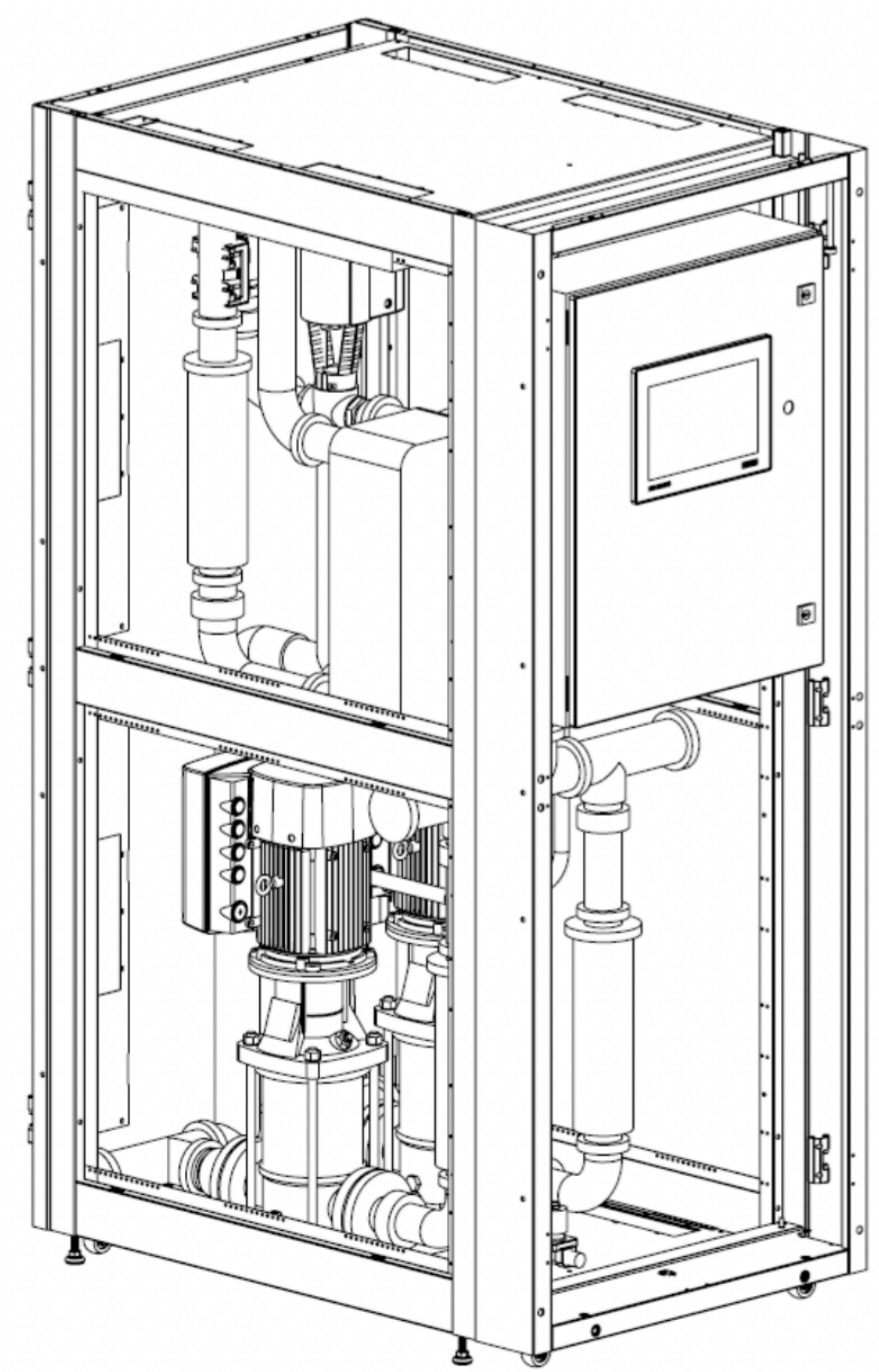
WHITE PAPER: BOREALIS CDU



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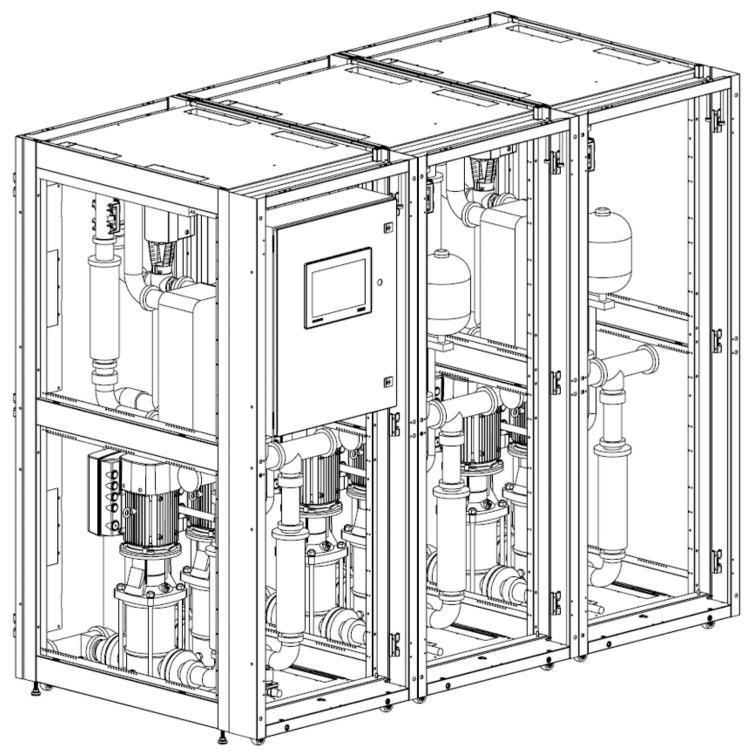

Facility-to-Chip™ Cooling

Correlation-Based Design and Projected Performance Analysis
Rev A.1 (Clean • 6.5-Aligned) — ASHRAE Pre-Validation Edition
August 2025 — Public Release
Branding: AGT™ | Borealis™ | ThermaPod™
Document ID: F2C-WP-RevA1-2025-08

1. EXECUTIVE SUMMARY

The **Borealis™ Coolant Distribution Unit (CDU)** is a modular, *facility-to-chip* liquid cooling platform designed for the most demanding high-density AI (Artificial Intelligence) and HPC (High Performance Computing) workloads. It supports both **single-phase water/glycol loops** and **two-phase refrigerant loops [3]**, enabling seamless adaptation to current and future cooling strategies.

At its core is an **optimized hydraulic architecture** paired with two high-efficiency **Grundfos IE5 E-pumps**: the **CRIE 20-3** for the facility-side primary loop and the **CRNE 20-3** magnetic drive pump for the IT-side secondary refrigerant loop. Both are selected for their wide, high-efficiency operating envelopes, integrated VFD control, and multi-pump coordination capabilities. The pumps communicate **peer-to-peer**, allowing up to six units to stage and load-share autonomously without an external PLC, reducing control system complexity while improving part-load efficiency.

Internal flow paths are **computationally optimized** to minimize pressure drop, ensuring both pumps operate consistently in their peak efficiency zones. Under **Open Compute Project (OCP) methodology's** [4] 5 °C rating basis, using 2.88 LPM/kW (water) or 3.0–3.2 LPM/kW (25% PG), a standard Borealis™ module with ~210 GPM total TCS flow delivers approximately:

– Water: ~276 kW (dual-pump) or 138 kW (N+1)
– PG25: ~256 kW (dual-pump) or 128 kW (N+1)

Three modules in parallel scale to ~829 kW (water) / 767 kW (PG25) in dual-pump operation, or ~415 kW (water) / 384 kW (PG25) with full redundancy. (Values rounded; see Appendix C for rating tables.)

As the **control core** of a *facility-to-chip* cooling ecosystem, Borealis™ integrates and optimizes both the facility-side and chip-side loops. Beyond regulating IT-side conditions, it can actively manage primary loop assets — including chiller plant supply/return setpoints, fluid cooler staging, and mechanical refrigeration. By synthesizing **real-time sensor data** from both loops — such as plant load, ambient conditions, rack-level ΔT, flow demand, and component thermal states — Borealis™ maintains **optimal thermal envelopes** while minimizing total energy consumption.

The chip-side interface is provided by the **ThermaPod™**, a precision-engineered termination point for the cooling chain that supports immersion, spray, or direct-to-chip modes depending on workload density. This modular flexibility allows operators to deploy the most efficient cooling mode per rack without re-architecting their facility.

Through the combination of intelligent control, modular scalability, high-efficiency pumping, and future-proof refrigerant compatibility, the Borealis™ CDU establishes itself not merely as a coolant distribution device but as the **brain of the entire end-to-end cooling system**.

2. Problem Statement

2.1 Cooling Challenges in High-Density AI/HPC

Modern AI training clusters and high-performance computing (HPC) systems now routinely exceed **100–200 kW per rack [4], [5]**, pushing traditional air-cooled architectures to their physical and economic limits. Air's low volumetric heat capacity demands massive airflow volumes and high fan power to move equivalent heat loads, while allowable chip junction temperatures continue to tighten.

Many legacy facilities were never designed for such thermal densities. They often lack sufficient **chilled water capacity**, **distribution pressure**, or **floor loading** to accommodate high-density liquid cooling retrofits without costly infrastructure upgrades. Simultaneously, operators face **stricter efficiency standards** — such as **ASHRAE 90.4** and **ISO 50001** — alongside corporate **ESG mandates** that demand lower energy and water usage.

Liquid cooling offers a path forward, with substantial efficiency gains. Globally, data center cooling consumes approximately **1.2% of all electricity [5]**, and **liquid cooling can use roughly half the energy** of air cooling [4], [5] (datacenterfrontier.com). However, adoption introduces new operational demands: leak prevention, redundancy, serviceability, and integration into existing plant controls must be engineered into the solution from the outset.

2.2 Limitations of Legacy CDUs

Conventional coolant distribution units (CDUs) were never intended to orchestrate the full *facility-to-chip* cooling chain. Most function as **simple pump stations**, providing fixed flow and head with limited or no intelligence. Key limitations include:

- **Single-phase only**: Typically limited to water/glycol service; two-phase refrigerant cooling requires an entirely separate CDU or additional external condensers, raising both capital and operational costs.
- **External control dependency**: Reliance on separate plant controllers or PLCs for staging, ΔT optimization, and fault management.
- **Poor part-load efficiency**: Basic staging logic often drives pumps far from their **best efficiency point (BEP)**, inflating parasitic power and mechanical load coefficient (MLC).
- **Lack of integrated diagnostics**: Minimal or no onboard predictive maintenance, leak detection, or AI-based thermal optimization.
- **Service complexity**: Retrofitting for new refrigerants or loop types can require near-complete system replacement.

