $P_{IT} \approx 4.77$ MW
- $\dot{Q} \approx P_{IT}$ (all IT power becomes heat, first order)
- Design liquid rise: $\Delta T = 12^{\circ}$C (envelope 8–15 °C)
- Mechanical zoning: 1 MW maximum fault domain per zone

It produces:

1. Required coolant flow $\dot{m}$, $\dot{V}$ at the pod boundary
2. Per-zone flow targets
3. Pumping power order-of-magnitude from ΔP budgets
4. A control-oriented thermal state model and time constants
5. Commissioning identification and validation gates for the twin

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B.2 Notation and Constants

Symbol	Meaning	Units
$\dot{Q}$	heat rate	W
P_{IT}	IT electrical power	W
$\dot{m}$	mass flow rate	kg/s
$\dot{V}$	volumetric flow rate	$\mathrm{m^3/s}$
ρ	fluid density (water, 25–30 °C)	$\mathrm{kg/m^3}$
c_p	specific heat (water)	$\mathrm{J/(kg \cdot K)}$
ΔT	temperature rise	K or °C
ΔP	pressure differential	Pa
η_{pump}	pump + motor + VFD efficiency	–
C	effective thermal capacitance	J/K
τ	thermal time constant	s

Water properties (PoC design basis)
- $\rho \approx 997\ \mathrm{kg/m^3}$
- $c_p \approx 4180\ \mathrm{J/(kg \cdot K)}$

B.3 Thermodynamic Closure (Heat → Flow)

B.3.1 Fundamental single-phase relation

For an incompressible single-phase coolant loop:

$$\dot{Q} = \dot{m}\, c_p\, \Delta T$$

Rearranging gives required mass flow:

$$\dot{m} = \frac{\dot{Q}}{c_p\, \Delta T}$$

Using density to convert to volumetric flow:

$$\dot{V} = \frac{\dot{m}}{\rho}$$

B.3.2 Witness workload heat rate

$$\dot{Q} \approx P_{IT} \approx 4.77 \times 10^6\ \mathrm{W}$$

B.3.3 Pod-level mass flow

With $\Delta T = 12^{\circ}\mathrm{C}$:

$$\dot{m} = \frac{4.77 \times 10^6}{4180 \times 12}$$

Compute denominator:

$$4180 \times 12 = 50{,}160$$

So:

$$\dot{m} \approx \frac{4.77 \times 10^6}{50{,}160} \approx 95.1 \text{ kg/s}$$

B.3.4 Pod-level volumetric flow

$$\dot{V} = \frac{95.1}{997} \approx 0.0954 \text{ m}^3\text{/s} \approx 95 \text{ L/s}$$

Pod-level result (witness case)

$$\boxed{\dot{m} \approx 95.1 \text{ kg/s}}, \qquad \boxed{\dot{V} \approx 0.095 \text{ m}^3\text{/s} \approx 95 \text{ L/s}}$$

B.4 Zone-Level Distribution (1 MW Fault Domains)

B.4.1 Per-zone flow at 1 MW

For a zone cap of $\dot{Q}_{zone} = 1$ MW:

$$\dot{m}_{zone} = \frac{1.0 \times 10^6}{4180 \times 12} \approx 19.9 \text{ kg/s}$$

$$\dot{V}_{zone} = \frac{19.9}{997} \approx 0.0200 \text{ m}^3\text{/s} \approx 20.0 \text{ L/s}$$

Per-zone result

$$\boxed{\dot{V}_{zone} \approx 20 \text{ L/s per 1 MW zone at } \Delta T = 12^\circ\text{C}}$$

B.4.2 Mapping the witness workload to zones

Witness load is served by approximately five 1 MW zones in aggregate:

$$\frac{4.77 \text{ MW}}{1 \text{ MW/zone}} \approx 4.77 \text{ zones}$$

Nominal flow if distributed across 5 zones:

$$5 \times 20 \text{ L/s} = 100 \text{ L/s}$$

This matches the pod-level 95 L/s within rounding and distribution overheads.

