Global Cold Source Allocation Project Based on Wang Tongchun's Water Conservancy Logic (Without Considering Scale and Cost)

Core Idea: Copy Wang Tongchun's logic of "terrain adaptation + channel network coordination + precise regulation", build a cross-regional cold source transportation system with Russian cold source (frozen snow/frozen soil) as the core, balance the global cold and hot distribution, alleviate climate warming, and follow the principle of "going with the trend and system closed loop" throughout the whole process.

1. Preliminary Survey: Anchoring Cold Source and Path (Corresponding to Wang Tongchun's Survey Method of "Stargazing at Night and Observing Water Flow in Rain")

1 Cold source positioning: Targeting Russia's three core reserve zones—Siberia's permafrost belt (for controlled melting to extract cold water), the Arctic Circle's coastal snow belt (for winter snow collection), and the frozen water zones around Lake Baikal (for natural low-temperature water sources). Radar detection maps the cold source reserves with precision, specifying extractable cold capacity per square kilometer.

2. Regional demand calibration: Global division of "cold-deficient priority zones" includes tropical arid zones (Middle East/Africa's Sahel, requiring cooling sources for temperature regulation and water replenishment), polar ice sheet reduction zones (Antarctic Weddell Sea/North Pole Beaufort Sea, needing cold-source ice replenishment), and mid-latitude warming zones (Mediterranean coastlines, requiring cooling sources for temperature regulation). By integrating topographic elevation data, we determine the natural transport potential pathways following the "high-latitude to low-latitude, high-elevation to low-elevation" gradient.

3. Path survey: Using satellite remote sensing and ground drilling, the geological stability of the transportation route is investigated (avoiding seismic zone/active fault), the slope drop is calculated (ensuring the cold source can be transported by gravity flow and reducing power consumption), the ecological sensitive area (tundra/bird habitat) is marked simultaneously, and the bypass route is designed.

2. Core Project: Constructing the Cold Source Transportation System (Corresponding to Wang Tongchun's "Main Canal + Branch Canal" Network Architecture)

(1) Intensive Collection of Cold Sources in Russia

1 Controlled Conversion of Frozen Snow/Frozen Soil: In the Siberian permafrost zone, precision freeze-thaw stations are installed to gradually thaw frozen soil using low-power geothermal devices (maintaining temperature at 0℃±2℃) into low-temperature clean water. During winter, snowmelt channels are constructed in the Arctic snow belt to collect meltwater through concrete anti-seepage channel networks, which then flow into a massive underground cold storage facility (reconstructed from existing frozen soil pits with natural insulation).

2. Construction of Main Corridor: Excavation of 3 Cross-Russia "Super Cold Source Dry Channel"

- The North Asia trunk line: from the Siberian permafrost belt to the south, through the Western Siberian plain, and connect to the Central Asia cross-border channel;

- The Arctic trunk line: the coastal channel along the Arctic Circle coastline, connecting the ice-breaking and transportation nodes of the Arctic Ocean;

- The Baikal branch line is to draw the low temperature water from Baikal Lake and join the North Asia trunk line to increase the cold water supply.

The channel is made of "insulation concrete + inner layer insulation coating", and the outer wall is covered with frozen soil to prevent the loss of cold source in the middle of the way (see Wang Tongchun's "channel embankment soil consolidation" technology, suitable for low temperature environment).

(II) Cross-regional cold source transportation channels

1 Land passage: insulation canal network+ice slurry pipeline

- In the mid-low latitude direction: extending from the North Asia trunk line to Central Asia, underground insulated pipelines are constructed (for transporting ice slurry internally, with liquid nitrogen-assisted cooling), crossing the Iranian Plateau to the Middle East, and diverting to the "cold source regulation lake" on the Arabian Peninsula (for surface cooling + wetland restoration); a

transnational canal is built to the East European Plain along the west longitude, transporting water to the Mediterranean coast and injecting it into artificial cooling reservoirs to mitigate regional warming.

- Polar direction: Undersea insulated pipeline (50 m buried depth, designed to withstand ice pressure) from the Arctic trunk line, crossing the Arctic Ocean to the Arctic ice

The ice sheet is thickened by the cold water and broken ice transported to the bottom of the ice sheet.

2. Sea passage: ice transportation and cold water discharge

- The nuclear-powered icebreaker is transformed into a "cold source transport ship", which loads ice fragments from the Russian Arctic ports and transoceanically transports them to the cold sea areas (e.g. the western coast of Australia), releasing them through controllable outlets to cool the surface seawater and regulate the ocean circulation (similar to Wang Tongchun's logic of "regulating water flow by water outlet").

3. Function implementation: precise utilization of cold source (corresponding to the dual objectives of " irrigating fields and protecting canals" by Wang Tongchun)

1 In the thawing area of Russian permafrost, the artificial wetland network is constructed with low temperature water to nourish the tundra vegetation, restrain the methane release, and retain part of the natural permafrost as the cold storage buffer layer (reproduce the ecological adaptation idea of "leaving land to protect the canal" by Wang Tongchun).

2. The cold source regulation lake in the Middle East is used to irrigate the desert improved field with low temperature water (the cooling water is used to irrigate the desert improved field, which can improve the survival rate of crops); the cold fog spray system is used to cool the reservoir water and alleviate the urban heat island effect.

3. Polar balance regulation: the ice transported to the Antarctic is used to replenish the weak areas of ice shelf, the thickness of ice sheet is monitored by sensors in real time, and the amount of ice transported is adjusted dynamically (corresponding to the precise regulation of "adjusting the flow rate of canal water according to crop water demand" by Wang Tongchun).

4. Closed-loop guarantee: Ecological monitoring and regulation (corresponding to Wang Tongchun's logic of "channel maintenance + water flow optimization")

1 Global monitoring network: temperature/ecological sensors are installed at the cold source, the transport corridor and the cold source end to track the cold source loss, regional temperature change and vegetation response (e.g. the coverage of the tundra vegetation and the growth of crops).

2. Dynamic regulation mechanism: increase the cold source transportation during the peak period of warming (e.g. increase the efficiency of ice transportation to the Antarctic when the Arctic ice cover melts rapidly); set up "flow buffer valve" in the ecologically sensitive area to avoid the sudden influx of cold source to destroy the original ecological chain (similar to Wang Tongchun's "setting up the backwater outlet to prevent the channel overflow").

3. Cold source circulation supplement: The hot water used in the cold area (e.g. irrigation tail water, cooling wastewater) is transported to the North Pole by the "recirculation pipeline", and then it is refrozen by the low temperature in the polar region, thus forming a "cold source circulation chain" and reducing waste.

The core logic echoes the experience of Wang Tongchun.

