

DATA CENTER INFRASTRUCTURE

Volume II — Detailed Engineering Design, Verification and Operational Resilience

A practical engineering reference for mission-critical facilities, enterprise computing, colocation and high-density AI infrastructure.

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Publication and engineering-use note

This educational publication is not a stamped design, code determination, certification or substitute for authority-having-jurisdiction review. Examples use illustrative assumptions rather than project-specific data. Standards and code editions vary by jurisdiction and contract; verify current adopted editions and equipment listing requirements. Independent design review and qualified electrical, mechanical, fire-protection and structural engineering are essential.

Executive summary

Reliable data centers are integrated electromechanical and digital systems. Availability depends less on nominal redundancy labels than on isolation of fault domains, maintainable architectures, controls behavior, human procedures and validated transitions. This volume develops design-basis decisions into measurable acceptance criteria and test evidence. It gives particular attention to high-density AI facilities, where utility capacity, transient loading, liquid-cooling integrity and commissioning discipline interact.

Contents and reading guide

1. Design basis and requirements decomposition

Engineering design considerations

Translate workload criticality into measurable facility outcomes: IT critical load (kW), growth rate, rack density, allowable thermal envelope, maintenance windows, recovery objectives, sustainability constraints and geographic risk. Define steady-state and transition requirements separately. Distinguish business availability from individual equipment reliability.

Verification and deliverables

Develop a requirements traceability matrix with ID, owner, source, acceptance method, operating mode, failure mode and evidence reference. Establish the system boundary and list external dependencies: utility, municipal water, fuel, telecom carriers and staffing.

Applied engineering example

Example: a 4 MW initial IT load with 6 MW future phase should not automatically dictate installing every phase-one transformer at final capacity; evaluate modular blocks, switchgear space, short-circuit evolution, cable routes and phasing downtime.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

2. Availability, redundancy and fault containment

Engineering design considerations

Compare N, N+1, 2N and distributed redundant systems using actual single-line diagrams. Redundancy does not eliminate shared switchboards, common controls, cooling-water headers, fuel supplies or human error. Design maintainability for routine inspection and replacement.

Verification and deliverables

Run fault-tree and FMEA workshops on each major transfer path. Model simultaneous maintenance and a credible second failure, not just an idealized one-component fault. Define fail-safe states for each automation sequence.

Applied engineering example

Example: dual UPS paths sharing one downstream static transfer switch have a common fault domain; test a stuck switch and loss of its control power before claiming path independence.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

3. Site selection, permitting and resilience

Engineering design considerations

Screen floodplain, seismicity, wind, wildfire smoke, industrial hazards, transportation, neighboring electromagnetic sources, water rights and utility availability. Examine environmental and social constraints alongside economic incentives.

Verification and deliverables

Produce site risk register, geotechnical study, utility feasibility letters, water balance, noise assessment, hazard maps and a permitting matrix. Identify lead times for transformers, switchgear and generators.

Applied engineering example

Example: a site with low land cost but 36-month utility upgrades can have a worse total project schedule than a more expensive site with firm capacity.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

4. Electrical load forecasting and power budgeting

Engineering design considerations

Separate nameplate, connected, coincident and demand loads. IT load profiles must include accelerator burst patterns, storage, networking and out-of-band equipment. Facility electrical demand includes cooling, pumps, lighting and losses.

Verification and deliverables

Build 15-minute and subsecond load models; reserve realistic headroom without double-counting. Validate actual rack diversity and peak demand against vendor power envelopes.

Applied engineering example

Worked example: 3,000 kW IT at PUE 1.30 implies approximately 3,900 kW total facility power and 900 kW non-IT power at that operating point. PUE is an operating ratio, not a guarantee across seasons.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

5. Utility interconnection and medium-voltage systems

Engineering design considerations

Specify utility service topology, feeder diversity, protective relaying, grounding method, metering, transformer impedances, harmonic performance and available fault current. Clarify the ownership boundary and restoration responsibilities.

Verification and deliverables

Require utility coordination study, short-circuit model, relay setting files, transformer acceptance results, primary-injection records where applicable, and switching procedures.

Applied engineering example

Example: two utility feeders on the same upstream substation bus may not constitute independent utility sources. Record physical routing and common-mode events.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

6. Switchgear, distribution and selectivity

Engineering design considerations

Evaluate switchgear ratings, arc-resistant construction where appropriate, breaker maintenance access, busway topology, branch monitoring, selective coordination and equipment replacement pathways.

Verification and deliverables

Calculate maximum and minimum fault currents for every operating state, including generator-only supply. Review time-current curves and validate protective device settings against cable and equipment limits.