B.5 Rack-Level Sanity (100 kW Baseline)

For a 100 kW rack:

$$\dot{m}_{rack} = \frac{100{,}000}{4180 \times 12} \approx 1.99 \text{ kg/s}$$

$$\dot{V}_{rack} \approx \frac{1.99}{997} \approx 0.0020 \text{ m}^3\text{/s} \approx 2.0 \text{ L/s}$$

B.6 Pumping Power (ΔP Budget $\rightarrow$ Watts)

$$P_{pump} \approx \frac{\Delta P \cdot \dot{V}}{\eta_{pump}}$$

B.6.1 Zone pumping order-of-magnitude

Assume a PoC zone budget:

- $\Delta P_{zone} = 100$ kPa $= 100{,}000$ Pa
- $\dot{V}_{zone} \approx 0.020$ m^3/s
- $\eta_{pump} = 0.70$

$$P_{pump,zone} \approx \frac{100{,}000 \times 0.020}{0.70} \approx 2{,}857 \text{ W} \approx 2.9 \text{ kW}$$

If the witness workload uses ~5 zones:

$$P_{pump,total} \approx 5 \times 2.9 \text{ kW} \approx 14.5 \text{ kW}$$

B.7 Thermal State Model (Digital Twin Anchor)

B.7.1 First-order energy balance

$$C\frac{dT_{out}}{dt} = \dot{Q}(t) - \dot{m}(t)\, c_p \left(T_{out}(t) - T_{in}(t)\right)$$

This is a **control-oriented abstraction** sufficient for estimation, anomaly detection, and supervisory set-point control.

B.7.2 Steady-state check

At steady state:

$$\dot{Q} \approx \dot{m}c_p(T_{out} - T_{in}) \Rightarrow \Delta T \approx \frac{\dot{Q}}{\dot{m}c_p}$$

B.8 Time Constant and Transient Behavior

Dominant time constant:

$$\tau = \frac{C}{\dot{m}c_p}$$

Illustrative inventory:

- $V_{eq} \approx 5 \text{ m}^3$
- $m_{eq} \approx 5000$ kg

$$C \approx m_{eq}c_p \approx 5000 \times 4180 \approx 2.09 \times 10^7 \text{ J/K}$$

With $\dot{m} \approx 20$ kg/s:

$$\dot{m}c_p \approx 20 \times 4180 = 83{,}600 \text{ W/K}$$

$$\tau \approx \frac{2.09 \times 10^7}{83{,}600} \approx 250 \text{ s}$$

B.9 Discrete-Time Estimator (Online Digital Twin)

For sampling interval Δt:

$$\hat{T}_{out}[k+1] = \hat{T}_{out}[k] + \frac{\Delta t}{\hat{C}} \left(\dot{Q}[k] - \dot{m}[k]\, c_p \,(\hat{T}_{out}[k] - T_{in}[k])\right)$$

Telemetry sources:

- $\dot{Q}[k]$: rack/block power metering
- $\dot{m}[k]$: flow meter
- $T_{in}[k]$: supply temperature
- $T_{out}[k]$: return temperature probe

B.10 Commissioning Identification of C (Evidence Gate)

Procedure:

1. Hold T_{in} approximately constant
2. Hold $\dot{m}$ constant
3. Apply a bounded step or ramp in $\dot{Q}$
4. Measure $T_{out}(t)$
5. Fit $\hat{C}$ by minimizing prediction error

Acceptance (PoC intent):

$$\text{RMSE}(T_{out}) \leq 0.5^\circ\text{C}$$

B.12 Outputs Exported (Witness Case)

- Pod-level flow:

$$\dot{V} \approx 0.095 \text{ m}^3/\text{s} \approx 95 \text{ L/s}$$

- Zone-level flow:

$$\dot{V}_{zone} \approx 0.020 \text{ m}^3/\text{s} \approx 20 \text{ L/s}$$

- Rack flow:

$$\dot{V}_{rack} \approx 2 \text{ L/s}$$

- Zone time constant (illustrative):

$$\tau \approx 250 \text{ s}$$

  # Appendix C — Hydraulics, Piping, and ΔP Budgets

C.1 Purpose

This appendix converts the thermal requirements from Appendix B into **buildable hydraulic quantities**:

- header diameters from the single witness flow ($\approx$ 95 L/s)
- per-zone distribution at $\approx$ 20 L/s
- velocity and ΔP budgets
- pumping power and sensitivity
- fault-domain containment rules

All calculations are SI; water at 25–30 °C is assumed.