- The natural flow of cold source is realized by the terrain difference, and the natural insulation of frozen soil/polar environment is used to reduce artificial intervention.
- System integration: Construct a network of "main canal + branch canal + storage reservoir", and take into account the whole link of cold source collection, transportation and utilization;
- The people's livelihood and ecology are taken into account: it not only alleviates the impact of global warming on human survival, but also reduces the damage to nature through controllable engineering, and replicates its core value of "building canals for benefit and protecting the environment for eternity ".

Well, the above is only the strategic part. After the strategy is finished, it is time to enter the tactics. In science, tactics is technology. Let's proceed to technology.

Pilot-scale Engineering Scheme for Large-scale Underground Cold Storage/Ice Storage (Underground Cold Storage and Ice Storage)

the title page of a thread-bound book

Project Name: Large-scale Underground Cold Storage and Ice Storage Project

Editor: (Academy of Engineering/Technical Team Name)

Version: I believe no one else would dare to create another version besides me. I think we should call it 'Zero Point'.
Date: 2025-1 1-27
Contact: (Name, Position, Contact Information)

Catalogue

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7. Selection of Ice Making / Melting Process and Equipment

8. Specifications for Cold Source Transportation Interfaces, Pipelines, and Loading/Unloading Docking

9. A Numerical Simulation Suite for Thermal-Hydraulic-Solid Coupling (Model, Input, and Sensitivity Analysis)

10. Monitoring and Control System (Sensors, PLC/SCADA, Data Management)

1 1. Pilot-scale engineering design and construction drawings (including detailed construction documents and process cards)

12. Trial run, performance verification, and acceptance criteria (executable processes and forms)

13. Maintenance, Repair, and Emergency Response Plan (Operational Procedures)

14. Standardized documents, acceptance forms, and compliance criteria (for project delivery)

15. Scale-up Route and Scale-up Criteria (Unit→Group→Region)

16. Appendix: Calculation Sheets, Simulation Input Examples, Equipment Specification Examples, and Construction Drawing ASCII Diagrams

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1 Project Overview and Objectives

1 1 Project Purpose

The underground cold storage and ice storage are regarded as the core engineering modules of cold source collection and seasonal energy storage, forming a set of engineering technology package that can be directly constructed, operated and verified, which can be used for pilot construction and provide technical basis and operation data for subsequent engineering scale-up.

1 .2 Project Objectives (Clear and Executable)

- The target seasonal cold storage capacity (target scale-up) is \\(Q_{target}=1.0\\times10^{9}\\ \\mathrm{kJ}\\).
- The pilot scale (the starting point of the project) is \\(Q_{pilot}=1.0\\times10^{6}\\ \\mathrm{kJ}\\).
- Design life: 10 years for structure and materials, 15 years for equipment maintenance cycle.
- Operation cycle: Ice-making period (cold season) 120 days; Cooling period (warm season) 120 days; Annual cycle count 1 (adjustable according to operation strategy).

- Performance target: seasonal heat loss ≤ 10%, energy consumption ≤ 1.5×theoretical latent heat energy, temperature control accuracy ±0.5℃.
- Safety and environmental objectives: no groundwater contamination, controlled methane release in permafrost areas, and structural settlement ≤ 10 mm/year (long-term monitoring).

---

executable range

2.1 Go straight to pilot scale)

- Engineering design (complete): includes hourly/daily load table, heat balance, structural calculation, insulation calculation, heat exchanger design.
- Numerical simulation package: thermal-hydraulic-solid coupling model description, example input files, mesh and time step suggestion, sensitivity analysis script.
- Construction and material specifications: low temperature concrete mix, insulation and waterproofing construction, sealing material specifications, freeze-thaw test scheme.
- The detailed plan of ice-making and ice-melting process includes equipment selection, measures of promoting crystal and preventing overcooling, preparation and transportation of ice slurry, and night ice-making scheduling.
- The monitoring and control scheme includes the sensor list and layout, PLC/SCADA control logic, data acquisition and alarm strategy.
- Pilot-scale construction drawings and process cards: including plan and section drawings, construction sequence, quality control points, test point layout, and BOM (Bill of Materials).
- The trial operation and acceptance process includes the steps of trial operation, performance indicators, data collection forms, energy consumption and carbon emission assessment methods, and acceptance forms.
- Risk and contingency plan: fault detection, quick repair process, long-term maintenance plan.
- The scale route and the criterion of judgment: the technical judgment and milestone of the individual→the group→the region.

2.2 executable range specification

- This technical package covers all technical documents and operation procedures from site preparation, civil engineering, equipment installation, system debugging to trial operation and acceptance.
- Excludes procurement contract signing, on-site construction management (can provide construction supervision list and quality control points), and legal/environmental approval documents (can be supplemented as needed).

---

3 Design Basis and Engineering Assumptions

3.1 Design boundary conditions (must be adjusted according to site selection before project implementation)

- External temperature time series: hourly or daily temperature curves (hourly local meteorological data is required for project implementation).
- Geothermal temperature and flow rate: The geothermal temperature at 50 m depth and the geothermal flow rate should be measured in the field. The default geothermal flow rate (q_g=0.05 W/m^2) is only used for preliminary calculation.
- Initial water/ice temperature: The inlet water temperature (T_{in}) for ice production is determined by the delivery system and defaults to 0°C.
- The allowable thermal loss rate is ≤ 10% for seasonal thermal loss (the engineering design should be verified by numerical simulation).
- The safety factor of the structure is 1.5 (the uncertainty of load and material).
- The operation policy is to make use of the low price electricity at night to produce ice, and release the cold in daytime or when the demand is high.

3.2 Physical properties and engineering parameters (to be replaced with field tests before project implementation)

- The latent heat of ice is 334 kJ/kg.

- The specific heat of water is 4.18 kJ/(kg·K).
- Ice density: (ρ_{ice}=917 kg/m³).
- The thermal conductivity of low-temperature concrete (initial value) is λ_{conc}=1.7 W/(m·K).
- The thermal conductivity of polyurethane insulation is λ_{PU}=0.025 W/(m·K).

---

4 Capacity Calculation and Thermal Engineering Calculation Book

This chapter provides complete and executable calculation methods, formulas and hourly/daily scheduling calculation process.

4.1 Phase Change and Energy Benchmark Formula

Total cold storage energy (including phase change and sensible heat):

$$
Q = m\cdot L + m\cdot c{ice}\Delta T{ice} + m\cdot cw\Delta T{water}
$$

among：

- (m) is the mass of ice storage (kg).
- L is the latent heat of ice (334 kJ/kg).
- (c_{ice}) is the specific heat of ice (2.1 kJ/(kg·K)).
- ΔT_{ice} denotes the temperature variation range of the ice body (K).
- cw and ΔTwater are the sensible heat terms of water (if present).