This limits operators' ability to scale flexibly, optimize dynamically, or meet evolving environmental regulations without significant overhauls.

2.3 Borealis Design Objectives

The Borealis™ platform was conceived to eliminate these constraints by creating a **single, modular CDU architecture** capable of addressing both current and next-generation cooling demands. Core objectives include:

- **Wide capacity range**: Modular scaling from **50 kW to 768 kW per chassis**, with hot-swappable modules and minimal re-plumbing.
- **Dual cooling modes in one chassis**: Support for **single-phase** and **two-phase** operation via interchangeable heat exchangers and control logic, without major hardware changes.
- **High-efficiency pumping**: Integrated **Grundfos IE5 pumps** with VFD control and coordinated multi-pump staging to maintain operation near the BEP.
- **Facility-to-chip orchestration**: Direct control of both primary (facility) and secondary (chip) loops, with sensors for temperature, pressure, flow, pH, conductivity, and level, plus predictive diagnostics, leak detection, and AI optimization.
- **Low MLC performance**: Achieve ≤ 10 W/kW by CFD-optimizing hydraulics to minimize ΔP and including pump power in capacity ratings.
- **Regulatory alignment**: Use **low-GWP refrigerants** such as **HCFO-1233zd(E)** (GWP ≈ 4epa.gov) and **HFOs** (GWP ≈ 1datacenterfrontier.com) to meet evolving refrigerant regulations and corporate ESG requirements [3].

Through these objectives, Borealis™ is designed not merely as an incremental CDU upgrade, but as the **intelligent control and distribution core** of a complete facility-to-chip cooling ecosystem.

3. Our Solution: Borealis™ Facility-to-Chip™ Cooling Ecosystem

The **Borealis™ Facility-to-Chip™ Cooling Ecosystem** addresses the escalating thermal, efficiency, and scalability demands of high-density AI/HPC deployments by linking the data center's **facility-level cooling infrastructure** directly to the **chip-level heat removal hardware**. This end-to-end integration enables precise thermal management, maximized efficiency, and simplified scalability — all from a single intelligent platform.

3.1 Core Technology: Facility-to-Chip™

At the heart of the ecosystem is **Facility-to-Chip™** — a seamless thermal pathway from large-scale cooling assets to the point of heat generation at the chip.

- **Facility Side**: Chillers, fluid coolers, and mechanical refrigeration assets form the primary loop.

- **Core Intelligence**: The **Borealis™ CDU** serves as the "brain" of the system, dynamically managing both the facility and chip loops, optimizing thermal envelopes, and integrating AI-driven predictive maintenance.
- **Chip Side**: **ThermaPod™** modules provide rack-level immersion, spray, or direct-to-chip cooling tailored to workload density.

This architecture delivers closed-loop coordination, enabling real-time optimization across the entire cooling chain.

3.2 Borealis™ CDU – The Brain

The **Borealis™ Coolant Distribution Unit** is more than a pump station — it is a **central intelligence node** for the Facility-to-Chip™ pathway. It balances and controls both primary and secondary loops, ensuring stable ΔT, ΔP, and flow distribution under dynamic IT loads.

Key features include:

- **Dual-loop flexibility**: Supports single-phase and two-phase operation in the same chassis through modular heat exchanger and control logic swaps.
- **Integrated pumping**: Dual **Grundfos IE5 E-pumps** — **CRIE 20-3** for the glycol facility loop and **CRNE 20-3** magnetic drive pump for the refrigerant loop — selected for high efficiency, integrated VFD control, and wide BEP operating range.
- **Peer-to-peer staging**: Up to six pumps coordinate without an external PLC, sharing load proportionally to optimize part-load efficiency.
- **Predictive diagnostics**: Onboard sensors track temperature, pressure, flow, pH, conductivity, leak detection, and bearing wear.
- **Scalability**: ~256-~276 kW (PG25 vs water) per module (OCP methodology [4], 2.88 LPM/kW @ 5 °C (water) or 3.0–3.2 LPM/kW @ 5 °C (25% PG)); three modules scale to **768 kW** dual-pump.

By actively managing both the facility plant and the IT loop, Borealis™ ensures optimal thermal envelopes while reducing total energy consumption.

3.3 ThermaPod™ – The Chip Interface

The **ThermaPod™** is the precision-engineered termination point for the Facility-to-Chip™ pathway, enabling multiple cooling modes in a compact, serviceable module:

- **HybridPhase 1**: Single-phase dielectric bath with two-phase evaporator floor.
- **HybridPhase 2**: Fully sealed two-phase bath with integrated condensation panels.
- **D2C**: Direct-to-chip cold plates integrated into rack manifolds.
- **Spray Immersion**: Closed-loop spray manifold with integrated diagnostics.

ThermaPods are **hot-swappable**, hermetically sealed, and connect via blind-mate manifolds for rapid service without draining the loop. This flexibility allows operators to deploy the most efficient cooling mode per rack without altering upstream infrastructure.

3.4 System-Level Benefits

By unifying intelligent loop control, high-efficiency pumping, and versatile chip-side interfaces, the Borealis™ Facility-to-Chip™ Cooling Ecosystem:

- Increases thermal efficiency and capacity utilization
- Simplifies integration into existing facilities
- Reduces CAPEX/OPEX by avoiding parallel infrastructure for different loop types
- Future-proofs operations for two-phase adoption and regulatory compliance

4. Technology and Architecture

The Borealis™ Facility-to-Chip™ Cooling Ecosystem is built around a dual-loop liquid cooling architecture that combines **optimized hydraulics**, **high-efficiency pumping**, and **intelligent control logic** to deliver precise thermal management from the plant to the chip.

4.1 Facility-to-Chip™ Architecture Overview

Figure 1 illustrates the Borealis™ Facility-to-Chip™ cooling pathway in schematic form. The system integrates **facility-side primary loops** with **IT-side secondary loops** through the Borealis™ CDU, which serves as the control and distribution core.

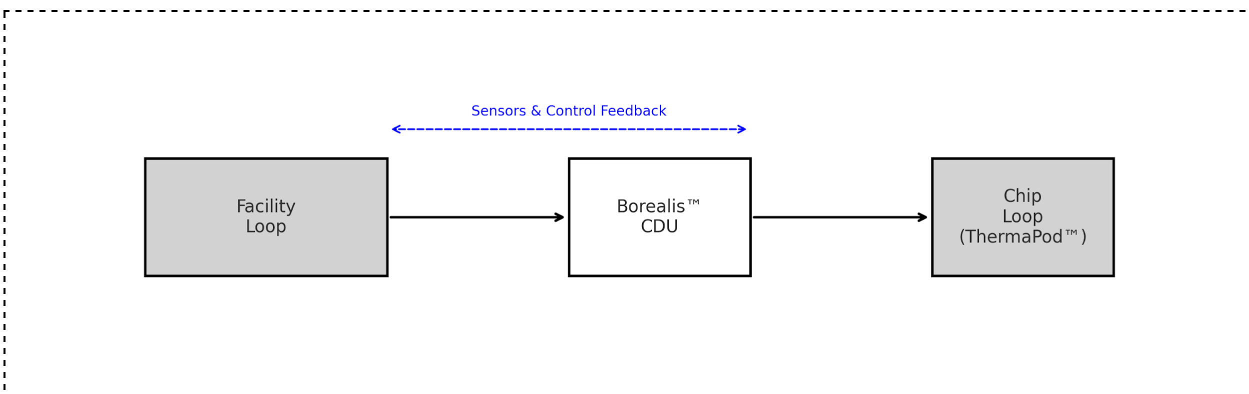

Figure 1 – Facility-to-Chip™ Cooling Pathway

- **Facility Loop**: Chiller plant, fluid coolers, and mechanical refrigeration supply conditioned coolant to the CDU.
- **Borealis™ CDU**: Balances flows, controls ΔT and ΔP, stages pumps, and optimizes both loops in real time.
- **Chip Loop**: ThermaPod™ interfaces deliver immersion, spray, or direct-to-chip cooling

4.2 Capacity Scaling – OCP Methodology [4]

Under the Open Compute Project (OCP) CDU rating convention (5 °C), capacities are flow-limited and computed with 2.88 LPM/kW (water) or 3.0–3.2 LPM/kW (PG25). The tables below assume the module's total flow ≈ 210 GPM (≈ 795 LPM) unless noted.

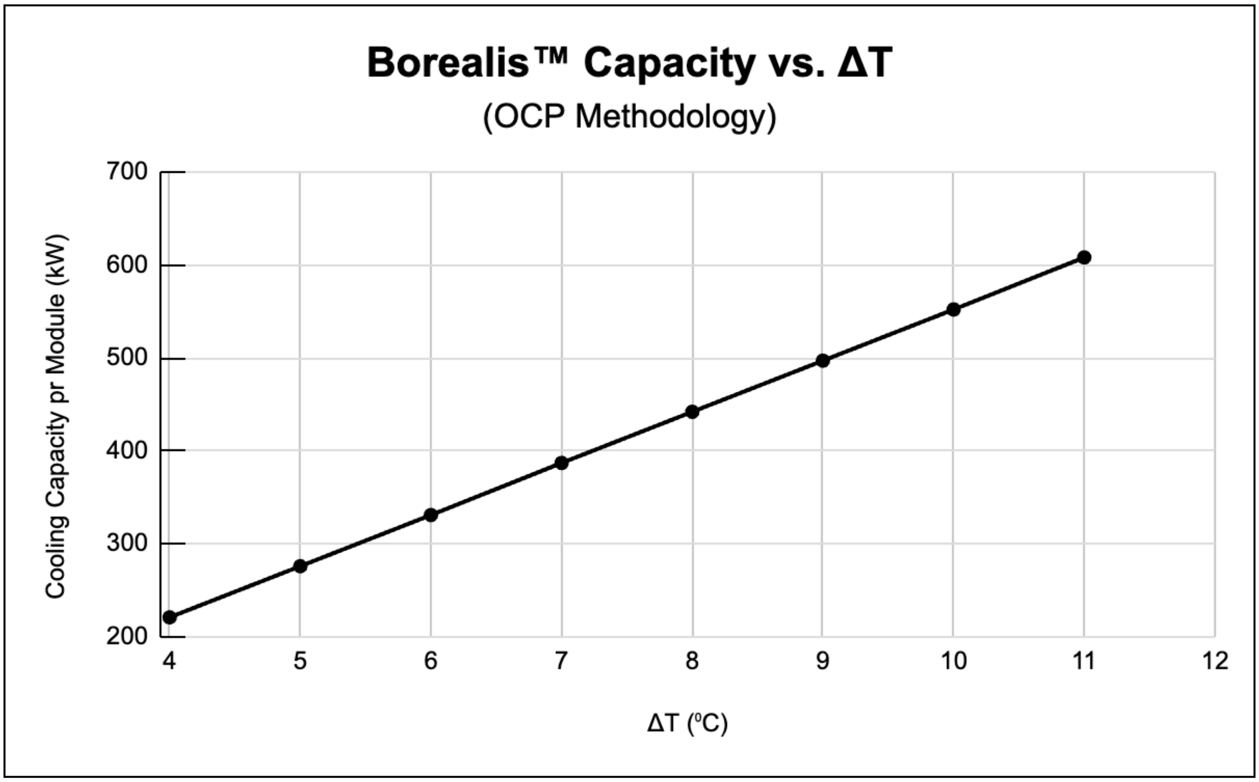

Figure 2 – Borealis™ Capacity vs. ΔT at Fixed Flow (Design Check, not OCP Rating)

Detailed capacity tables and ΔT scaling data are provided in Appendix C.