C.2 Continuity → Pipe Diameter

For design velocity v:

$$A = \frac{\dot{V}}{v}, \qquad d = \sqrt{\frac{4A}{\pi}}$$

C.2.2 Pod-level header (witness case)

From Appendix B:

$$\dot{V} \approx 0.095 \text{ m}^3/\text{s} \ (95 \text{ L/s})$$

Use $v = 2.0$ m/s:

$$A = \frac{0.095}{2.0} = 0.0475 \text{ m}^2$$

$$d = \sqrt{\frac{4 \times 0.0475}{\pi}} \approx 0.246 \text{ m}$$

$$\boxed{d \approx 0.25 \text{ m}}$$

Interpretation

- Primary header class $\approx$ **DN250** (DN250–DN300 depending on allowances)

- The full 10 MW pod (200 L/s) would approach **DN350** class

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C.3 Zone Branch Sizing

Zone flow:

$$\dot{V}_{zone} \approx 0.020 \text{ m}^3/\text{s (20 L/s)}$$

Using $v = 2.0$ m/s:

$$A_{zone} = \frac{0.020}{2.0} = 0.010 \text{ m}^2$$

$$d_{zone} = \sqrt{\frac{4 \times 0.010}{\pi}} \approx 0.113 \text{ m}$$

$$\boxed{d_{zone} \approx 110 \text{ mm}}$$

Practical class: **DN100–DN125** per 1 MW zone.

C.4 Rack Manifold Sanity

For 100 kW rack:

$$\dot{V}_{rack} \approx 2 \text{ L/s} = 0.002 \text{ m}^3/\text{s}$$

If internal manifold velocity target $v = 1.5$ m/s:

$$A_{rack} = \frac{0.002}{1.5} = 0.00133 \text{ m}^2$$

$$d_{rack} \approx 0.041 \text{ m}$$

Approx: **DN40** class at rack interface.

C.5 ΔP Budget Philosophy

$$P_{pump} = \frac{\Delta P \cdot \dot{V}}{\eta}$$

Segment	Target ΔP

C.5.1 PoC zone budget

Segment	Target ΔP
Rack cold plates & hoses	$\leq$ 40 kPa
CDU HEX + internals	$\leq$ 40 kPa
Distribution & valves	$\leq$ 20 kPa
Total zone	$\leq$ **100 kPa**

C.5.2 Zone pumping power (order-of-magnitude)

$$\dot{V}_{zone} = 0.020 \text{ m}^3/\text{s}, \quad \Delta P = 100{,}000 \text{ Pa}, \quad \eta = 0.70$$

$$P_{pump,zone} = \frac{100{,}000 \times 0.020}{0.70} \approx 2.9 \text{ kW}$$

Sensitivity:

$$P_{pump} \propto \Delta P$$

C.6 Velocity Limits (Rationale)

Location	Limit	Reason
Primary headers	$\leq$ 2.0 m/s	erosion, noise, transients
Secondary runs	$\leq$ 1.5 m/s	controllability
Rack hoses	$\leq$ 1.2 m/s	connector wear
Drain lines	$\geq$ 0.6 m/s	sediment transport

C.7 Transient & Water Hammer Considerations

Rapid valve closure can generate:

$$\Delta P_{wh} \approx \rho a \Delta v$$

Mitigations:

- rate-limited actuators
- surge arrestors
- controlled pump ramps
- commissioning verification of worst-case closures

C.8 Segmentation and Fault Domains

Containment rule:

A single failure shall not exceed **1 MW thermal radius**.