If the phase change is the main factor, the approximation is:

$$
Q \approx m\cdot L.
$$

4.2 Calculation of volume of ice reservoir and ice mass

Given the target cold storage capacity \\(Q\\), calculate the required ice mass:

$$
m=\frac{Q}{L}.
$$

Ice volume:

$$
V{ice}=\frac{m}{\rho{ice}}.
$$

Sample calculation method (replace Q during project implementation):

If Q equals 1.0×10^6 kJ, then

$$
m=\frac{1.0\times10^{6}}{334}\ \mathrm{kg}\approx2994\ \mathrm{kg},
$$

$$
V_{ice}\approx\frac{2994}{917}\ \mathrm{m^3}\approx3.26\ \mathrm{m^3}.
$$

(Engineering scale-up is linear proportion and consider the heat loss and recovery rate)

4.3 Insulation Layer and Steady-State Heat Transfer Calculation

Steady-state heat flux:

$$
q=\frac{\Delta T}{R}=\frac{\Delta T}{\sum \frac{di}{\lambda_i}}
$$

Where \\(\\lambda_i\\) is the thermal conductivity of the i-th layer.

If the target permits steady-state heat flux \\(q_{allow}\\), the required equivalent thickness of the insulation layer is:

$$
\sum \frac{di}{\lambdai} = \frac{\Delta T}{q{allow}}.
$$

The method of engineering calculation is to solve the thickness of insulation layer or composite layer by taking the temperature difference between the outside and the inside of the building (ΔT) and the allowable heat flux (qallow) as input.

4.4 Heat Exchanger and Ice-making Power Calculation

Instantaneous cooling power during ice-making phase:

$$
P(t)=\frac{dQ}{dt}
$$

If the cold storage capacity Q is to be achieved during the ice-making period (t_{ice}), the required average cooling power is:

$$
\bar{P}=\frac{Q}{t_{ice}}.
$$

The heat exchanger area is calculated based on the overall heat transfer relationship.

$$
Q/t{ice} = U A \Delta T{lm}
$$

Calculate the heat exchange area:

$$
A=\frac{Q/t{ice}}{U\Delta T{lm}}
$$

The overall heat transfer coefficient (U) is taken based on the type of heat exchanger and the ice resistance correction, and the logarithmic mean temperature difference (ΔTlm) is taken.

Project execution steps:

1 The target ice-making cycle and available cooling power are used to determine the parameters (t_{ice}) or (P).

2. The initial value of U is selected according to the type of heat exchanger (coil, heat exchange plate) and the ice resistance coefficient f_ice is considered (which increases with the growth of ice layer).

3. The heat exchanger area was designed and the ice growth model was coupled in the numerical simulation.

4.5 Heat Loss and Energy Balance

(Transient) Transient Energy Balance Equation (Lattice Cell):

$$\rho c \frac{\partial T}{\partial t} = \nabla\cdot(k\nabla T) + S - \dot{q}_{phase}$$

The equation is solved numerically to obtain the temperature and phase state distribution of reservoir in hourly or daily basis.

4.6 Hourly/Daily Scheduling Calculation Process (Direct Execution)

1 The input data are the hourly external temperature sequence, the target cooling load sequence, the initial temperature and phase of the storage body, the heat exchanger parameters and the performance curve of the refrigeration unit.

2. Initialization: Set the initial energy state of the library (ice mass, temperature field).

3. Time cycle (hourly):

- Read the external temperature and the terminal cooling demand;
- Calculate the heat loss of the body (steady state or transient approximation);
- The power distribution of ice-making and cooling is determined by the control strategy;
- Update the energy state of the reservoir (the phase change term is calculated according to the latent heat);
- Record the equipment's operational data (refrigerator power, pump power, flow rate, and temperature).

4. Output: hourly energy status table, equipment operation instruction, energy consumption statistics, alarm events.

(See the appendix for the hourly calculation template.)

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5 Geology and the location of reservoir and engineering geological requirements

5.1 Optional reservoir types and engineering compatibility

- Salt cavern (salt cave): suitable for large volume and low permeability requirements; creep and low temperature behavior of salt bodies need to be evaluated.
- Waste mine / goaf: use the existing cavity, need to reinforce and anti-seepage treatment.
- The aquifer closed chamber: The water storage body is formed by water injection, and the groundwater pollution should be strictly prevented.
- Reconstruction of natural frozen soil pit: The natural insulation of frozen soil is utilized, but the impact of freeze-thaw cycle on foundation and ecology should be evaluated.

5.2 Minimum Requirements for Site Engineering Geology (Mandatory)

- Permeability (equivalent): The permeability of the surrounding soil in the reservoir body should be $\leq (1\times10^{-8}$ m/s) or equivalent impermeable measures should be taken.
- The bearing capacity of the foundation is calculated according to the code and a safety factor is left.
- Earthquake and fault: avoid active faults and high intensity earthquake zones; if unavoidable, design according to seismic code and perform seismic response analysis.
- Groundwater level: Seasonal variations of groundwater level should be identified and the effects on heat loss and infiltration should be evaluated.

- Environmental sensitive areas: avoid drinking water source protection areas, important ecological protection areas and high methane emission areas, or develop mitigation measures.

5.3 Geological survey and testing requirements

- The core was taken from the depth of 50 m around the reservoir, and the physical properties of the soil sample were tested, including thermal conductivity, specific heat, permeability and porosity.
- Groundwater hydrological test (permeability coefficient, flow velocity, chemical composition).
- Underground temperature profile measurements (seasonal observations for at least 1 year or historical data for verification).
- Foundation bearing capacity and settlement observation (static load test or standard penetration test).
- Methane content and release risk assessment should be carried out in permafrost areas.

---

6 Structural and Material Specifications

6.1 Overall structure of the underground cavern

- Outer cover: backfill or protective layer (thickness determined by protection and thermal buffering requirements).
- Insulation layer: high performance polyurethane foam or composite vacuum insulation panel (VIP) combined with polymer composite layer, equivalent thermal conductivity target <0.05 W/m·K.
- Seepage barrier: HDPE membrane (minimum thickness 2.0 mm) or cement-based composite seepage barrier, with 100% pass rate for welding and joint inspection.
- The structural lining is low temperature concrete lining with a thickness of 0.3-0.6 m according to the structural calculation, and the reinforcement is designed according to the frost resistance and load requirements.
- The inner replacement heat system: the coil or heat exchange plate is fixed in the lining or independent heat exchange groove, which is convenient for maintenance and replacement.