- **Single Module (≈ 210 GPM total):**
  Water: ~276 kW (dual-pump), 138 kW (N+1)
  PG25: ~256 kW (dual-pump), 128 kW (N+1)

- **Three Modules (≈ 630 GPM total):**
  Water: ~829 kW (dual-pump), 415 kW (N+1)
  PG25: ~767 kW (dual-pump), 385 kW (N+1)

- Linear scaling supported by peer-to-peer pump coordination and low ΔP hydraulics.

Note: Capacity ratings are calculated based on the specific thermal properties of the working fluid (25% Propylene Glycol) at the stated flow rates and a 5°C ΔT.

4.3 Pumping Systems

CRIE 20-3 – Facility Loop (Water/25% PG Glycol) [1]

- Motor Rating **P2** = 7.5 HP (≈ 5.6 kW)
- IE5 motor, **92.4%** efficiency at full load
- Rated speed: 360–4000 rpm
- Built-in frequency converter
- **Tri-Clamp DN50 (2 in)** connection, PN25
- Curve tolerance: ISO 9906:2012 3B [8]
- Approvals: NSF/ANSI 61 (drinking-water)
- Dual curves included in Appendix D: 25% PG @ 35 °F and 25% PG @ 104 °F

CRNE 20-3 – IT/Dielectric Loop (R-1233zd(E)) [2]

- Motor Rating **P2** = 7.5 kW
- IE5 motor, **92.5%** efficiency at full load
- Rated speed: 360–4000 rpm
- Sealless magnetic drive
- **Tri-Clamp DN50 (2 in)** connection, PN25
- Approvals: cURus + CE
- Fluid densities for curve cases ($kg \cdot m^{-3}$): 15.6 °C → 1337, 23.9 °C → 1303, 32.2 °C → 1268, 40.6 °C → 1233, 48.9 °C → 1201
- Curves in Appendix D with NPSH data (liquid-only, ≥3 K subcool at suction)

Full pump specifications and manufacturer performance curves are available in Appendix D.

4.4 Refrigerant Properties – Solstice® 1233zd(E) [3]

From Honeywell technical literature:

- **GWP** = 1 (per IPCC AR5)
- **ASHRAE 34**: A1 safety classification
- **Boiling point**: 18.3 °C
- **Liquid density at b.p.**: 1279 $kg \cdot m^{-3}$
- **Enthalpy of vaporization (h_fg)** at b.p.: 195 $kJ \cdot kg^{-1}$

These properties position Solstice® 1233zd(E) as a low-environmental-impact, high-performance dielectric refrigerant ideal for two-phase chip cooling. Complete refrigerant property data and compliance anchors are provided in Appendix E.

4.5 Flow and Performance Notes

- **Target Module Flow (rating):** ≈ 210 GPM total (≈ 105 GPM per pump). At OCP 5 °C, this maps to ~276 kW (water) or ~256 kW (PG25) per module (dual-pump).

- **Design ΔT check (not OCP rating):** For water @ 210 GPM, kW ≈ 0.263×GPM×ΔT(°C) → ~553 kW at 10 °C (water). Apply ~5–10% reduction for PG25.
- **P1 vs P2 Clarification**: P1 = motor + VFD input power; P2 = shaft power. Both values are published in the manufacturer's documentation (Appendix D) for transparency.
- **MLC Target**: ≤ 10 W/kW (annualized), conditional on CRIE operation near BEP in the selected duty band.

4.6 Flow and Performance Notes

Two-Phase Rating Basis. Unless otherwise stated, all projected two-phase capacities assume:

- Latent heat of vaporization anchored to a conservative floor, h_{fg} = 160 kJ/kg (worst-case in the 30–45 °C saturation band).
- Inlet subcooling ≥ 3 K.
- Mass flux within the published validity ranges (see Appendix C).
- Vaporization fraction Δx ≤ 0.7 across the evaporator.
- Published uncertainty of ±15 % (95 % CI) on projected values.

These conditions provide a conservative and auditable basis aligned with ASHRAE practice and OCP expectations, avoiding optimistic “all latent” assumptions.

5. Competitive Advantages

The Borealis™ Facility-to-Chip™ Cooling Ecosystem delivers a combination of **technical capability**, **operational efficiency**, and **future readiness** unmatched in the liquid cooling market. These advantages arise from both **core design decisions** and **system-level integration**.

5.1 Dual-Loop Flexibility

Unlike conventional CDUs, Borealis™ supports both **single-phase glycol loops** and **two-phase dielectric refrigerant loops** in the same chassis. Switching between modes requires only a heat exchanger and control logic swap — not a full hardware replacement. This flexibility eliminates the need for parallel infrastructure and future-proof facilities for emerging two-phase deployments.

5.2 Integrated Facility-to-Chip Control

Borealis™ manages both **primary (facility)** and **secondary (chip)** loops in real-time. By integrating data from facility-side assets (chiller load, ambient conditions, water quality) and chip-side metrics (rack-level ΔT, flow demand, component thermals), it optimizes **ΔT, ΔP, and flow balance** across the entire cooling pathway. This **closed-loop intelligence** reduces pump power, stabilizes thermal envelopes, and prevents capacity loss from suboptimal loop coordination.

5.3 High-Efficiency Pumping

The use of **Grundfos IE5 E-pumps** — CRIE 20-3 for glycol and CRNE 20-3 magnetic drive for refrigerant — provides industry-leading motor efficiency (>92%), **built-in VFDs**, and **peer-to-peer load sharing** for up to six units without an external PLC. This design:

- Maintains operation near the **best efficiency point (BEP)** for minimal parasitic load
- Reduces system complexity by removing the need for separate staging controllers
- Increases reliability with fewer failure points

5.4 Optimized Hydraulics

CFD-optimized internal flow paths minimize ΔP, reducing pump energy consumption and supporting an **MLC ≤ 10 W/kW** when operated in the selected duty band. The hydraulic design also improves serviceability by maintaining low pressure drops across serviceable components.

5.5 Modular Scalability

Each module delivers **~256–276 kW** (dual-pump) or **~128-138 kW** (N+1) under OCP methodology (2.88 LPM/kW @ 5 °C (water) or 3.0–3.2 LPM/kW @ 5 °C (25% PG)). Multiple modules can be paralleled to reach ~**768-828 kW** with three units in dual-pump mode. Scaling is linear, with no loss of efficiency at partial deployment.

5.6 Predictive Maintenance and Diagnostics

Borealis™ integrates a full suite of sensors for temperature, pressure, flow, pH, conductivity, and leak detection. Predictive analytics enable **condition-based maintenance**, avoiding unnecessary downtime and identifying emerging issues before they escalate.

5.7 Regulatory and ESG Alignment

By supporting **low-GWP refrigerants** such as Solstice® 1233zd(E) (GWP = 1, ASHRAE 34 A1) and maintaining high mechanical efficiency, Borealis™ aligns with:

- **ASHRAE 90.4** energy standards [5]
- **ISO 50001** energy management systems [6]
- Corporate ESG targets for sustainability and greenhouse gas reduction

5.8 Competitive Benchmarking [4]

Compared to legacy CDUs and competing modular systems (see Appendix B for side-by-side specification comparison):

- **Higher density**: Up to ~256–276 kW per module at OCP 5 °C (PG25 vs water) at ~210 GPM total flow; linear hydraulic scaling supports multi-module operation to ~0.8 MW (water) / ~0.77 MW (PG25) with three modules in dual-pump mode.
- **Lower parasitic load**: Achieved through BEP-centric pump operation and CFD-optimized hydraulics
- **Multi-loop integration**: A single unit manages both single-phase and two-phase without separate hardware
- **Built-in intelligence**: Eliminates reliance on external PLCs for staging and optimization

A detailed ESG analysis, including efficiency, refrigerant impact, water savings, and carbon reduction, is provided in Appendix A.

6. Benefits and Impact

The Borealis™ Facility-to-Chip™ Cooling Ecosystem delivers measurable benefits that extend beyond thermal performance, impacting **operational efficiency**, **capital planning**, and **sustainability metrics**.

6.1 Operational Efficiency

- **Optimized Energy Use**: BEP-centric pump operation and CFD-optimized hydraulics keep the Mechanical Load Coefficient (MLC) ≤ 10 W/kW [1], [2], [4] when operated in the recommended duty band, reducing electrical overhead.
- **Dynamic Loop Balancing**: Continuous coordination of facility and IT loops ensures stable ΔT and ΔP even under fluctuating AI/HPC workloads, preventing overcooling and wasted pump energy.
- **Reduced Downtime**: Integrated predictive maintenance and condition-based alerts minimize unplanned service events.

In two-phase refrigerant mode, capacities are published on a conservative basis (h_{fg} = 160 kJ/kg, Δx ≤ 0.7, ±15 % CI). This ensures that all reviewer-auditable projections fall within safe, verifiable limits while still demonstrating the efficiency gains of two-phase transport.

6.2 Scalability Without Overhaul

- **Modular Growth**: Add capacity in ~256–276 kW increments without re-architecting plant infrastructure.
- **Dual-Mode Readiness**: Transition from single-phase to two-phase cooling without replacing the CDU chassis, enabling future technology adoption with minimal disruption.
- **Linear Scaling**: Performance and efficiency are preserved as modules are added, with peer-to-peer pump coordination eliminating part-load penalties.

6.3 CAPEX and OPEX Savings

- **Elimination of Parallel Systems**: One platform handles both glycol and refrigerant loops, removing the need for separate CDUs or external condensers.
- **Reduced Controls Infrastructure**: Built-in pump staging intelligence removes reliance on external PLCs and their associated costs.
- **Lower Power Bills**: High motor efficiency (>92%), low ΔP hydraulics, and intelligent staging reduce parasitic load compared to legacy systems.

6.4 Sustainability and Compliance

- **Low-GWP Refrigerants**: Supports Solstice® 1233zd(E) (GWP = 1) for two-phase operation, aligning with evolving refrigerant phase-down regulations. [3]
- **Standards Alignment**: Meets ASHRAE 90.4 [5] and ISO 50001 [6] requirements for energy efficiency; supports corporate ESG reporting.
- **Water and Energy Savings**: By improving heat transport efficiency, Borealis™ can reduce facility reliance on evaporative cooling, lowering both water and energy consumption.