Therefore:

- isolation valves at each zone boundary
- no common headers without sectionalization
- wet components segregated from electrical rooms

Design spill volume per zone:

$$V_{spill,max} = \dot{V}_{zone} \times t_{detect}$$

With 20 L/s and 10 s detection:

$$V_{spill,max} \approx 200 \text{ L}$$

C.9 Instrumentation Requirements

Minimum per zone:

- supply $T_{TC,in}$
- return $T_{TC,out}$
- flow $\dot{m}$ or ΔP proxy
- valve position
- leak detection (cable + point)

C.10 Commissioning Evidence

Acceptance tests derived from this appendix:

1. Flow verification:
$$\dot{V}_{zone} \geq 20 \text{ L/s}$$
2. ΔP envelope:
$$\Delta P_{zone} \leq 100 \text{ kPa}$$
3. Velocity audit: confirm $v \leq 2$ m/s in primaries
4. Transient test: staged valve closure without excursions
5. Leak isolation: single-zone containment proven # Appendix D — Sustainability Model and KPI Closure (Witness-Case Extended)

D.1 Purpose

This appendix converts the single witness workload into auditable sustainability quantities:

- annual energy (IT and facility)
- heat export potential (MWh$_{th}$)
- water sensitivity under adiabatic/evaporative augmentation
- KPI boundaries and required metering

- a PoC measurement plan that makes reporting defensible

The intent is not "green claims," but metered contracts.

D.2 Inputs from the Witness Case

From Appendix F:

$$P_{IT} \approx 4.77 \text{ MW}$$

Design intent:

- $\text{PUE}_{design} = 1.15$
- utilization factor $U = 0.70$ (example)

Facility power:

$$P_{fac} = P_{IT} \times \text{PUE}$$

$$P_{fac} \approx 4.77 \times 1.15 = 5.4855 \text{ MW}$$

D.3 Annual Energy (MWh/year)

D.3.1 IT energy

$$E_{IT,year} = P_{IT} \times 8760 \times U$$

Compute:

$$E_{IT,year} \approx 4.77 \times 8760 \times 0.70 \approx 29{,}300 \text{ MWh/yr}$$

D.3.2 Facility energy

$$E_{fac,year} = P_{fac} \times 8760 \times U$$

$$E_{fac,year} \approx 5.4855 \times 8760 \times 0.70 \approx 33{,}600 \text{ MWh/yr}$$

D.3.3 Overhead energy (derived)

$$E_{overhead,year} = E_{fac,year} - E_{IT,year} \approx 4{,}300 \text{ MWh/yr}$$

D.4 Heat Reuse Potential

Thermal energy available at IT boundary (first order):

$$\dot{Q} \approx P_{IT}$$

Annual thermal energy:

$$E_{heat,year} \approx P_{IT} \times 8760 \times U \approx 29{,}300 \text{ MWh}_{th}/\text{yr}$$

Heat pump relation (if needed):

If $COP = \frac{Q_{delivered}}{W_{hp}}$:

$$W_{hp} = \frac{Q_{delivered}}{COP}, \qquad Q_{source} = Q_{delivered}\left(1 - \frac{1}{COP}\right)$$

D.5 Water Sensitivity (Adiabatic/Evaporative Augmentation)

Latent heat of vaporization:

$$h_{fg} \approx 2.45 \text{ MJ/kg}$$

Evaporation mass flow to reject heat Q:

$$\dot{m}_{evap} \approx \frac{Q}{h_{fg}}$$

For $Q = 4.77$ MW $= 4.77$ MJ/s:

$$\dot{m}_{evap} \approx \frac{4.77}{2.45} \text{ kg/s} \approx 1.95 \text{ kg/s} \approx 1.95 \text{ L/s}$$

Daily water (if operating adiabatic continuously):

$$V_{day} \approx 1.95 \text{ L/s} \times 86400 \text{ s/day} \approx 168{,}000 \text{ L/day} \approx 168 \text{ m}^3\text{/day}$$

Annual at utilization $U = 0.70$:

$$V_{year} \approx 168 \text{ m}^3\text{/day} \times 365 \times 0.70 \approx 43{,}000 \text{ m}^3\text{/yr}$$

D.6 KPI Definitions (Time-Series, Not Scalars)

D.6.1 PUE(t)

$$\text{PUE}(t) = \frac{P_{fac}(t)}{P_{IT}(t)}$$

Requirements:

- computed as a time series with time-aligned meters
- reported as distributions/percentiles, not a single number

D.6.2 WUE(t)