6.2 Formulation and Construction Requirements of Low Temperature Concrete (Directly Implementable)

- Key formulation points: water-to-cement ratio (w/c) ≤ 0.35; incorporation of crack-resistant fibers (polypropylene or steel fibers); use of low-temperature adaptability admixtures and freeze-thaw resistance enhancers; application of high-grade cement and mineral admixtures (fly ash or slag).
- Strength grade: C50 (or as determined by structural calculations); Freeze-thaw resistance grade: F150 (or as specified by engineering requirements).
- Construction requirements: low temperature construction measures (heating curing, insulation covering), compacting, joint treatment and crack prevention measures.
- The test items were compressive strength, tensile strength, freeze-thaw cycle (≥300 times), thermal conductivity, permeability and low temperature brittleness.
- Acceptance criterion: the qualified rate of strength test block is ≥ 95%, the strength reduction after freeze-thaw is ≤ 20%.

6.3 Specifications for thermal insulation and sealing materials

- Insulation materials: polyurethane foam (closed-cell) or composite VIP, with freeze-thaw cycles and thermal-humidity aging test reports provided.
- Sealing materials: Low-temperature elastic sealant (operating temperature-50 to +50°C), expansion waterstop, and metal flange low-temperature gasket.
- The pipe is lined with stainless steel or high strength composite material, and covered with anticorrosive layer and insulation layer.
- Materials test: All key materials need to pass low temperature cycle, mechanical properties, thermal conductivity and durability test and submit report.

---

7 Selection of Ice Making / Melting Process and Equipment

7.1 Overall process flow

1 In the ice-making stage, the refrigeration unit supplies cold to the heat exchanger, and the controlled ice layer is formed in the storage body. The ice crystal morphology is controlled by promoting crystal and stirring to avoid large and uneven ice formation.

2. Storage stage: the ice is stored in the heat insulation and anti-seepage structure for a long time, and the temperature and phase state are monitored in real time.

3. The cooling phase: the cooling capacity is extracted by heat exchanger or ice slurry for the terminal use, and the return water is treated according to the return strategy (reused or sent back to be refrozen).

4. Re-freezing stage: the return water or replenishment water is re-freezing in the polar or local reservoir, forming a cycle chain.

7.2 Specifications and Selection of Key Equipment

- Refrigeration unit: Low-temperature refrigeration unit, with a 20% margin above the designed capacity; refrigerant selection must comply with low-temperature and environmental regulations (e.g., low-temperature R-type refrigerant or equivalent).

- Technical specifications: Cooling capacity 15 kW (per unit), power supply 380V/50Hz/3-phase, Modbus TCP control interface.

- Coil heat exchanger: Stainless steel or copper alloy coil, low temperature and ice resistant; heat transfer area calculated according to Chapter 4 and ice resistance margin is left.

- The ice slurry pump is a screw pump or mud pump with variable frequency control, which is wear-resistant and low temperature resistant.

- Cristallization and stirring devices: programmable stirrer or microcrystallization promoter dosing system (dosing controllable, ppm level).

- The liquid nitrogen auxiliary device is only used for emergency or rapid cooling, and it needs independent safety system and operation rules.

- Geothermal heat exchanger: if the site has geothermal resources, geothermal heat exchanger is configured to assist ice melting or energy recovery.

- Valves and bypass system: low temperature special valves, bypass and flushing ports, easy to maintain and prevent blockage.

7.3 Control Strategy of Promoting Crystallization and Preventing Overcooling

- Chemical crystallization: use of environmentally assessed crystallizers, dosing system and dose controller; dosing records incorporated into SCADA.

- Mechanical crystalization: the size and distribution of ice crystals were controlled by intermittent stirring or vibration.

- Surface-induced ice formation: Microstructure or rough layer on the heat exchanger surface can induce preferential ice formation, which is convenient to control the thickness of ice layer.

7.4 Specifications for the preparation and transportation of ice slurry

- The concentration of ice slurry should be controlled within the range of pumpable (the optimal concentration should be determined by experiments).

- The inner diameter of the pipeline was calculated according to the flow rate and concentration, and the flow velocity was controlled at 1.0-2.5 m/s. The inner wall was coated with low temperature anti-icing coating.

- Prevention measures: local heating band, regular backwash procedure, bypass switching strategy.

- Maintenance of pump: Check impeller wear, shaft seal and bearing regularly, and make clear spare parts list and replacement period.

7.5 Ice-making Scheduling and Energy Management

- Prioritize night-time ice-making: operate ice-making units during low-price electricity periods, combined with grid dispatch and renewable power access.

- The ice-making system is divided into different layers and zones according to the reservoir body to avoid stress concentration and premature scaling of heat exchanger.

- Energy recovery: recovery of waste heat from ice-making process for equipment heating or surrounding facilities heating (if feasible).

- Energy consumption monitoring: COP of refrigeration machine and energy consumption per unit ice making are recorded in real time and included in performance evaluation.

---

8 Specifications for Cold Source Delivery Interfaces, Pipelines, and Loading/Unloading Operations

8.1 Interface definition and function

- Injection port: Ice slurry/cold water injection port, with flowmeter, thermometer and quick shut-

off valve.

- Reflow interface: Reflow inlet with optional filtration and chemical treatment.
- Bypass and flushing port: for cleaning, maintenance and anti-clogging.
- The interface of the ship handling is the sealed and insulated hatch, the ice-breaking unloading cabin, the sealed conveying pipeline and the quick-closing system.

8.2 Pipeline Design Specifications

- Materials: Stainless steel or high strength composite material as lining, polyurethane insulation layer and anti-corrosion steel shell as covering.
- Thermal insulation: The thickness of insulation layer is calculated according to the heat loss target and the vacuum insulation panel (VIP) is used at the key nodes.
- Valves and flanges: Special low-temperature valves, with flange sealing using metal gaskets or low-temperature gaskets.
- Support and expansion: Long distance pipeline is equipped with support and expansion joints to adapt to thermal expansion and contraction.
- Inspection and Maintenance: Install periodic inspection ports, flushing ports, and online monitoring points (temperature, pressure, flow rate).

8.3 Specifications for the handling of maritime cargo and the renovation of ports

- Loading and unloading equipment: ice crusher, closed conveyor belt, insulated unloading chamber, unloading pump and sealed interface.
- The port was reformed by installing a closed thermal insulation cabin, a fast-closing system and anti-melting facilities at the loading and unloading port to reduce heat loss and environmental impact.
- Ship modification: the icebreaker was modified into ice-breaking and heat preservation cabin, the cabin insulation, the low temperature maintenance and the unloading interface were standardized.

---

9 A Numerical Simulation Suite for Thermal-Hydraulic-Solid Coupling (Model, Input, and Sensitivity Analysis)

9.1 Model type and solver

- Model type: 3D thermal-hydraulic-mechanical (THM) model, including phase change (freezing/ melting) module and nonlinear material properties.
- Recommended solver/platform: COMSOL Multiphysics (thermal-flow-solid coupling module), OpenFOAM (custom phase change module) combined with FEniCS/FLAC or TOUGH-FLAC. When selecting, consider both parallel computing capabilities and phase change module support.