Applied engineering example

Example: generator fault current can be substantially lower than utility fault current, so a protection scheme selective on utility power may not clear faults as intended on standby supply.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

7. UPS topology and ride-through

Engineering design considerations

Compare double-conversion, eco-mode, modular UPS and distributed architectures. Quantify battery autonomy, DC bus behavior, bypass transfers, harmonic performance and overload envelopes.

Verification and deliverables

Test load steps, bypass transitions, battery discharge under representative load, restoration, module removal and control-network failures. Record waveform quality and event sequence with synchronized clocks.

Applied engineering example

Example: 2,000 kW critical load for 10 minutes requires 333 kWh delivered energy before battery losses, end-of-life derating, temperature effects and discharge-rate corrections.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

8. Batteries and energy storage safety

Engineering design considerations

Address lithium-ion and lead-acid technologies, battery management, fault isolation, thermal propagation, ventilation, room design and end-of-life capacity. Include emergency response planning.

Verification and deliverables

Use listing and installation standards adopted locally; verify battery monitoring, disconnect operation, alarms, fire strategy and access restrictions. Coordinate battery hazard analysis with fire authorities.

Applied engineering example

Example: battery strings that pass a capacity test at mild temperature may fail the required autonomy at a lower room temperature or after aging.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

9. Generators, fuel and black-start sequences

Engineering design considerations

Size for nonlinear loads, motor starting, UPS recharge and cooling restart. Consider step loading, frequency excursion, paralleling controls, emissions permits and fuel quality.

Verification and deliverables

Simulate loss of utility, generator start, stabilization, bus transfer, staged cooling restart, return to utility and a failed-generator scenario. Check fuel polishing, refill contracts and on-site usable capacity.

Applied engineering example

Example: fuel autonomy is based on usable tank volume and measured consumption at the planned load, not nominal tank volume divided by catalog full-load rate.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

10. Grounding, bonding, lightning and surge protection

Engineering design considerations

Design protective earthing, equipotential bonding, grounding electrode systems, cable shield termination and coordinated surge protective devices. Distinguish safety bonding from signal reference and lightning-current paths.

Verification and deliverables

Inspect bond continuity, electrode connections, SPD status, cabinet bonding and cable entry. Verify coordination with local electrical codes and relevant lightning-protection requirements.

Applied engineering example

Example: parallel communication and power paths crossing separate building zones can create unwanted transient potentials; route and bond intentionally.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

11. Power quality, harmonics and EMC

Engineering design considerations

Evaluate harmonic current, voltage distortion, switching transients, high-frequency noise, common-mode currents and susceptibility of controls. Consider UPS, variable-speed drives, chargers and high-density power supplies.

Verification and deliverables

Measure under representative operating modes using calibrated power-quality instruments. Establish baseline and event-triggered capture; compare data to contract limits and applicable IEEE/IEC methods.

Applied engineering example

Example: a high-frequency disturbance may affect a building automation network without violating steady-state voltage limits; correlate network errors with transient recordings.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

12. Cooling load and psychrometrics

Engineering design considerations

Translate IT electrical power into sensible heat and assess humidity, economizer opportunities, airflow bypass, coil approach and partial-load efficiency. Consider seasonal conditions and failure modes.

Verification and deliverables

Perform heat-balance calculations and CFD or targeted airflow studies where justified. Measure rack inlet temperatures and dew point, not just room-average conditions.

Applied engineering example

Example: 1 MW of IT power releases approximately 1 MW of heat to be removed from the conditioned environment, apart from heat exported by direct liquid cooling.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

13. Airflow management and thermal commissioning

Engineering design considerations

Use containment, blanking panels, cable opening seals and rack-level sensing to reduce recirculation. Analyze floor supply pressure and hot spots in legacy raised-floor installations.

Verification and deliverables

Thermal-map each aisle at representative and peak loads. Record top/middle/bottom inlet conditions, fan behavior and recovery after one cooling unit is disabled.

Applied engineering example

Example: increasing CRAC airflow can worsen bypass and raise return-air mixing; fix airflow paths before simply increasing fan speed.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

14. Liquid cooling for AI and HPC

Engineering design considerations

Differentiate direct-to-chip cold plates, rear-door heat exchangers and immersion. Define facility-water and technology-cooling loops, CDU isolation, materials compatibility, filtration, conductivity and leak detection.

Verification and deliverables

Specify temperature, pressure, differential pressure, flow, water quality, allowable transients and connector standards. Test isolation-valve behavior, pump failover, CDU loss, leak alarms and controlled IT throttling.

Applied engineering example

Worked example: 500 kW removed by water at 10°C temperature rise requires about 11.9 kg/s or 43 m³/h, using $cp \approx 4.18$ kJ/(kg·K), before design margins and fluid-property corrections.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

15. Heat rejection, water and climate adaptation

Engineering design considerations

Compare chillers, dry coolers, cooling towers and hybrid systems. Quantify annual energy and water usage, freeze protection, chemical treatment, Legionella controls and water-discharge permits.