Where make-up water exists:

$$\text{WUE}(t) = \frac{\dot{V}_{makeup}(t)}{P_{IT}(t)}$$

Interval form:

$$\text{WUE}_{interval} = \frac{V_{makeup}}{E_{IT}} \quad \text{[L/kWh]}$$

D.6.3 Heat export metering

Exported thermal power:

$$\dot{Q}_{export}(t) = \rho\, c_p\, \dot{V}_{export}(t)\, \Delta T_{export}(t)$$

Exported energy:

$$E_{export} = \int \dot{Q}_{export}(t)\, dt$$

D.6.4 Carbon (operational)

If grid intensity is a time series $I_{grid}(t)$ in kgCO_2e/kWh:

$$CO2e = \int I_{grid}(t)\, P_{fac}(t)\, dt$$

D.7 Metering Contract (Minimum Required Meters)

Electrical:

- Utility import meter (true RMS, time-stamped)
- Plant distribution meters (cooling, UPS losses, BESS auxiliaries)
- IT boundary meters per block / PDU / RPP (depending on design)

Thermal / Water:

- Heat meter at export interface: $\dot{V} + T_{supply} + T_{return}$
- FW/TC loop meters per zone: $\dot{V}$, T_{in}, T_{out}, ΔP
- Make-up water meter where adiabatic exists

Time synchronization:

- PTP/NTP such that meter timestamps are aligned and drift is monitored

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D.8 “Fails to Ambient” Export Philosophy (Reliability Constraint)

Heat export must not become a single point of failure.

Contractual rule:

- Export path must **fail open** to ambient rejection.
- Off-taker unavailability shall not cause derate of IT load.

This implies bypass and buffering at the export interface.

D.9 Witness-Case Sustainability Summary

Using $P_{IT} = 4.77$ MW, $U = 0.70$, PUE $= 1.15$:

Quantity	Result
IT annual energy E_{IT}	~29,300 MWh/yr
Facility annual energy E_{fac}	~33,600 MWh/yr
Overhead energy	~4,300 MWh/yr
Heat potential E_{heat}	~29,300 MWh_{th}/yr
Evaporation rate (adiabatic continuous)	~1.95 L/s
Daily water (adiabatic continuous)	~168 m^3/day
Annual water (adiabatic continuous, $U = 0.70$)	~43,000 m^3/yr

Interpretation: even at ~5 MW class loads, adiabatic hours must be explicitly controlled and metered.

D.10 PoC Verification Plan

To make the PoC defensible:

1. Verify $P_{IT}(t)$, $P_{fac}(t)$ and compute PUE(t)
2. Verify heat balance closure:
$$P_{IT} \approx \rho c_p \dot{V} \Delta T + \text{loss terms}$$
3. If export exists, verify heat meter accuracy and availability
4. If adiabatic exists, verify make-up meter and compute WUE(t)
5. Time-sync audit: confirm timestamp alignment across power + flow + temperature

Acceptance intent: all reported KPIs must be reproducible from raw time-series data with documented calibrations. # Appendix E — Cross-Domain FMEA and Commissioning Mapping (Witness-Case)

E.1 Purpose

This appendix applies a structured Failure Modes and Effects Analysis (FMEA) to the 10 MW PoC architecture while explicitly referencing the **single witness workload** (Appendix F):

- $P_{IT} \approx 4.77$ MW
- $\dot{V} \approx 95$ L/s
- $\dot{V}_{zone} \approx 20$ L/s
- $\tau \approx 250$ s (illustrative)

The objective is to:

1. Identify failure modes that could violate the envelopes derived in Appendices A–D
2. Quantify risk using the common O/S/D scale

3. Map each high-RPN item to a commissioning evidence gate

E.2 Scoring Method (recap)

Risk Priority Number:

$$RPN = O \times S \times D$$

Range	Action
≥300	Architectural redesign
200–299	Mandatory mitigation + tests
120–199	Mitigation required
60–119	Manage with monitoring
<60	Accept / monitor

E.3 Electrical Domain (Witness-Linked)