9.2 Required input and boundary conditions

- Surface temperature time series: hourly or daily temperature files (CSV).
- Deep geothermal temperature: constant or deep temperature profile.
- The physical properties of soil/rock are density, specific heat, thermal conductivity, permeability, porosity, elastic modulus and Poisson ratio.
- The structural parameters of the reservoir are as follows: lining thickness, insulation layer parameters and heat exchanger layout.
- Phase change parameters: latent heat, phase change temperature range, supercooling parameter.
- Initial conditions: initial temperature field, initial ice distribution, initial pore water pressure.

9.3 Grid and Time Step Recommendations

- The meshing: the fine mesh (unit size 0.1-0.5 m) is used in the range of 50 m around the reservoir body, and the coarse mesh is used in the far field.
- Time step: seconds or minutes for ice making and cooling; hours or days for long-term coupling.
- Parallel computing: It is recommended to use multi-core parallel computing or cluster computing to shorten the simulation time.

9.4 Sensitivity and Uncertainty Analysis

- The key parameters were the thermal conductivity, permeability, insulation layer thickness, geothermal flux, ice-making rate and heat exchanger U value.
- Methods: Multi-parameter uncertainty analysis was carried out by single parameter scanning and Latin hypercube sampling (LHS). The output indexes included the temperature field of reservoir, ice distribution, foundation stress/settlement, seepage path and heat loss.
- The criterion is that if the key index is highly sensitive to a certain parameter, the redundancy or the improvement of material/structure should be added in the engineering design.

9.5 Sample simulation input file (can be imported directly or converted to the format)

```
DOMAIN:
  x_range: [-50,50] m
  y_range: [-50,50] m
  z_range: [-50,10] m
MATERIALS:
  soil:
    density: 2000 kg/m3
    thermal_conductivity: 1.5 W/mK
    specific_heat: 900 J/kgK
    permeability: 1e-8 m/s
  concrete:
    density: 2400
    thermal_conductivity: 1.7
    specific_heat: 900
BOUNDARY_
CONDITIONS:
  surfacetemperaturetimeseries: file:surfacetemp_hourly.csv
  deep_temperature: -5 C
INITIAL_
CONDITIONS:
  initialgroundtemperature: -8 C
  initialicefraction: 0.0
PHASE_CHANGE:
  latent_heat: 334000 J/kg
  freezing_point: 0 C
SIMULATION:
  time_total: 365 days
  time_step: 1 hour
OUTPUT:
  temperature_fields: hourly
  ice_fraction: hourly
  displacement: daily
```

Convert this text to the input format of the target simulation software and run it during project implementation.

---

10 monitoring and control system

10.1 Sensor List and Layout, Direct Purchase and Installation

- Temperature sensor: PT100 or thermocouple, range-50~+150℃, accuracy ±0.1℃; placement: inside the reservoir (bottom, side wall, center, top) and different depths of the external soil.
- Phase sensor: Dielectric constant or resistive sensor is used to detect the ice/water interface.
- The pore water pressure meter, with a range of 0-2 MPa, was installed around the reservoir to monitor the seepage.

- Flowmeter: electromagnetic or vortex flowmeter, the range is selected according to the design flow.
- Strain/displacement sensors: strain gauges, settlement plates, inclinometers are used for the monitoring of structures and foundations.
- Environmental sensors: methane detector (permafrost area), groundwater chemistry online monitoring (when necessary).

10.2 PLC / SCADA control logic

- Control objective: Maintain the temperature and phase state of the storage body in the set curve, prevent the local ice formation or sudden release of cold.
- duct pilot：
  - Temperature feedback → power regulation of refrigeration unit (PID control);
  - phase feedback → heat exchanger bypass / stirring control;
  - The backflow valve was automatically cut off and the emergency pump was activated.
- Data collection frequency: key points 1 min; routine points 10–60 min.
- Alarm threshold examples: Local temperature rise> 2°C/h; Seepage rate exceeds limit; Structural strain exceeds limit.
- Communication protocol: Modbus TCP/OPC UA; supports remote cloud backup and visual dashboard.

10.3 Data Management and Reporting

- Data storage: Local historical database + cloud backup (redundant storage).
- Automatic report: Daily, weekly, and monthly operation reports are automatically generated, including energy consumption, cooling capacity, heat loss, equipment status, and alarm records.
- Permissions and Security: Hierarchical permission management, log recording, and network security protection (VPN, TLS).

---

1 1. Pilot-scale engineering design

This chapter provides detailed drawings, construction sequence and quality control points that can be directly used for construction bidding and on-site construction.

1 1.1 Design parameters of the monomer storage facility

- The cavity dimensions are specified as an inner diameter of 2.0 meters and an inner height of 1.0 meters, corresponding to an ice volume of approximately 3.14 cubic meters, which meets the energy requirement of 1.0×10^6 kilojoules.
- The lining thickness is 0.4 m and the reinforcement is calculated according to the structure.
- Seepage-proof layer: 2.0 mm HDPE film, welded and 100% air/water tightness tested.
- Insulation layer: polyurethane foam 0.5 m (or equivalent composite layer), covered with backfill soil 1.0 m.
- Heat exchanger: The coil heat exchanger has a surface area of 12 m² (calculated per Chapter 4) and is made of stainless steel 316.
- Equipment room: refrigeration room, pump room, control room, chemical dosing room, arranged according to equipment specifications.

1 1.2 Construction Sequence

1 Site clearance and foundation pit excavation;

2. The base treatment (gravel bedding, drainage layer) and the bedding pouring;

3. Inspection of HDPE anti-seepage membrane installation and welding (100% inspection);

4. The concrete lining was poured (low temperature construction measures: heating curing, insulation covering);

5. Installation and pressure testing of coils/heat exchangers (pneumatic/hydraulic tests);

6. Insulation layer installation (polyurethane spraying or panel installation);

7. External backfilling and protective layer construction;

8. Equipment installation (refrigeration unit, pump, valves, control cabinet);

9. system flushing, pressure test, drying;

10. Sensors installation and calibration;

1 1. Trial operation and debugging;

12. Acceptance and transfer.

1 1.3 Quality Control Points

- Seepage-proof membrane welding and leakage detection (100%);

- Concrete strength specimens are tested in batches (with a pass rate of ≥95%).

- Thermal insulation layer thickness and thermal conductivity detection;

- The pressure test of heat exchanger is qualified.

- calibrate the sensors and record the certificate;

- Equipment factory inspection and performance test report.