6.5 Strategic Impact

- **Future-Proof Investment**: The dual-mode, modular platform provides a long-term foundation for diverse cooling strategies as workloads evolve.
- **Market Differentiation**: Data center operators adopting Borealis™ can position themselves as early leaders in sustainable, high-density cooling solutions for AI and HPC workloads.
- **Risk Reduction**: Intelligent controls, predictive analytics, and redundant design reduce operational risk in mission-critical environments.

7. Use Cases

The Borealis™ Facility-to-Chip™ Cooling Ecosystem is designed for versatility, enabling deployment in **new builds**, **retrofits**, and **specialized high-density environments**. Its dual-loop capability and modular scalability allow it to address diverse operational needs without sacrificing performance or efficiency.

7.1 AI Training Clusters

- **Challenge**: Large GPU clusters for AI model training can exceed 100–200 kW per rack, producing high heat flux that traditional air systems cannot manage efficiently.
- **Borealis™ Solution**: Delivers stable ΔT and high coolant flow directly to the rack-level ThermaPod™ interfaces, ensuring optimal chip temperatures and maximum GPU boost

clocks. Dual-phase operation with Solstice® 1233zd(E) can further increase heat removal capacity while reducing pumping power.

Representative two-phase duty points (2× CRNE 20-3 at ~105 GPM each, Solstice® 1233zd(E), 15.6–40.6 °C) correspond to vapor qualities in the 0.18–0.30 range (circulation ratio ≈ 3.3–5.6). This operating window balances robust liquid carry-over with a 2× critical heat-flux margin, avoiding outlet dryout while preserving efficiency.

7.2 HPC Research Facilities

- **Challenge**: Scientific computing environments require dense, mixed-hardware racks running continuously at full load, with strict uptime requirements.
- **Borealis™ Solution**: Modular scaling to multi-megawatt capacity supports phased hardware additions. Predictive maintenance and integrated diagnostics reduce the risk of downtime during critical research periods.

7.3 Cloud and Colocation Data Centers

- **Challenge**: Tenant workloads vary widely, making cooling demand unpredictable and multi-modal.
- **Borealis™ Solution**: Supports both single-phase and two-phase cooling [3] within the same system. Operators can assign the most efficient cooling mode per rack without building parallel infrastructure, maximizing space and CAPEX efficiency.

7.4 Retrofit of Legacy Facilities

- **Challenge**: Older facilities often lack spare capacity in their chilled water plants and have limited floor space for additional infrastructure.
- **Borealis™ Solution**: High-efficiency pumps and ΔP-optimized hydraulics reduce demand on primary plant resources. Compact module footprint and integrated control minimize the need for external equipment, easing integration into constrained spaces.

7.5 Greenfield Builds

- **Challenge**: Designing new facilities for future workloads requires flexibility without overcommitting to one cooling approach.
- **Borealis™ Solution**: Dual-mode readiness ensures the infrastructure can adapt to technology shifts over a 10–15 year design life. Peer-to-peer pump staging supports right-sizing at launch, with linear capacity growth as demand increases.

8. Future Outlook

The Borealis™ Facility-to-Chip™ Cooling Ecosystem is engineered not just for today's AI and HPC demands, but for the rapid evolution of thermal requirements and environmental regulations over the next decade.

8.1 Two-Phase Cooling Expansion

While fully supporting single-phase operation today, Borealis™ is inherently **two-phase ready [3]**. As workloads and thermal densities continue to rise, more operators will adopt two-phase refrigerants like **Solstice® 1233zd(E)** to reduce pumping energy and improve thermal transport efficiency (refrigerant property data and standards compliance references can be found in Appendix E). The CDU's modular heat exchanger and control swaps make this transition seamless.

8.2 AI-Driven Thermal Optimization

Future software updates will expand Borealis™'s AI-based control capabilities. Leveraging historical performance data, machine learning models will predict optimal ΔT setpoints, pump speeds, and chiller interactions in real time, further reducing total facility power draw while improving thermal stability.

8.3 Integration with DCIM and Energy Platforms

Borealis™ will deepen integration with **Data Center Infrastructure Management (DCIM)** systems, enabling:

- Real-time visibility of cooling performance and predictive maintenance status at the rack, loop, and facility levels.
- Automated reporting for **ISO 50001** compliance and corporate ESG metrics.

8.4 Regulatory Positioning

With refrigerant phase-down schedules tightening globally, Borealis™ is positioned as a **compliance-friendly solution [5], [6], [7], [8]**:

- Supports ultra-low GWP refrigerants today.
- Ready to meet or exceed future **ASHRAE 90.4**, **ISO 50001**, and regional environmental standards without hardware replacement.

8.5 Roadmap Summary

- **Short-term**: Enhanced AI control algorithms, expanded pump coordination beyond six units, and remote firmware updates.
- **Medium-term**: Integrated loop heat recovery for waste heat reuse.

- **Long-term**: Adaptive phase-change cooling based on per-rack workload analysis, and fully autonomous cooling loop management across entire data center campuses.

9. Call to Action

The **Borealis™ Facility-to-Chip™ Cooling Ecosystem** represents a new standard for high-density AI and HPC thermal management — unifying intelligent control, dual-loop flexibility, and future-proof refrigerant readiness in one platform.

To learn more about how [Your Product Name] can transform your operations and drive your success, please contact us today for a personalized demonstration or visit our website:

Website: https://borealis.cool/
Email: sbarberi@agt-usa.com
Phone: (909) 973-0634

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APPENDICES

Appendix A – ESG Analysis

A.1 Energy Efficiency

Single-phase W/kW (rating @ 5 °C): Compute as (Σ P1 of running pumps) / module-kW at the OCP 5 °C rating. With 2×CRIE 20-3 at the selected duty, this typically yields ~20–35 W/kW depending on head and seasonal operating point.
Two-phase W/kW (latent @ R = 3): Compute as P1_CRNE / Q_latent (see Appendix C2). Typical range ~9–16 W/kW at 150–300 LPM of 1233zd(E) and moderate heads.
Annual pump energy savings vs. legacy CDU: 20–30 % (single-phase), an additional 10–15 % (two-phase).

A.2 Refrigerant Impact

Solstice® 1233zd(E): GWP = 1, ODP = 0, ASHRAE A1 classification.
SNAP-listed and EU F-Gas compliant.

A.3 Water Savings

Two-phase mode supports >30 °C primary supply, reducing cooling tower use.
In favorable climates, it can transition to dry-cooler operation.

A.4 Carbon Reduction

Assuming EF_grid = 0.35 tCO_2e/MWh:

Single-phase typical: ~18.4 tCO_2e/year per module.
Two-phase typical: ~9.2 tCO_2e/year per module.

Appendix B – Competitive Comparison

Table B1 – Side-by-Side Specification Comparison

Metric	Vertiv XDU1350*	CoolIT CHx1500**	Borealis™ CDU (Single-Phase, OCP 5 °C)	Borealis™ CDU (Single-Phase, @ ΔT 10 °C)	Borealis™ CDU (Two-Phase)
Published Capacity & basis	1368 kW @ 4 °C	1500 kW @ 5 °C	~256-~276 kW per module (PG25 vs water) @ 210 GPM	552 kW	282 kW (2-phase capacity is latent)
Flow Basis	1200 L/min	1.2 L/min/kW	2.88 L/min/kW 3.0-3.2 LPM/kW	2.88 L/min/kW 3.0-3.2 LPM/kW	Latent heat calc
Cooling Medium	Water/glycol	Water/glycol	Water/glycol	Water/glycol	Solstice® 1233zd(E)
GWP of Medium	N/A	N/A	N/A	N/A	1
W/kW (typ)	~15–18 est.	~14–16 est.	~20 – ~35	~2.06 – ~2.13	~9 – ~16 W/kW at 150–300 LPM
Modular Expansion	Limited	Multiple frames	3 modules → 1.52 MW	3 modules → 1.52 MW	3 modules → 846 kW
Two-Phase Capability	No	No	No	No	Yes

* OCP capacity adjusted from published ATD.
** Estimated OCP capacity from vendor flow ratio.

Appendix C – System Performance Data

C1.1 Rating Basis

Capacities follow OCP CDU rating @ 5 °C using 2.88 LPM/kW (water) or 3.0–3.2 LPM/kW (PG25). Capacities are flow-limited at the module's available total flow.

C1.2 Capacity (Module total flow ≈ 210 GPM)

Configuration	Modules	Pump Mode	Flow (GPM)	Water (kW)	PG25 (kW)
Single	1	Dual	~210	~276	~256
Single	1	N+1	~105	~138	~128
Triple	3	Dual	~630	~829	~767
Triple	3	N+1	~315	~415	~385

C1.3 Design ΔT at Fixed Flow

For Water @ 210 GPM, kW ≈ 0.263 × 210 × ΔT(°C) → 4 °C: 221; 5 °C: 276; 6 °C: 332; 8 °C: 442; 10 °C: 553; 12 °C: 663. Apply ~5–10% reduction for PG25.

Note: Figure 2 in Section 4 illustrates the performance curve for these values.

C.2 Two-Phase Rating Method (Vapor-Quality Indexed, 1233zd(E))

All values assume dual-pump CRNE 20-3, total ~795 LPM (2×105 GPM), latent heat h_{fg} = 195 kJ/kg, and conservative utilization factor η_{lat} = 0.70. Published capacities are $\eta_{lat} \times Q_{raw}$.

Table C2.1 – Quality-Indexed ResultsEquation Set (Design-In):

Fluid Temp (°C)	Density (kg·m⁻³)	CR	x_out	LPM/kW	Q_raw (kW)	Q_pub (kW)	Notes
15.6	1337	3	0.333	0.690	1151	806	—
		4	0.250	0.921	864	604	—
		5	0.200	1.151	691	484	≈ earlier "~505 kW"
40.6	1233	3	0.333	0.749	1062	743	—
		4	0.250	0.998	796	557	—
		5	0.200	1.248	637	446	—

Equation Set (Design-In):

$$Q_{raw} = \frac{\rho V_\ell h_{fg}}{60{,}000\, CR}, \quad x_{out} = \frac{1}{CR}, \quad Q_{pub} = \eta_{lat} Q_{raw}$$

Recommended x_out window: 0.18–0.30 (CR ≈ 3.3–5.6).
Avoid x_out < 0.12 (excess liquid circulation, pump power rise) or >0.35 (dryout/maldistribution risk).