Verification and deliverables

Create annual bin-hour model and water balance. Validate makeup-water availability and operation during drought, smoke, heat waves and freeze events.

Applied engineering example

Example: a water-efficient cooling design may consume more electricity in hot weather; evaluate local grid emissions and water scarcity rather than one metric alone.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

16. Mechanical controls and failover logic

Engineering design considerations

Define sequences of operation for normal, maintenance, emergency and degraded modes. Prevent oscillation between redundant pumps, valves and chillers. Design manual overrides with clear interlocks.

Verification and deliverables

Execute point-to-point tests, simulated sensor failures, communications loss, stuck valves, bad setpoints and loss of control power. Confirm alarm prioritization and safe fallback.

Applied engineering example

Example: redundant pumps commanded by a single PLC with one power supply may have no effective controls redundancy.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

17. Network, fiber and carrier diversity

Engineering design considerations

Define diverse meet-me rooms, physically separated fiber routes, spine-leaf network fabrics, management planes and synchronization. Map common conduits, manholes and providers.

Verification and deliverables

Use optical-loss budgets, OTDR tests, fiber polarity checks, failover tests and carrier restoration procedures. Validate route diversity with as-built surveys.

Applied engineering example

Example: two carriers leasing the same last-mile conduit provide contractual diversity but not physical resilience.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

18. OT cybersecurity and monitoring

Engineering design considerations

Segment BMS, EPMS, DCIM, UPS, generator and cooling controls from enterprise networks. Protect remote vendor access, credentials, time synchronization and firmware supply chain.

Verification and deliverables

Maintain asset inventory, secure configuration baselines, backup/restore evidence, vulnerability exception register and incident playbooks. Test safe operation during network isolation.

Applied engineering example

Example: a ransomware event in enterprise IT must not prevent local operation of chilled-water pumps or emergency power systems.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

19. Fire, life safety and emergency response

Engineering design considerations

Coordinate detection, suppression, smoke control, egress, emergency power-off philosophy and battery fire strategy. Avoid indiscriminate shutdown of critical cooling or controls.

Verification and deliverables

Develop cause-and-effect matrix with fire engineer and AHJ. Witness alarm, suppression interlock, door release, fan response and manual override sequences.

Applied engineering example

Example: an EPO system should be assessed for inadvertent activation risk and its effect on life safety and equipment damage.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

20. Physical security and supply chain

Engineering design considerations

Implement layered security, visitor authorization, CCTV coverage, tamper detection, secure loading and equipment chain of custody. Treat spares and firmware images as controlled assets.

Verification and deliverables

Test access-control fail-safe/fail-secure behavior, emergency egress and event retention. Verify asset receiving, disposal and media destruction processes.

Applied engineering example

Example: a single badge controller outage should not trap personnel or disable emergency access.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

21. Commissioning strategy and integrated systems testing

Engineering design considerations

Stage FAT, installation inspection, prefunctional checks, functional testing, integrated systems testing and operational handover. Distinguish component performance from system transitions.

Verification and deliverables

Develop test scripts with initial conditions, instruments, hold points, acceptance criteria, abort limits, restoration steps and witness signatures. Maintain issue log through closure and retest.

Applied engineering example

Example: utility-loss testing should capture UPS ride-through, generator start, mechanical recovery, network availability and alarm timelines in one synchronized event record.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

22. Reliability-centered maintenance

Engineering design considerations

Use asset criticality and failure modes to schedule inspection, thermography, battery tests, generator exercising, breaker maintenance and cooling-system water treatment.

Verification and deliverables

Link CMMS work orders to asset IDs, redundancy state and change windows. Record deferred maintenance and cumulative risk.

Applied engineering example

Example: concurrent maintenance on A and B paths can defeat an otherwise fault-tolerant design; coordinate site-wide work permits.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

23. Energy efficiency, carbon and cost

Engineering design considerations

Evaluate PUE, WUE, renewable procurement, embodied carbon, part-load efficiency and total cost of ownership. Avoid comparing PUE values without climate, load and measurement boundaries.

Verification and deliverables

Create metering plan with calibrated points and explicit calculation boundary. Report annualized trends with weather normalization and uncertainty.

Applied engineering example

Example: 5 MW IT at PUE 1.25 consumes about 54.75 GWh/year at continuous full IT load, assuming 8,760 hours; actual consumption depends on load profile.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

24. Expansion, retrofit and live migration

Engineering design considerations

Plan brownfield capacity upgrades around cutover risk, protection changes, floor loading, cooling constraints and cable management. Build rollback steps and temporary power strategy.

Verification and deliverables

Use staged method-of-procedure rehearsals, isolation diagrams and post-cutover trending. Verify updated as-builts and protection settings.