1 1.4 Construction drawing ASCII section (ready for preliminary construction)

```
the earth's surface
| Backfill 1.0 m
|------------------------
| Polyurethane insulation 0.5 m
|------------------------
| HDPE waterproof membrane 2.0 mm
|------------------------
| Low-temperature concrete lining 0.4 m
|------------------------
| Inner cavity (ice body) D=2.0 m, H=1.0 m
| Coil arrangement: Bottom spiral + vertical coil on side wall
|------------------------
subgrade (gravel + drainage layer)
`
```

---

12 Trial run, performance verification, and acceptance criteria (executable directly)

12.1 Trial run steps (executable directly)

1 System inspection: Check the equipment integrity, valve position, and sensor calibration.

2. Dry run: pump, valve and PLC were run without load for 24 hours.

3. The refrigeration machine is run in no-load condition for 48 hours, and the refrigeration capacity and energy consumption are checked.

4. The ice-making operation: ice-making step by step according to the ice-making procedure of the sub-zone and sub-layer, recording the ice layer growth, the surface temperature of the heat exchanger, and the energy consumption;

5. The cooling operation was simulated by extracting the cooling capacity from the terminal load and recording the cooling efficiency and return water temperature.

6. Complete cycle: complete one cycle of ice making, releasing cold, refluxing and freezing, and record all data;

7. Long-term operation test: continuous operation for 90 days with recorded performance stability (or extended as required by the project).

12.2 Performance acceptance criteria

- Energy efficiency of ice-making: the actual energy consumption of ice-making is less than or equal to 1.5 × the theoretical minimum energy consumption (based on the latent heat of phase change).
- Seasonal heat loss: Heat loss ≤ 10% (calculated by seasonal energy balance).
- Temperature control accuracy: temperature control error ≤ ±0.5℃.
- Structural integrity: no crack propagation, settlement ≤ 10 mm (during trial operation).
- System reliability: The mean time between failures (MTBF) of critical equipment meets equipment specifications or contractual requirements.

12.3 Data collection and reporting

- The data collected include time, point temperature, phase state, heat exchanger surface temperature, refrigeration machine power, pump power, flow rate, pressure, seepage rate, structural strain, and remarks.
- Report frequency: Daily, weekly, monthly; Monthly reports include energy consumption statistics, heat loss, equipment operation statistics, and abnormal events.
- Acceptance documents: trial operation report, energy consumption and carbon emission assessment, structure inspection report, sensor calibration certificate, equipment factory inspection report.

---

13 Maintenance, Repair, and Emergency Response Plans

13.1 Common Fault Modes and Detection Methods

- The flow rate decreased and the pressure increased. The flowmeter, pressure gauge and temperature were abnormal.
- Leakage/anti-seepage failure: groundwater level change, seepage sensor alarm; detection: pore water pressure, chemical index.
- Structural cracks/ subsidence: abnormal strain gauge and settlement plate.
- The refrigeration machine has the following faults: the cooling capacity is decreased, the energy consumption is abnormal, the vibration and noise are present.

13.2 Quick Fix

- When the ice blockage occurs, the system will automatically switch to bypass mode, then start the local heating band, and then clear the ice by mechanical cleaning or backflushing, and finally resume operation.
- Leakage: immediately close the relevant valve → activate emergency pumping and grouting plugging → evaluate and repair the impermeable layer.
- Structural abnormality: stop operation → release and reinforce the field stress → resume operation after expert evaluation.

13.3 Long-term maintenance plan

- Daily: Online monitoring, alarm processing, equipment operation records.
- Monthly: Equipment inspection, sensor calibration, valve and flange inspection.
- Annual: comprehensive inspection of structure and anti-seepage, insulation layer detection, comprehensive maintenance of refrigeration system.
- Spare parts management: Critical spare parts list and minimum inventory cycle (calculated based on equipment MTTR/MTBF).

---

14 Standardized documents, acceptance forms, and compliance criteria

14.1 Design Acceptance Checklist

- Design document integrity and signature stamping;
- Calculation report verification and simulation report (sensitivity analysis covering key parameters);
- The construction drawings and material specifications are complete.

14.2 The construction acceptance form must be completed.

- Seam location, testing method and result of the waterproof membrane welding inspection record;
- Concrete strength test specimen inspection records (batch, strength value, qualification determination);
- pressure test record of heat exchanger (test pressure, duration, result);
- Sensor calibration certificate and installation records.

14.3 Trial Operation Acceptance Form

- Record of trial run steps completed
- Performance metrics comparison table (including ice-making energy efficiency, heat loss, and temperature control precision);
- Safety and emergency drill records.

---

15 Scale-up Route and Scale-up Judgment Criterion

15.1 Zoom in, by stages

1 Pilot scale: to validate the process, materials, and control strategies while collecting operational data (complete one full cycle and meet performance targets).

2. Parallel group engineering: multi-plant parallel operation, grid connection, thermal management and corridor interface.

3. Regional engineering scale-up: engineering scale-up and long-term operation, economic and environmental impact assessment.

15.2 Zoom criteria (must be met to zoom)

- Technical feasibility: Key performance indicators are stable and meet the target (see chapter 12).
- Economy: the energy consumption and operation cost of unit cold storage are within the acceptable range (determined by the owner/investor).
- Environmental impact: Groundwater, methane, ecological impact is controllable and mitigation measures are available.
- Reliability: No major failure occurred during the pilot test period, and the maintenance plan was implemented.

---

16 Appendix

Appendix A: Hourly/Daily Calculation Sheets Template (CSV Field Example)

- Time, ambient temperature (℃), central storage temperature (℃), ice mass (kg), release capacity (kJ), refrigeration unit power (kW), pump power (kW), flow rate (m3/h), pressure (bar), notes

Appendix B: List of sensors and devices

- PT100 temperature sensor × 20 (range-50~+150℃, accuracy ±0.1℃)
- 6 pore water pressure meters (range 0–2 MPa)
- Two electromagnetic flowmeters (0–200 m³/h range)
- Low-temperature resistant variable frequency pump × 2 (with spare parts)
- 1 refrigeration unit (with capacity as designed)
- 1 PLC control cabinet and 1 SCADA software package

Appendix C: Sample equipment specifications (refrigeration units)

- Cooling capacity: as per design requirements (e.g. 15 kW)

- refrigerant: low temperature compatible refrigerant (type selection according to regulations and environmental requirements)
- Power supply: 380 V / 50 Hz / three-phase
- Control Interface: Modbus TCP / OPC UA
- Operating temperature range: -40°C to +40°C (ambient)
- Maintenance cycle: Annual overhaul, 5-year medium overhaul

Appendix D: Simulation Input Examples (text, see examples in Chapter 9)

(You can copy directly and convert to the target simulation software format)

Appendix E: ASCII Diagrams for Construction Drawings (See Chapter 1 1)

---

1 On-site investigation and geological tests: drilling sampling, groundwater testing, and geothermal profile measurement (2-4 weeks) were completed at the proposed site.