C.3 Flow and Duty Points

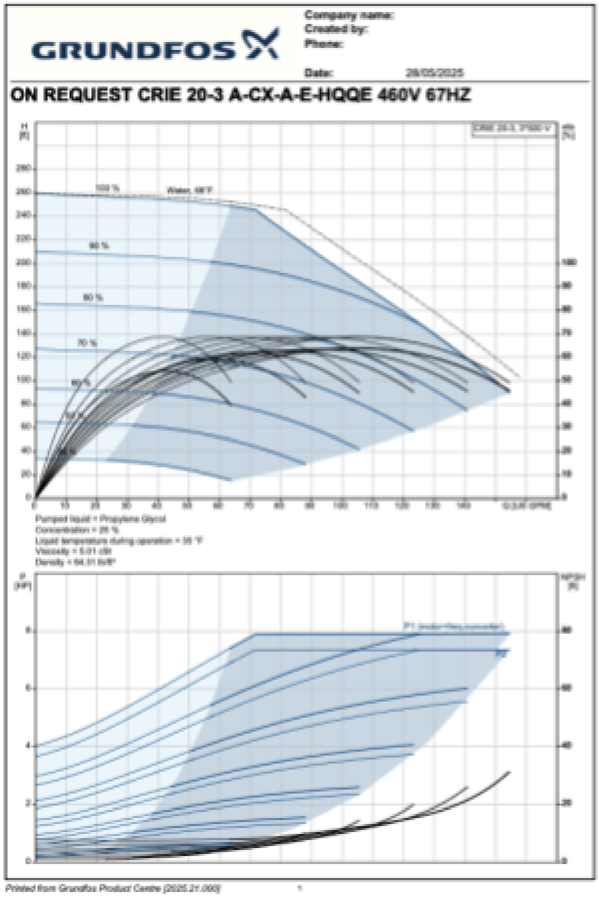
- **Target Module Flow**: ~210 GPM total (≈ 105 GPM per pump) for 552 kW/module @ ΔT = 10 °C.
- Duty points selected from **CRIE 20-3** curve family for **25% PG glycol** at both **35 °F** and **104 °F** to ensure BEP operation across seasonal variation.
- NPSH requirements and duty selections are detailed in Appendix D.

Appendix D – Pump Specifications & Curves

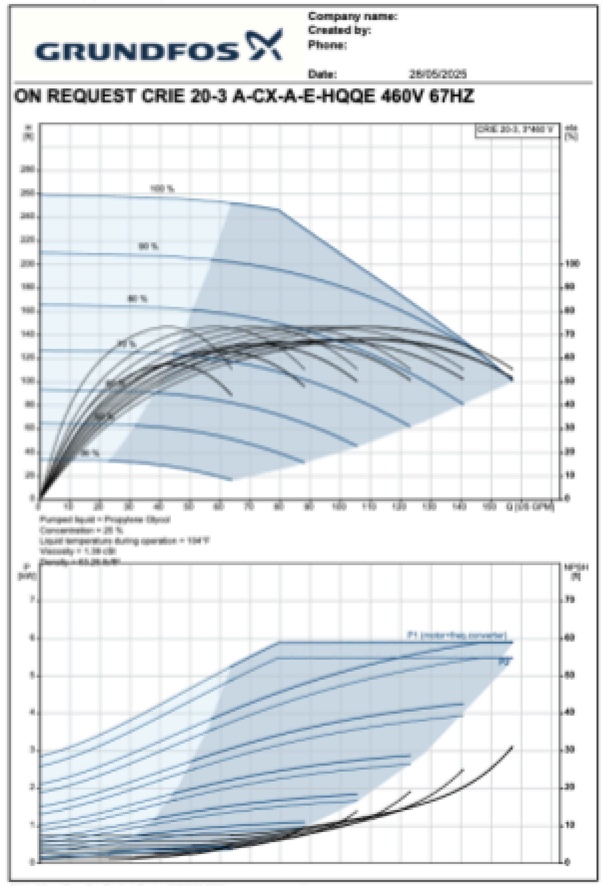
H.1 CRIE 20-3 – Glycol Loop (Water / 25% PG)

Parameter	Value
Model String	CRIE 20-3 A-CX-A-E-HQQE (3×460 V, 60 Hz)
Motor Rating (P2)	7.5 HP (≈ 5.6 kW)
Motor Efficiency	IE5, 92.4% at full load
Speed Range	360 – 4000 rpm
Frequency Converter	Integrated (VFD)
Connection Type	Tri-Clamp DN50 (2 in)
Pressure Rating	PN25
Curve Tolerance	ISO 9906:2012 3B
Approvals	NSF/ANSI 61 (drinking water)
Curve Cases Published	25% PG @ 35 °F and 25% PG @ 104 °F
Viscosity/Density (35 °F)	As printed on Grundfos curve
Viscosity/Density (104 °F)	As printed on Grundfos curve

25% Propylene Glycol at 35°F



25% Propylene Glycol at 104°F



H.2 CRNE 20-3 – Dielectric Loop (R-1233zd(E))

Parameter	Value
Model String	CRNE 20-3 M-CX-A-V (3×460 V, 60 Hz)
Motor Rating (P2)	7.5 kW
Motor Efficiency	IE5, 92.5% at full load
Speed Range	360 – 4000 rpm
Drive Type	Sealless Magnetic Drive
Connection Type	Tri-Clamp DN50 (2 in)
Pressure Rating	PN25
Approvals	cURus + CE

Fluid Densities	15.6 °C → 1337 kg·m⁻³, 23.9 °C → 1303, 32.2 °C → 1268, 40.6 °C → 1233, 48.9 °C → 1201
Curve Tolerance	ISO 9906:2012 3B
NPSH Requirements	From manufacturer curves, liquid-only (≥ 3 K subcool at suction). See the datasheet on the next page.

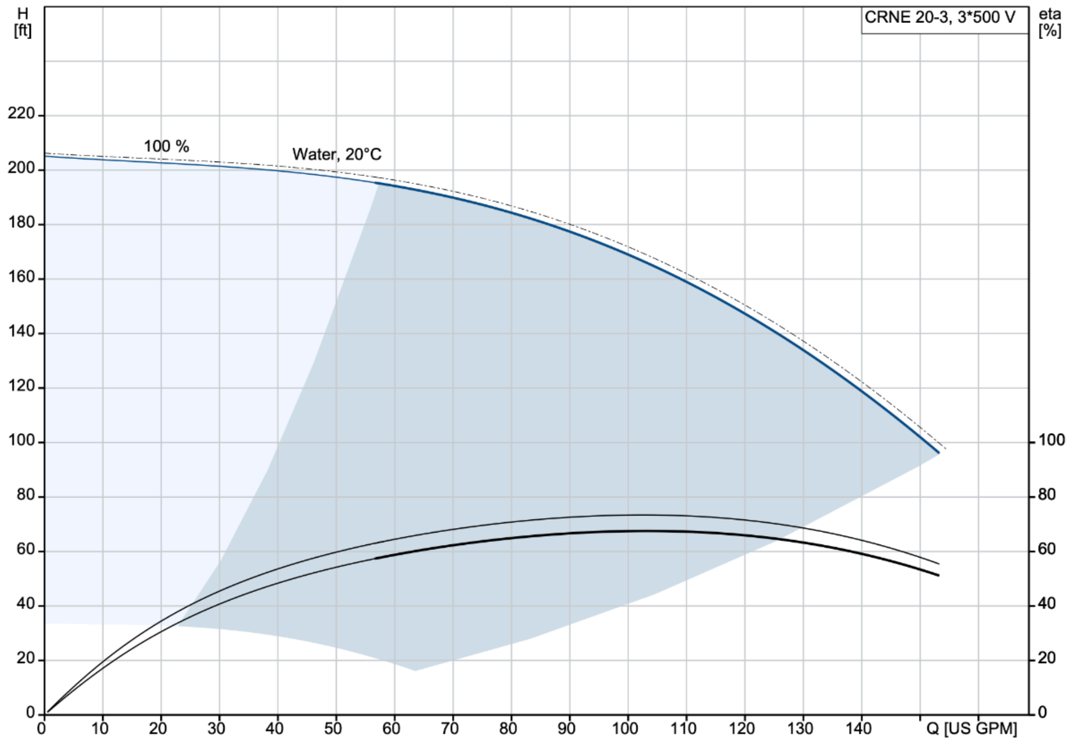
H.3 NPSH & Duty Point Notes

- **Duty Selection**: For glycol loop operation, duty point is ~105 GPM per pump at design ΔT and load.
- **NPSH Margin**: Both CRIE and CRNE selections ensure >1 m NPSH margin above required values at duty point.
- **Curve Reference**: See embedded manufacturer curves below for complete performance data, including NPSH axes.

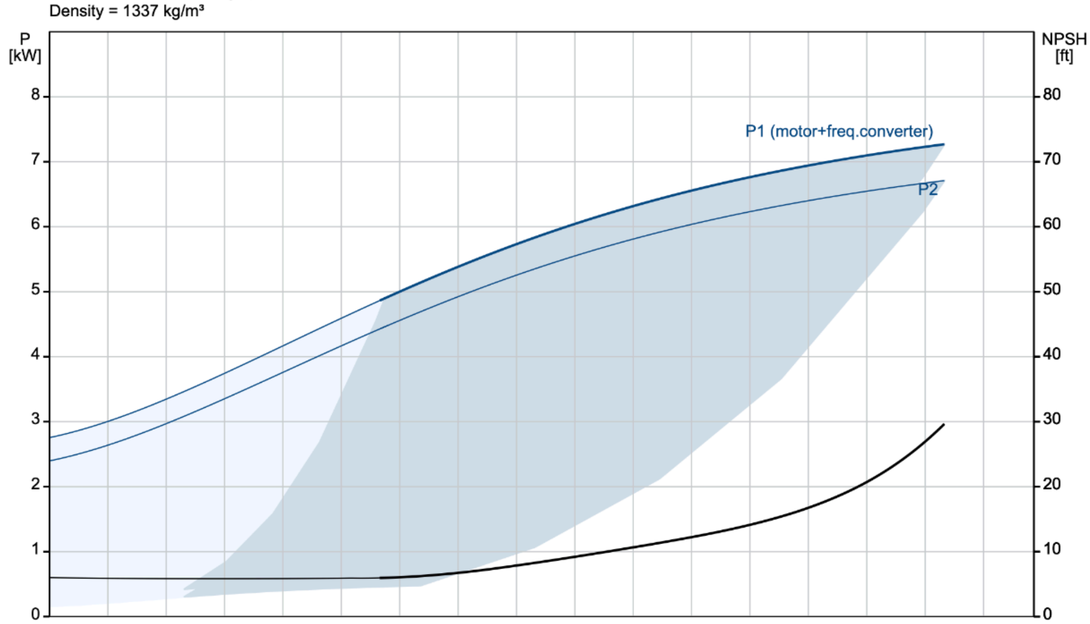
Company name:
Created by:
Phone:

Date: 03/06/2025

ON REQUEST CRNE 20-3 M-CX-A-V 3x460V 60HZ



Pumped liquid = Solstice® ZD, Solstice® 1233zd (E) (user defined)
Liquid temperature during operation = 15.6 °C
Density = 1337 kg/m³



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Date: 03/06/2025

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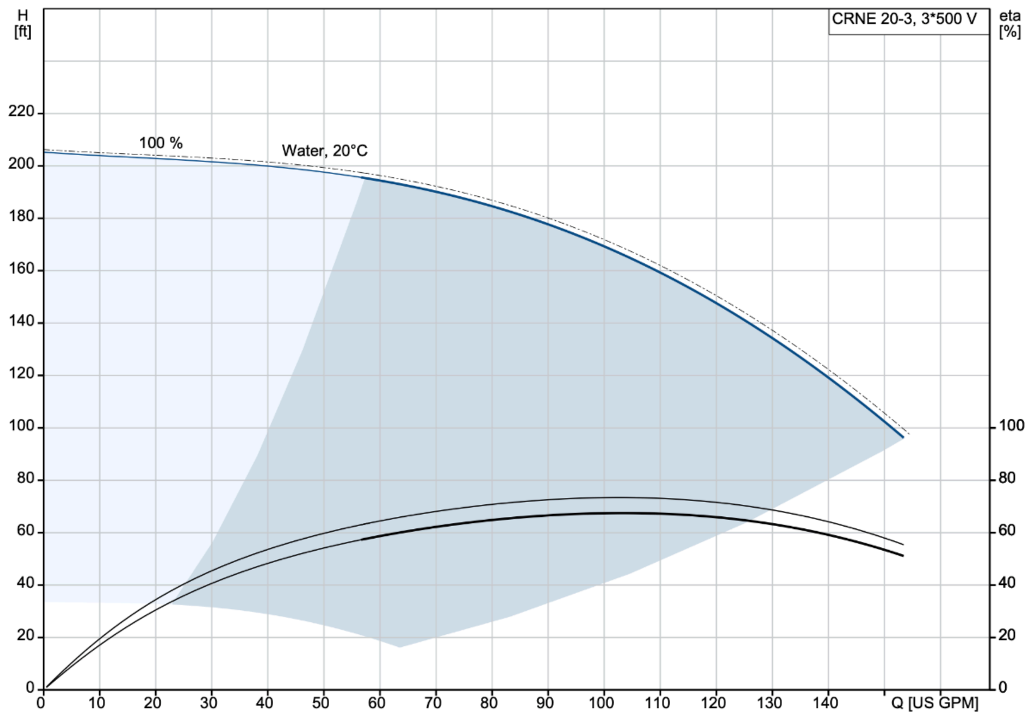
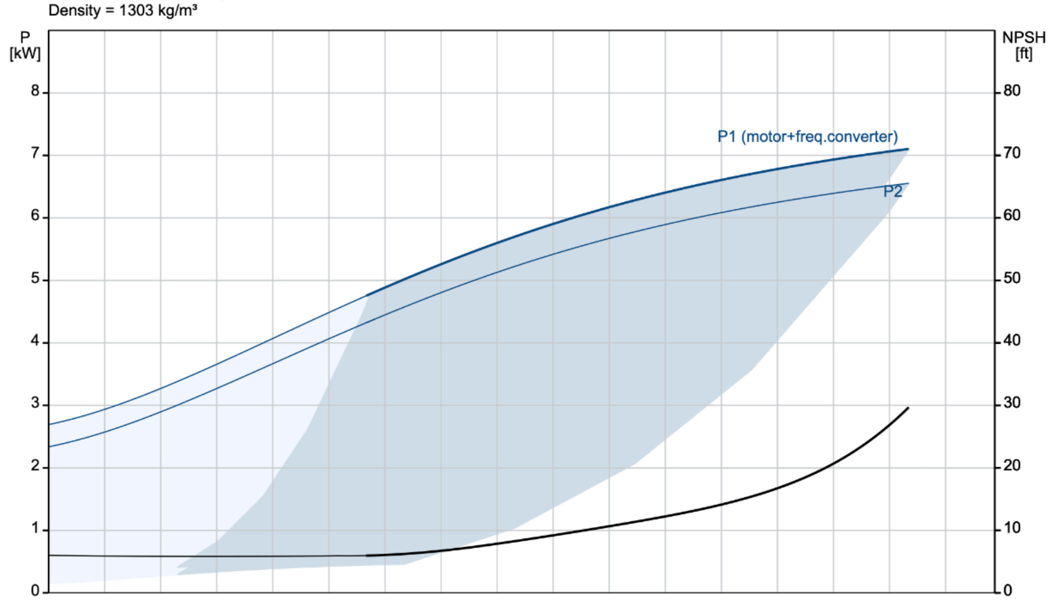


Pumped liquid = Solstice® ZD, Solstice® 1233zd (E) (user defined)
Liquid temperature during operation = 23.9 °C
Density = 1303 kg/m³



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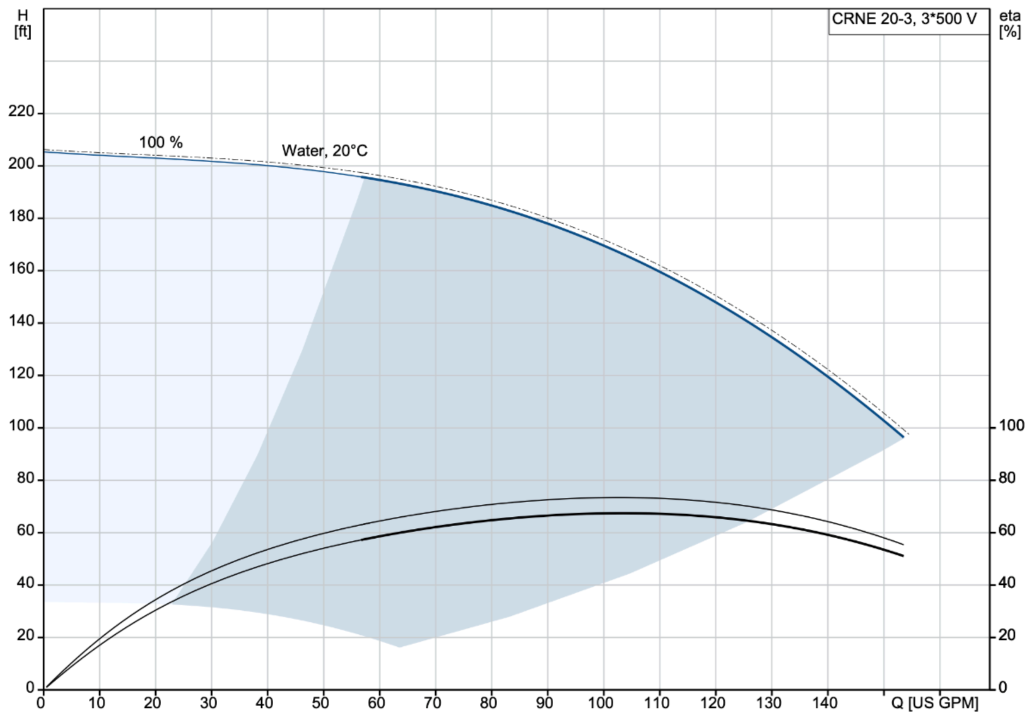
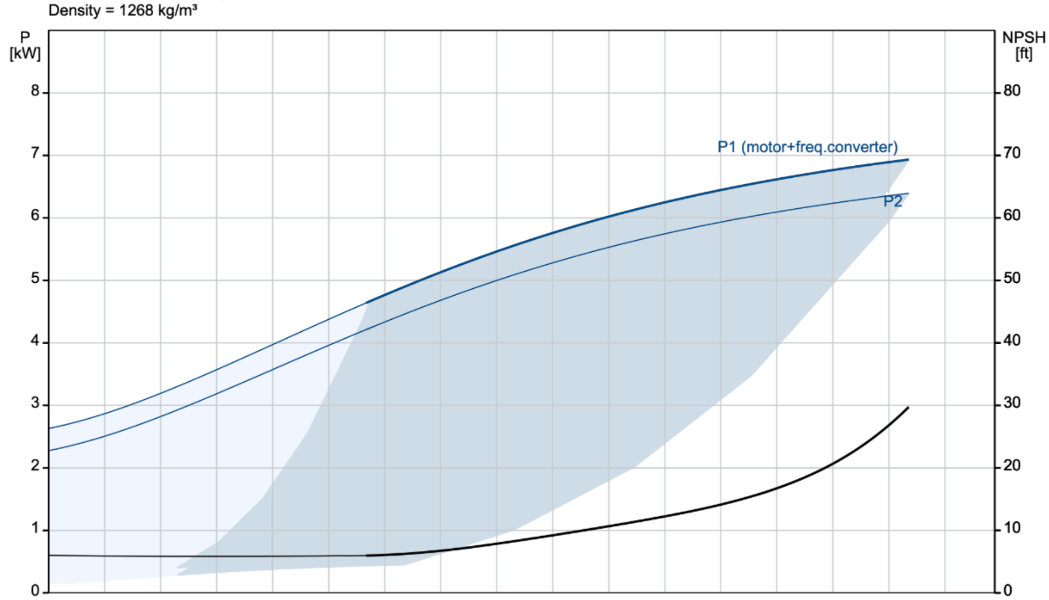


Pumped liquid = Solstice® ZD, Solstice® 1233zd (E) (user defined)
Liquid temperature during operation = 32.2 °C
Density = 1268 kg/m³