Failure Mode	O	S	D	RPN	Witness Impact	Mitigation	Commissioning Evidence
Block ramp exceeds envelope	5	8	4	160	Violates dP/dt limits	Scheduler staging + capping	HIL replay of ramps
Protection mis-coordination	3	9	6	162	Upstream trip near block limits	Settings governance	Selectivity test
UPS bypass failure	2	9	6	108	Loss of power quality	Periodic transfer tests	Bypass SAT
Harmonics at PCC	4	5	5	100	PQ breach	Filters + monitoring	PQ report
Powered but uncooled	3	10	6	180	Thermal runaway	Hard interlocks	Interlock FAT

E.4 Mechanical Domain

Failure Mode	O	S	D	RPN	Witness Link	Mitigation	Evidence
Loss of flow in 1 MW zone	4	9	5	180	20 L/s drop	Dual CDU + alarms	Flow fail test
Valve hunting	5	6	6	180	Violates τ model	Rate limits	Step response
Filter fouling	6	5	4	120	$\Delta P >$ 100 kPa	DP trending	PM records
Leak at rack	4	8	4	128	~200 L spill	Trays + isolation	Leak drill
Air ingress	4	7	6	168	Oscillatory ΔP	Degassing	Stability test

---

E.5 Digital Twin & Controls

Failure Mode	O	S	D	RPN	Witness Link	Mitigation	Evidence
Sensor drift	6	7	6	252	Bias in T_{out}	Redundancy	Calibration
Model obsolete	5	7	7	245	Wrong τ	BIM versioning	Re-fit gate
Time sync loss	5	6	7	210	KPI corruption	PTP/NTP	Audit
Unsafe actuation	3	10	6	180	Flow violation	Guardrails	Negative test

---

E.6 Sustainability Risks

Failure Mode	O	S	D	RPN	Witness Link	Mitigation	Evidence
Unmetered PUE	6	6	7	252	KPI invalid	Meter plan	Data audit
Stranded heat	6	6	6	216	Export not utilized	Fail-open	Contract
Water cap breach	4	8	6	192	Adiabatic overuse	Dry baseline	WUE logs

---

E.7 Commissioning Matrix

E.7.1 Electrical Tests

- Replay ramp to confirm:

$$\left|\frac{dP}{dt}\right| \leq 0.1 \text{ MW/s}$$

- Verify per-block metering and coordination
- Bypass and transfer tests

E.7.2 Mechanical Tests

- Prove:

$$\dot{V}_{zone} \geq 20 \text{ L/s}$$

- Confirm:

$$\Delta P_{zone} \leq 100 \text{ kPa}$$

- Leak isolation within single zone

E.7.3 Twin Validation

- RMSE:

$$\leq 0.5^{\circ}\text{C}$$

- Fault injection for drift and flow loss

E.7.4 Sustainability

- Reproduce PUE(t) from raw meters
- Verify heat meter closure

E.8 Top Residual Risks

1. Sensor integrity for twin ($RPN = 252$)
2. KPI auditability ($RPN = 252$)
3. Model validity after changes ($RPN = 245$)

Mitigation requires process + engineering, not hardware alone.

E.9 Conclusion

The witness workload demonstrates:

- envelopes can be met
- failure modes are observable
- each risk maps to a testable gate

No $RPN \geq 300$ remains after mitigations. # Appendix F — CausalCompute Alignment (Witness Workload Closure)

F.1 Purpose

This appendix demonstrates that the envelopes defined in the Basis of Design can host a representative AI training workload using an external first-principles sizing engine (CausalCompute, Steps 0–2).

This appendix is:

- a traceability bridge between ML intent and facility physics,
- an evidence layer showing that the BoD envelopes are internally consistent,
- a generator of measurable PoC acceptance criteria.

This appendix is not:

- a redesign of the facility,
- a procurement specification,
- a network topology design,
- a replacement for the thermo-hydraulic derivations in Appendices A–C.

F.2 Lifecycle Status

F.2.1 Status of the Basis of Design

The BoD is a pre-production engineering contract, not an as-built system.
It defines envelopes and evidence gates that detailed design must later satisfy.

F.2.2 Status of CausalCompute

CausalCompute is used here as a PoC witness engine.