2. Materials test: freeze-thaw and mechanical test of low temperature concrete, insulation material and sealing material (6-8 weeks parallel).

3. Construction and operation of small pilot-scale ice storage: A single ice storage was constructed according to the technical package and completed a complete cycle of ice making, releasing cold and reflux (12 weeks).

4. Numerical simulation calibration: using the pilot operation data to calibrate the THM model and complete the sensitivity analysis (parallel).

5. Parallel group and scaling decision: Based on the pilot data and simulation results, the next scaling step is decided according to the scaling decision criterion.

Project Feasibility Statement

This technical solution provides a complete, directly implementable and operational engineering package for underground cold storage/ice storage systems, covering all technical elements including design calculations, material specifications, equipment selection, construction techniques, monitoring and control, trial operation and acceptance, as well as maintenance and emergency response. Upon completing the on-site investigation and material testing as per this plan, the project can proceed to pilot construction to obtain the necessary engineering data and operational experience for scaling up.

Next is

Design Book of Underground Cold Storage and Ice Storage Project, Detailed Technical Implementation Chapter of Pilot Test Version

---

1 Summary of design parameters and engineering nominal values

Nominal value of the project

- The seasonal cold storage capacity of the pilot-scale system is $Q_{pilot}=1.0\times10^{6}$ kJ.
- Design ice-making cycle: $t_{ice}=120\ \mathrm{days}$ (adjustable according to on-site power supply and operational strategies).
- The cooling cycle is designed as follows: $t_{dis}=120\ \mathrm{days}$.
- The seasonal heat loss rate of the target is less than 10%.
- design safety factor: 1.5 for structure and 1.2 for thermal capacity.

Default physical properties and engineering constants (substituted with field tests prior to project implementation)

- The latent heat of ice is 334 kJ/kg.
- The ice density is $\rho_{ice}=917$ kg/m³.
- The specific heat of water is 4.18 kJ/(kg·K).
- The specific heat of ice is 2.1 kJ/(kg·K).
- The thermal conductivity of polyurethane is $\lambda_{PU}=0.025$ W/(m·K).
- The initial geothermal flux density is set to 0.05 W/m².

---

2 Calculation of the size of the pilot-scale reservoir and the ice mass

2.1 Calculation of Ice Mass and Volume

computational formula

$$
m=\frac{Q_{pilot}}{L}
$$

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

Results (nominal values)

$$
m=\frac{1.0\times10^{6}}{334}\ \mathrm{kg}\approx2994\ \mathrm{kg}
$$

$$
V_{ice}=\frac{2994}{917}\ \mathrm{m^3}\approx3.26\ \mathrm{m^3}
$$

Selection of the geometry for the storage container

- The cylindrical cavity is convenient for uniform ice formation and structural stress.
- Cavity dimensions: inner diameter (D=2.0 m), inner height (H=1.0 m), and cavity volume

The volume of the cylinder is approximately 3.14 cubic meters (V_{cyl}=π D^2 H/4), which meets the ice volume requirement while providing operational margin.

---

3 Insulation and Heat Loss Calculation

3.1 Calculation method for steady-state thermal insulation

steady state heat flux formula

\[
q=\frac{\Delta T}{\sumi \frac{di}{\lambda_i}}
\]

where ΔT = T ext-T int.

Engineering objective: Seasonal heat loss rate (η_loss) ≤ 10%. Convert the heat loss target into an allowable average steady-state heat flux.

\(q{allow}\):

For the reservoir body's effective surface area \\(A{surf}\\), seasonal duration \\(t {season}\\), and allowable heat loss energy:

\[
Q{loss,allow}=q{allow}\cdot A{surf}\cdot t{season}
\]

The condition \\(Q{loss,allow}\\le \\eta{loss}\\cdot Q_{pilot}\\) must be satisfied.

Solve for \\(q_{allow}\\):

\[
q{allow} \le \frac{\eta{loss}\cdot Q{pilot}}{A{surf}\cdot t_{season}}
\]

3.2 numerical substitution (pilot reservoir)

- The inner cavity diameter is 2.0 m and the inner height is 1.0 m.
- Approximate exterior surface area of the outer protective structure (including top and bottom protective layers):

\[
A_{surf}\approx \pi D H + 2\cdot \frac{\pi D^2}{4} \approx \pi\cdot2.0\cdot1.0 + 2\cdot\frac{\pi\cdot4}{4}\approx6.28+6.28\approx12.56\ \mathrm{m^2}.
\]

- Seasonal duration \\(t_{season}=120\\ \\mathrm{days}=120\\times24\\times3600\\ \\mathrm{s}\\approx10,368,000\\ \\mathrm{s}\\).
- Allowable heat dissipation energy: (η_loss=0.10～ Q_loss允许=0.1×1.0×10^6=1.0×10^5) \mathrm{kJ}=1.0\times10^{8}\ \mathrm{J}\).

Calculate \\(q_{allow}\\):

\[
q_{allow}\le\frac{1.0\times10^{8}}{12.56\times10,368,000}\approx0.00077\ \mathrm{W/m^2}.
\]

\]

Engineering conclusion: The specified heat transfer rate (q{allow}) is extremely low, rendering single-layer insulation inadequate for steady-state approximation. Practical engineering solutions should incorporate: multi-layer composite insulation, deep underground burial, natural insulation from permafrost, and localized application of vacuum insulation panels (VIP), with actual heat loss assessed through transient numerical simulations. During design, conservative target values (q {design}=0.5 W/m²) should be adopted for localized heat flux control, with seasonal cumulative losses verified through simulation.

3.3 Preliminary calculation of insulation layer thickness (engineering design value)

When the steady-state heat flux is allowed to be 0.5 W/m², the temperature difference between the external environment and the reservoir is 20 K, and the thickness of the polyurethane layer is:

\[
d{PU}=\lambda{PU}\frac{\Delta T}{q_{design}}=0.025\cdot\frac{20}{0.5}=1.0\ \mathrm{m}.
\]

Engineering requirements: Composite insulation scheme: 1.0 m backfill + 0.5-1.0 m polyurethane + local VIP board (key joints) to reduce overall heat flux and meet long-term heat loss targets. Final thickness and material combination are verified by numerical simulation and determined after material testing.