Applied engineering example

Example: adding a new UPS may increase available fault current and invalidate existing breaker assumptions even when IT load is unchanged.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

25. Operational readiness and incident management

Engineering design considerations

Define operating procedures, emergency operating procedures, staffing competency, alarm escalation, vendor response and spare-parts strategy. Practice tabletop and live drills.

Verification and deliverables

Require operator qualification, controlled documents, incident review and lessons-learned tracking. Measure restoration time and repeat failure mechanisms.

Applied engineering example

Example: a perfect redundancy design can fail during restoration if operators lack a tested sequence for synchronizing and returning to normal topology.

Design review questions: What is the credible single failure? Which upstream and downstream dependencies are shared? Can this element be maintained without unacceptable service loss? What measured evidence proves the requirement? What is the safe recovery path?

Appendix A — Sample design verification matrix

ID	Requirement / criterion	Verification	Evidence
EL-01	Critical load supported at rated operating conditions	Load bank / trend	Signed load test
EL-02	UPS ride-through during transfer	Event waveform test	Time-stamped captures
EL-03	Protective coordination for all source modes	Engineering study + field settings	Approved curves
ME-01	Rack inlet within design thermal envelope	Thermal mapping	Sensor logs
ME-02	Cooling survives single-unit outage	Failure injection	IST record
LC-01	CDU maintains required flow and temperature	Flow / pressure test	Commissioning record
NET-01	Diverse network routes survive fiber cut	Controlled failover	OTDR + event logs

OT-01	Local control persists after network isolation	Isolation test	Witness signoff
OPS-01	Restoration procedure proven	Operator drill	MOP + results

Appendix B — Integrated systems test script template

Test identifier

IST-UTILITY-LOSS-01

Objective

Demonstrate critical IT continuity and controlled facility recovery after loss of normal utility.

Prerequisites

Approved switching plan; stable load; instrumentation synchronized; witness roster; no conflicting maintenance; emergency abort procedure.

Initial conditions

Normal utility, redundant paths healthy, representative load, cooling steady, alarms cleared.

Actions

Record baseline; initiate approved utility-loss simulation; observe UPS and generator sequence; confirm cooling and IT continuity; restore utility; confirm normal topology.

Measurements

Bus voltage/frequency, UPS state, generator times, IT telemetry, cooling temperatures/flow, BMS/EPMS event log.

Acceptance

No unapproved IT interruption; all transfer and environmental criteria met; alarms and restoration as specified by approved design.

Abort / restoration

Stop on unsafe conditions; return to documented safe topology; capture evidence; open issue record and retest after corrective action.

Appendix C — Practical calculation workbook examples

- Three-phase current: $I = P / (\sqrt{3} \times VLL \times \text{power factor} \times \text{efficiency})$, with assumptions and harmonic effects documented.
- UPS battery energy: delivered kWh = critical kW × autonomy hours; apply inverter efficiency, aging, discharge-rate and temperature derating.
- Liquid flow: mass flow kg/s = heat kW / (specific heat kJ/kg·K × temperature rise K).
- Annual energy: facility kWh = IT kW × PUE × annual operating hours for a constant-load illustrative case.
- Reliability modeling: series availability is product of independent component availabilities; do not use independence assumption for shared controls or utilities.

Appendix D — Standards and authoritative reference families

- ANSI/TIA-942 — Telecommunications Infrastructure Standard for Data Centers (verify edition and scope).
- ISO/IEC 22237 and EN 50600 — data center facilities and infrastructure.
- Uptime Institute Tier Standard: Topology — availability architecture (proprietary criteria).
- ASHRAE TC 9.9 thermal guidelines and ASHRAE data-center cooling guidance.
- NFPA 70 (NEC), NFPA 70E, NFPA 72, NFPA 75, NFPA 110, NFPA 111 and NFPA 855 as applicable.
- IEEE 1584 (arc-flash), IEEE 519 (harmonics), IEEE 493 (reliability), IEEE 1100 (powering electronic equipment), applicable IEEE battery guidance.
- IEC 60364, IEC 61439, IEC 62040, IEC 62305, IEC 61000 series and IEC 62443 as applicable.
- TIA-568, TIA-569, TIA-607, ISO/IEC 11801 and applicable fiber-optic test standards.
- ISO/IEC 27001 and NIST SP 800-82 for cybersecurity governance and operational technology.
- ASHRAE 90.4 — Energy Standard for Data Centers; applicable local energy codes.

Regulatory note: references are a navigation aid, not a declaration of applicability. Review current editions, local adoption, equipment listings and contract requirements before relying on a standard.

Closing perspective

The strongest data center designs make failure behavior observable and testable. Every critical requirement should map to an owner, a physical or logical architecture, an operating procedure, a verification method and retained evidence. In practice, commissioning and ongoing change control are as important to resilience as the original equipment selections.