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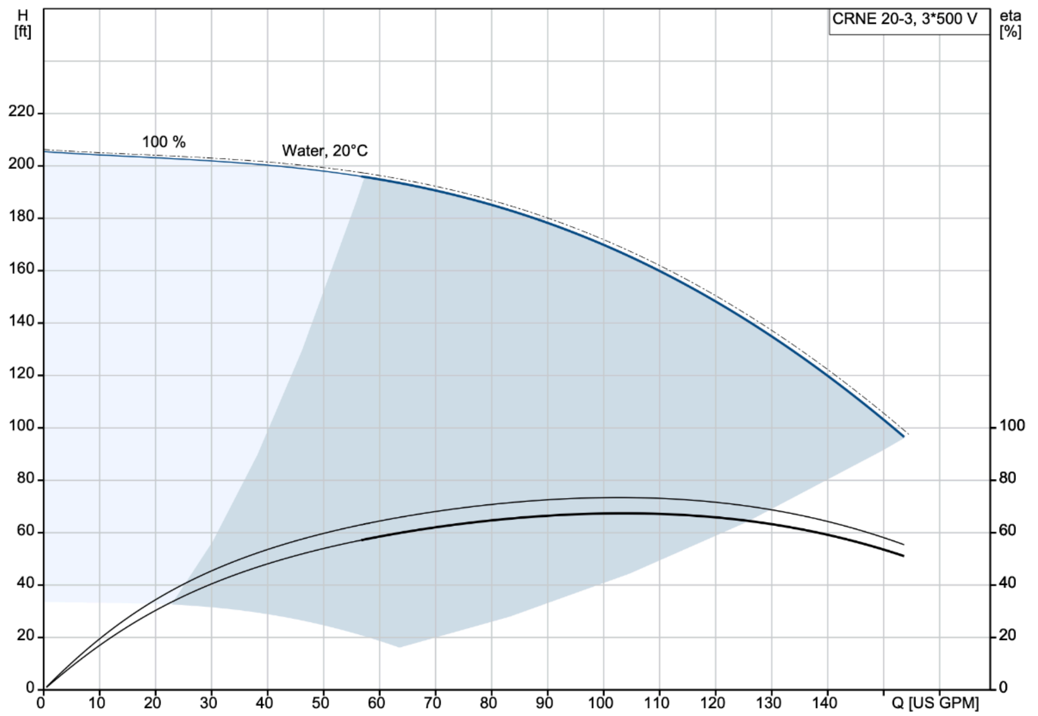
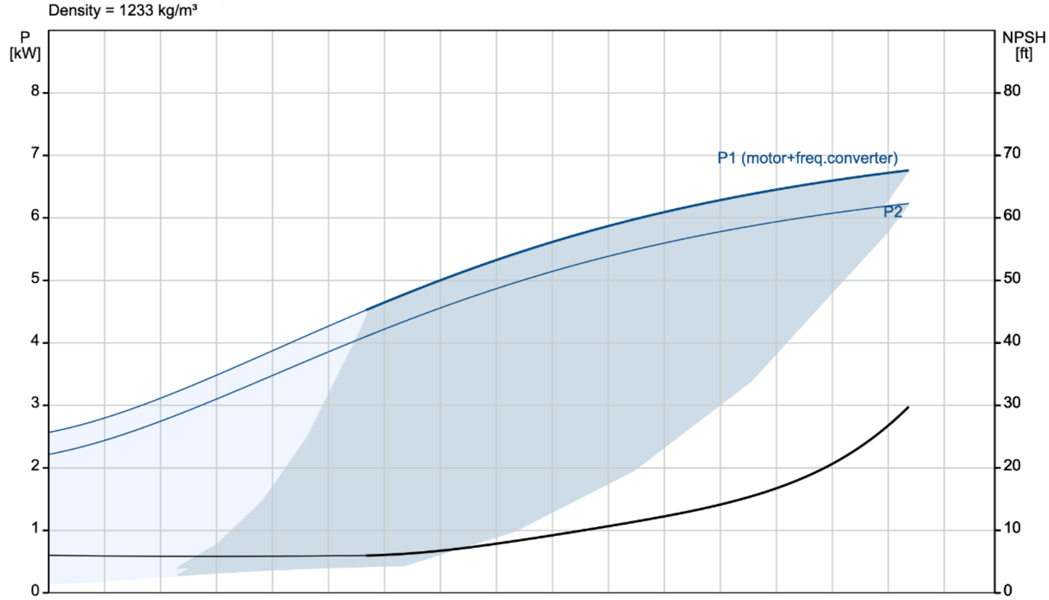


Pumped liquid = Solstice® ZD, Solstice® 1233zd (E) (user defined)
Liquid temperature during operation = 40.6 °C
Density = 1233 kg/m³



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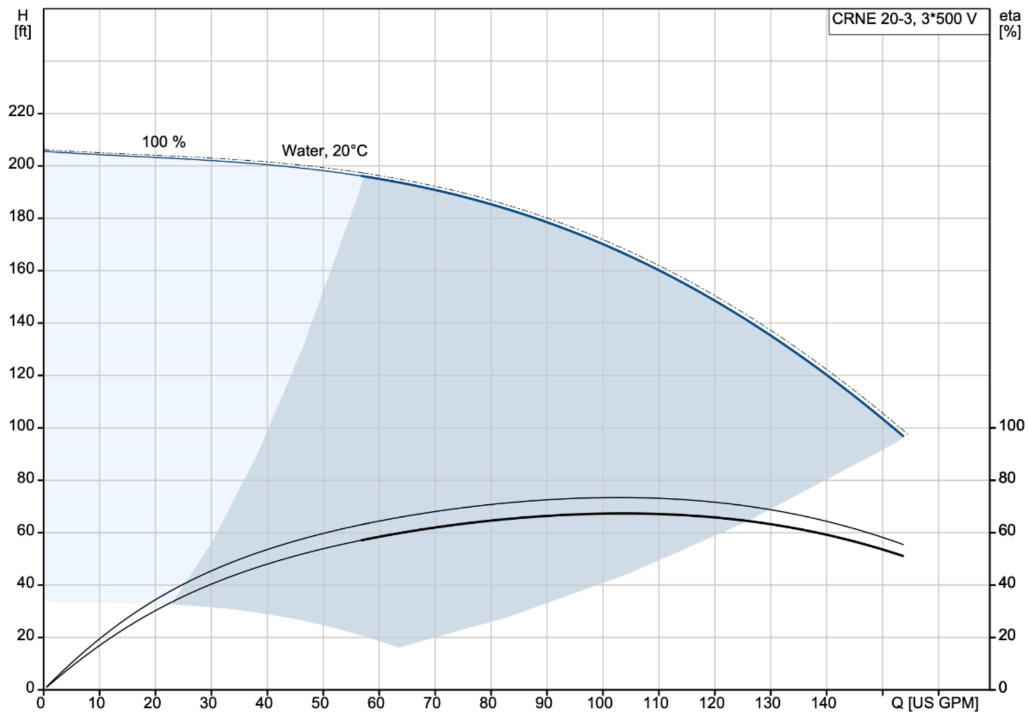
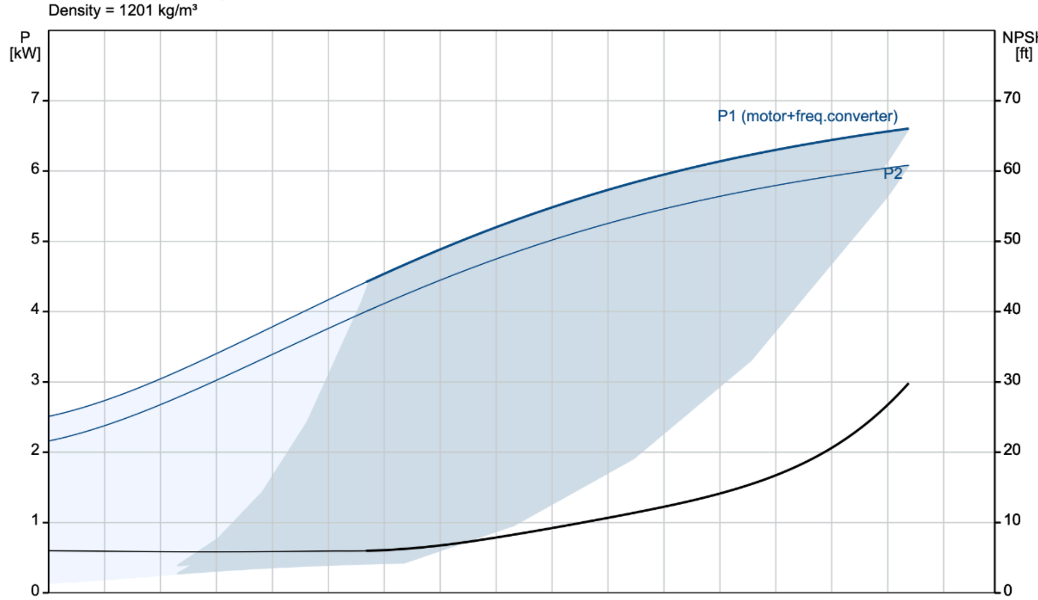


Pumped liquid = Solstice® ZD, Solstice® 1233zd (E) (user defined)
Liquid temperature during operation = 48.9 °C
Density = 1201 kg/m³



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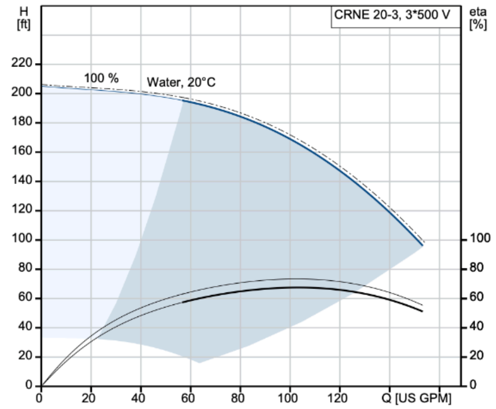
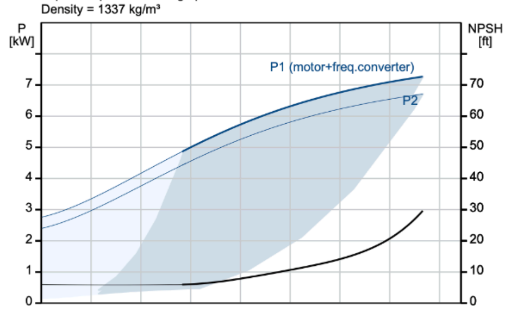
Description	Value
General information:	
Product name:	CRNE 20-3 M-CX-A-V
Product No:	ON REQUEST
Based on:	ON REQUEST
Price:	
Technical:	
Pump speed on which pump data are based:	3526 rpm
Pump with motor (Yes/No):	Y
Stages:	3
Impellers:	3
Low NPSH:	N
Pump orientation:	Vertical
End suction pump (Yes/No):	No
Pump low temp.:	No
Magnetic drive:	Yes
Shaft seal arrangement:	Sealless
Energy approvals for motor:	CE
CE approved (Yes/No):	Y
cURus approved:	Y
CCCs approved:	No
China MEPS (CEL):	No
South Korea MEPS (Kemco):	No
Explosion approval NEC:	N
Curve tolerance:	ISO9906:2012 3B
Pump version:	M
Model:	A
Electropolished:	No
Pump cleaned and dried:	No
Colour of the pump:	RAL 9004
Report, duty point test:	No
Report, surface roughness:	No
Report, vibration:	No
Report, motor test:	No
Report, cleaned pump:	No
Report, electropolished pump:	No
Report, material quality:	No
Materials:	
Base:	Stainless steel
	EN 1.4408
	AISI 316
Base plate:	Cast iron
	EN 1563 EN-GJS-500-7
	ASTM A48
Impeller:	Stainless steel
	EN 1.4401
	AISI 316
Motor stool material:	Cast iron
Material code:	A
Code for rubber:	V
Bearing:	SIC
Installation:	
Maximum ambient temperature:	50 °C
Max pressure at stated temp:	25 bar / 90 °C
	25 bar / -20 °C