Allowed conclusions:

- envelope admissibility at the facility boundary (MW, L/s, kW/rack)
- sensitivity to explicit assumptions (η, ΔT, checkpoint policy)

Disallowed conclusions:

- procurement GPU counts or guarantees
- network topology or congestion claims
- ramp compliance verification
- reliability closure (N+1) or operational readiness

F.3 Methodological Duality — Bottom-Up vs Top-Down

```
BoD - Bottom-Up (Facility-First)
Power → Heat → Fluid → Space → Operations
         |________________________________
                                          |
Workload → FLOPs → Time → GPUs → Power → Heat
CausalCompute - Top-Down (Workload-First)
```

Convergence: heat is the handoff point.

The tool delivers an implied heat rate:

$$\dot{Q}_{\text{tool}} \approx P_{IT}$$

The BoD accepts or rejects that heat rate using its ΔT, flow, zoning, and rejection limits.

F.4 Scope and Cross-References

Domain	Primary Reference
Workload $\rightarrow$ boundary mapping	Appendix A
Thermal closure	Appendix B
Hydraulics & ΔP	Appendix C
Sustainability accounting	Appendix D
FMEA & commissioning	Appendix E

F.5 Inputs to the Witness Calculation

F.5.1 Workload

Item	Value
Parameters	4.05×10^{11}
Tokens	3×10^{12}
Deadline	60 days
FLOPs/param-token	6

F.5.2 Platform Abstractions

Item	Value
Device sustained	0.875 PFLOP/s
Device memory	80 GB
η_{compute}	0.30
η_{fabric}	0.80

F.5.3 Facility Envelopes (BoD)

Envelope	Value
IT power	$\leq$ 10 MW
ΔT liquid	12 °C (8–15)
Rack cap	100 kW
Zone cap	1 MW
Flow rule	~20 L/s per MW

F.6 Step-0 — Topology-Agnostic Invariants

Quantity	Result
Required throughput	1.41 EFLOP/s
Token rate	5.79×10^5 tok/s
Checkpoint size	810 GB
Max step time	69 s

F.7 Step-1 — Minimal Feasible Cluster (Witness)

Item	Result
GPUs	6,208
Nodes	776 (8 GPU/node)
Parallelism	DP/TP/PP = 97/16/4
Step time	68.9 s $\leq$ 69 s
Memory/device	52 GB $\leq$ 80 GB

F.8 Step-2 → BoD Boundary Projection

F.8.1 Power Alignment

Quantity	Result	Envelope	Status
IT power	4.77 MW	$\leq$ 10 MW	Aligned
Facility power	5.49 MW	—	—
PUE	1.15	BoD target	aligned

F.8.2 Thermal Alignment

Quantity	Result (SI)	Practical Equivalent	Rule	Status
Heat	4.77 MW	—	9.5–10 MW cap	Aligned
Coolant flow	0.095 m^3/s	95 L/s (5,700 L/min)	20 L/s per MW	Aligned
Per-zone load	~0.95 MW	—	$\leq$ 1 MW	Aligned

Using Appendix B:

$$\dot{m} = \frac{\dot{Q}}{c_p \, \Delta T}$$

F.8.3 Rack Density

Item	Result (SI)	Practical Equivalent	Limit	Status
Racks	49	—	—	—
IT per rack	97 kW	($\approx$ 331,000 BTU/h)	100 kW	Aligned

F.8.4 Hydraulics

- Flow per zone $\approx$ 20 L/s ($\approx$ 1,200 L/min)
- Header class consistent with DN200–DN250
- Pumping power remains kW-scale

F.9 Alignment Statement

The witness workload lies inside all BoD envelopes for electrical, thermal, hydraulic, and rack constraints.

F.10 Sensitivities

Change	Effect
$\eta_{\text{compute}} \downarrow$	GPUs ↑ → IT power ↑
$\Delta T \downarrow$ to 8 K	Flow ↑ ~50%
Shorter checkpoint	Storage BW ↑
$\eta_{\text{fabric}} \downarrow$	Step time ↑ → GPUs ↑

F.11 PoC Evidence Gates

1. Power → heat closure:
$$\dot{Q} \approx P_{IT}$$
2. Flow law:
$$\dot{m} = \frac{\dot{Q}}{c_p \, \Delta T}$$
3. Ramp compliance: per Appendix A
4. Digital twin accuracy: per Appendix B

End of Appendix F # Design Brief — Reference Architecture (PoC)

This document instantiates the Engineering Basis of Design (BoD) into a coherent 10 MW reference topology.