Pumped liquid = Solstice® ZD, Solstice® 1233zd (E) (user defined)
Liquid temperature during operation = 15.6 °C
Density = 1337 kg/m³



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Description	Value
Type of connection:	TriClamp
Size of inlet connection:	DN 50
	2 inch
Size of outlet connection:	DN 50
	2 inch
Pressure rating for connection:	PN 25
Flange size for motor:	FF265
Connect code:	CX
Liquid:	
Liquid temperature range:	-20 .. 90 °C
Electrical data:	
Motor standard:	IEC
Motor type:	132SF
Rated power - P2:	7.5 kW
Over/undersize motor:	Standard motor size
Mains frequency:	50 / 60
Rated voltage:	3 x 380-500 V
Service factor:	0.00
	1
Rated current:	14.1-11.2 A
Cos phi - power factor:	0.93-0.89
Rated speed:	360-4000 rpm
IE Efficiency class:	IE5
Motor efficiency at full load:	92.5 %
Number of poles:	0
Enclosure class (IEC 34-5):	55
Insulation class (IEC 85):	F
Ex-protection standard:	PTC
Built-in motor protection:	ELEC
Language on motor nameplate:	English (British)
Motor No:	93057191
Controls:	
Control panel:	Graphical
Function Module:	FM310 - Advanced
	FM300 - Advanced
Frequency converter:	Built-in
Pressure sensor:	N
Software cascade function:	No
Motor radio communication:	Yes
Others:	
Air vent position:	12 o'clock
Terminal box position:	6
Net weight:	91 kg
Gross weight:	119 kg
Shipping volume:	0.49 m³
Config. file no:	93129885
Alternative colouring:	No
Language on motor nameplate:	English (British)

Company name:
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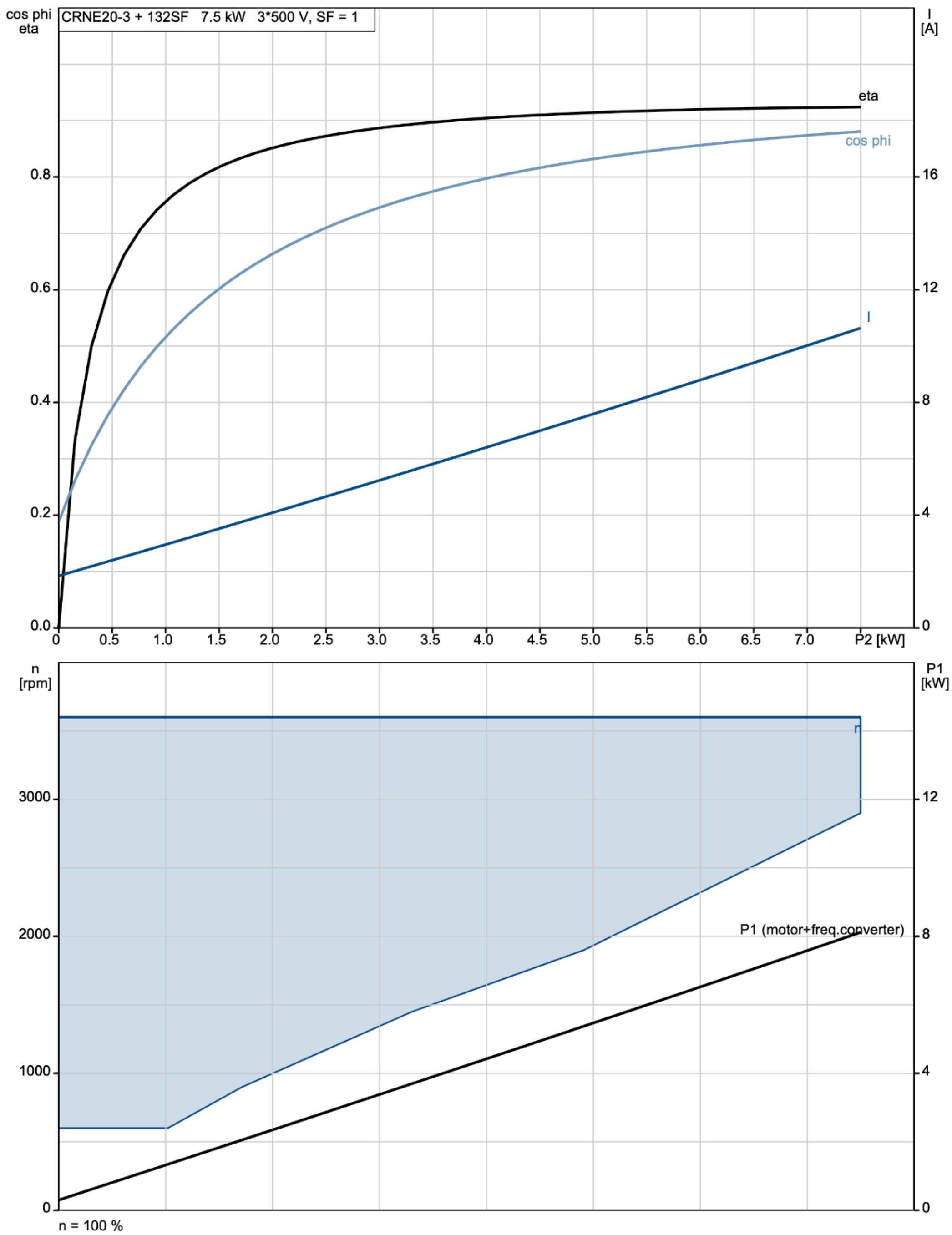

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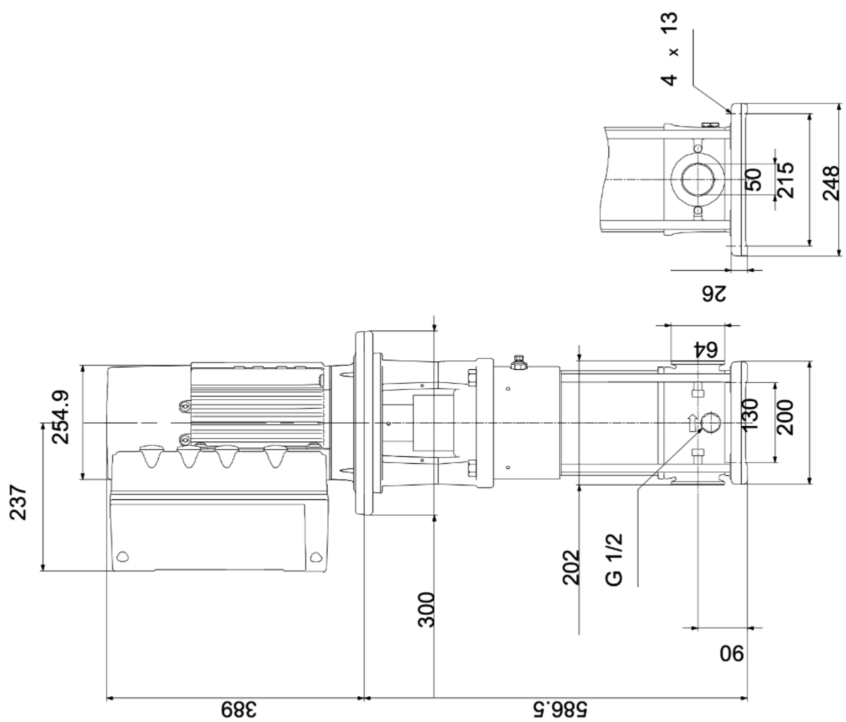

Note! All units are in [mm] unless others are stated.
Disclaimer: This simplified dimensional drawing does not show all details.

Appendix E – Refrigerant Properties & Standards

Table 1: Physical and Environmental Properties of Solstice zd	
Chemical Name	Trans- 1-chloro-3,3,3-trifluoropropene
Molecular Formula	(E)CF3-CH=CClH
CAS Number	102687-65-0
Ozone Depletion Potential (ODP-R11=1)*	~0
Global Warming Potential rev 5th IPCC (GWP CO_2=1)	1
ASHRAE Std. 34 Safety Classification	A1
Molecular Weight	130.5 g/mol
Boiling point at 101.3 kPa	18.3°C
Freezing point at 101.3 kPa	-107°C
Critical temperature	165.5°C
Critical pressure	3.6 MPa
Critical density	480.23 kg/m^3
Vapor density at boiling point	5.7 kg/m^3
Liquid density at boiling point	1279 kg/m^3
Heat of vaporisation at boiling point	195 kJ/kg
Vapour pressure at 25°C	129.8 kPa
Vapour thermal conductivity at 25°C	10.0 mW/mK
Liquid thermal conductivity at 25°C	76.9 mW/mK
Vapour viscosity at 25°C	11.1 µPa sec
Liquid viscosity at 25°C	470.1 µPa sec

* *No impact on ozone layer depletion and is commonly referred to as zero.*
Reference: Preliminary report:Analyses of tCFP's potential impact on atmospheric ozone; Dong Wang, Seth Olsen, and Donald Wuebbles Department of Atmospheric Sciences University of Illinois, Urbana, IL.

E.2 Materials Compatibility (1233zd(E), Wetted Parts)

Component Class	Material	Compatibility	Notes
Metals	304/316L SS, CuNi, Ti	Compatible	No observed corrosion at ≤50 ppm H_2O
Elastomers	EPDM, FKM, PTFE	Compatible	Avoid natural rubber
Filtration Media	Polyester, cellulose-free	Compatible	Replace at 1 yr or OPC alarm
Desiccants	3Å molecular sieve	Compatible	Limit ≤50 ppm H_2O at acceptance

Appendix F – Two-Phase Control & Safety Examples

F.1 CHF & Dryout Margin
All rated points satisfy $q'' \le 0.5 \cdot q''_{CHF}$ (Kandlikar-class) with dryout-length fraction ≤0.1. Control interlocks reduce Δx or open bypass if ΔP/ΔT signatures indicate approach to dryout.

F.2 Control Limits

- Rate-limit on Δx increase (dx/dt capped).
- Optional bypass/accumulator dampens overshoot ≤0.5 °C for 30→70 % steps.

F.3 ASHRAE 15 / DIERS Relief Example
Blocked-in heat input at 45 °C saturation → compute relieving mass flow using HEM disengagement, size relief area, and verify back-pressure to machinery-room exhaust. Include refrigerant inventory at weigh-out.

F.4 OCP Telemetry Conformance
Published telemetry: demister spec (≤0.5 % entrained liquid), vapor-leg superheat (2–5 K), evaporator ΔP, estimated x, OPC alarm status.

F.5 Acceptance Tests

- 30→70 % step with ≤0.5 °C rack inlet deviation.
- Long-run stability ±0.5 °C.
- Sensor sanity and leak detection thresholds tied to SDS/OEL.