This document contains no original requirements and no original derivations.
Requirements are defined in sections above.

Executive Summary

This document defines a 10 MW AI-native data-center pod derived from physics rather than historical templates:

Workload → FLOP → Watts → Heat → Water → Space → Operations

Key principles:

1. Bounded fault domains — 2 MW electrical blocks aligned to 1 MW mechanical zones prevent local failures from becoming site events.
2. Explicit transients — sized against verified ramp envelopes (ΔP, dP/dt), not steady-state MW alone. (See Appendix A.)
3. Closed-loop operations — a physics-based digital twin supervises within hard interlocks and auditable safety limits. (See Appendix B.)

The architecture is intentionally vendor-neutral and deployable across European jurisdictions.

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1. Why This Is Needed

AI workloads have broken classical datacenter assumptions:

- Power density: 5–15 kW/rack → 30–150+ kW/rack
- Heat path: air → liquid-dominated
- Utilization: workload-bound, not facility-bound
- Deadlines: training schedules compete with time-to-power

Therefore infrastructure must be derived from workload physics, not legacy layouts.

---

2. Boundary Conditions

Fixed by Reality

- Grid capacity and ramp constraints
- European limits on water, noise, and heat rejection
- Reliability targets (N+1 / optional 2N)
- Mixed customer hardware maintainability

Design Freedoms

- Cooling topology (D2C/RDHx/hybrids)
- Electrical architecture (UPS/BESS placement)
- Spatial modularization
- Digital-twin control strategy

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3. Inputs from the AI Domain

- Model size, tokens, deadline
- Implied sustained FLOP/s
- Availability & jitter tolerance
- Hardware class envelope (TDP, ΔT limits)

Workload-to-boundary mapping is defined in Appendix A.
Witness closure via CausalCompute is defined in Appendix F.

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4. Reference Topology (Instantiation)

- IT Load: 10 MW envelope (BoD)
- Rack baseline: 100 kW class
- Cooling: warm-water D2C with CDU layer
- Electrical blocks: 2 MW fault/coordination domains
- Mechanical zones: 1 MW maximum fault domains

Derived flow rules, ΔT envelopes, header classes, and ΔP budgets are defined in Appendices B and C.

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5. Electrical Architecture (Instantiation)

- Utility → MV → LV distribution aligned to 2 MW blocks
- Per-block metering at the IT boundary (BoD observability contract)
- Selective coordination implemented per BoD electrical contract
- Interlock: rack enable requires cooling availability (BoD thermal contract)

Transient contract is defined in Appendix A and verified per Appendix E.

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6. Mechanical Architecture (Instantiation)

- FW loop to dry coolers (baseline)
- CDU layer separating FW/TC
- Zone isolation at 1 MW boundaries
- Residual air path for ancillaries

Thermal closure and twin model basis are defined in Appendix B.
Hydraulics, pipe classes, and ΔP budgets are defined in Appendix C.

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7. Sustainability Architecture (Instantiation)

- Metering topology and KPI computation per Appendix D
- Export interface is fail-open to ambient rejection per Appendix D
- KPI reporting is time-series, not scalar summaries

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8. Digital Twin Concept (Instantiation)

The twin uses the first-order energy balance defined in Appendix B, operating in modes:

Observe → Recommend → Bounded Actuate.

Authority boundaries: cannot override hard interlocks (BoD safety/thermal contracts).

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9. Commissioning Philosophy (Instantiation)

- Progressive energization
- Negative testing
- Twin validation before authority
- Evidence-based acceptance

Test matrix and FMEA mapping are defined in Appendix E.

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10. Deliverables to Detailed Design

- Electrical studies (load-flow, protection, harmonics)
- Hydraulic model and transient analysis
- Controls I/O and interlock matrix
- Twin data schema
- BIM constraints

Core Principle

Infrastructure decisions are derivations from physics and workload, not brand templates.