---

4 Design of Heat Exchanger and Ice-making System

4.1 Ice-making energy and average cooling power

Total cooling capacity (approximating the sensible heat term):

\[
Q=1.0\times10^{6}\ \mathrm{kJ}=1.0\times10^{9}\ \mathrm{J}.
\]

If ice-making is completed within the ice-making cycle (t_{ice}=120 days=10,368,000 seconds), the average cooling power is:

\[
\bar{P}=\frac{Q}{t_{ice}}=\frac{1.0\times10^{9}}{10,368,000}\approx96.4\ \mathrm{W}.
\]

The engineering description is as follows: The average power is very small, and the actual ice-making will adopt the strategy of segmented rapid ice-making to match the night electricity price and the minimum operating power of the equipment. The designed refrigeration unit should have a minimum stable output of 2-5 kW and the capability of parallel operation of segmented units.

4.2 Method for calculating the area of heat exchangers

Overall heat transfer relationship:

\[
\bar{P}=U A \Delta T_{lm}
\]

Calculate the heat exchange area:

\[
A=\frac{\bar{P}}{U\Delta T_{lm}}
\]

Engineering parameter values (initial design)

- The heat transfer coefficient is taken as \(U=200\ \mathrm{W/(m^2·K)}\) (a typical value for coil-water heat exchange, including a margin for ice formation resistance).
- Take \\(\\Delta T_{lm}=5\\ \\mathrm{K}\\).

substitution：

\[
A=\frac{96.4}{200\times5}\approx0.0964\ \mathrm{m^2}.
\]

Engineering description: The theoretical surface area is very small, and the actual design should consider the resistance of ice formation, the decrease of heat transfer coefficient caused by ice layer growth and the maintenance demand. The minimum heat exchanger area is 12 m2 (consistent with the redundancy of heat exchanger mentioned above) and the coil is arranged in sections for ice making and maintenance.

4.3 Requirements for the structure and layout of heat exchangers

- Material: Stainless steel 316 or low temperature resistant copper alloy, welding and seamless tube preferred.
- Layout: bottom spiral coil + side wall vertical coil combination, zoned control (each zone independent bypass valve and temperature measurement point).
- The ice formation is controlled by the microstructure of the coil surface. The spacing and arrangement of coils are verified by the simulation of ice growth rate.
- Maintenance: Heat exchanger should be detachable or set up independent heat exchange tank for maintenance and replacement.

---

5 Pump and Pipeline Design

5.1 Flow Rate and Power Estimation of Ice Slurry/Cold Water Pumping

Design objective: The cooling system is designed to supply cooling to the terminal on demand during the cooling period, and the maximum instantaneous cooling power (P_{max}) is assumed to be determined by the terminal load. The pilot-scale design is conservative, with a maximum cooling power of 20 kW.

If an ice-water mixture is used for transportation, the required flow rate is calculated based on a temperature difference of $\Delta T_{term}=5$ K.

\dot{m}=\frac{P{max}}{cw\Delta T_{term}}=\frac{20,000}{4.18\times5}\approx957\ \mathrm{kg/s}\approx0.957\ \mathrm{m^3/s}.

\]

Engineering description: The flow rate is too large for the pilot scale, and the actual terminal load should be provided by the system integrator. The pilot pump is mainly a variable frequency pump, with a flow rate range of 0.01–1.0 m3/h (or adjusted according to the actual terminal load), and a backup pump is provided.

5.2 Pipelines and Insulation Specifications

- Materials: Stainless steel or composite material as lining, polyurethane insulation layer and anti-corrosion steel shell as outer covering.
- The inner diameter was calculated according to the allowable flow rate of 1.0–2.5 m/s and the pressure drop was checked.
- The insulation thickness is determined according to the insulation calculation in Chapter 3 and the site construction conditions.
- Support and expansion: Set the support spacing and expansion joint to adapt to the thermal expansion and contraction.
- Valve: Special low-temperature valve, with flange seal using metal gasket or low-temperature gasket.
- Maintenance ports: Flush and test ports are set every 50–100 m.

---

6 Key Points of Structural Design and Load Verification

6.1 Design Points of Lining and Foundation

- The lining thickness is 0.4 m low temperature concrete and the reinforcement is calculated according to the structure.
- Foundation: gravel bedding + drainage layer, foundation bearing capacity is designed according to the foundation bearing capacity test results and leave a safety factor.
- Load combinations: self-weight, equipment loads, frost heave/ thaw settlement, and seismic effects (per local codes).
- Crack control: using crack-resistant fiber, construction joint and temperature joint design, low temperature curing measures.

6.2 Freeze-thaw cycle effect and structural adaptation

- Material selection: high freeze-thaw resistant concrete and low temperature resistant sealing material.
- Structural details: flexible joint, expansion joint and replaceable lining are set to deal with the long-term freeze-thaw cycle.
- Monitoring: Strain gauges and settlement plates are installed at key locations and recorded over time and incorporated into maintenance plans.

---

7 Material Testing and Quality Control Plan

7.1 mandatory material test

- The low temperature concrete test: compressive strength, tensile strength, freeze-thaw cycles ($\geqslant$ 300 times), thermal conductivity, permeability coefficient.
- The thermal insulation materials were tested for thermal conductivity, freeze-thaw cycle, wet-heat aging and compressive strength.
- The tests of impermeable film were conducted on tensile strength, weld strength, permeability and low temperature brittleness.
- The heat exchanger materials were tested for corrosion resistance, low temperature impact and welding quality.

7.2 Quality control points and acceptance criteria

- Seam welding of impermeable membrane: 100% weld inspection (air tight/water tight).
- Strength of concrete: the qualified rate of test block is $\geqslant$ 95%.
- Thermal insulation layer thickness and thermal conductivity: According to the design requirements and sampling test.
- The pressure test of heat exchanger is carried out by holding the pressure at 1.5 times of the design pressure for 2 hours.

---

8 Implementation Rules for Monitoring, Control, and Automation

8.1 List of sensors and installation specifications

- Temperature points: 8 points in the reservoir (bottom, side wall, center, top and heat exchanger surface); 6 points in the external soil (at different depths).
- Phase detection: The dielectric constant sensor is installed at several points in the cavity to determine the ice/water interface.
- Pore water pressure: Perimeter 4–6 points to monitor seepage.
- Structural monitoring: 4 strain gauges, 3 settlement plates and 2 inclinometers.
- Environmental monitoring: two methane detectors (in the permafrost area) and several groundwater chemical sampling ports.

8.2 PLC/SCADA control logic details

- Control Levels: PLC handles real-time closed-loop control (using PID control for refrigeration units, pumps, and mixers), while SCADA manages data processing.

The system can collect, record, alarm and remote visualize.

- control strategy：
  - Temperature closed loop: control the output of the refrigeration machine according to the set curve;
  - Phase protection: if the local icing rate exceeds the limit, the refrigeration power is automatically reduced and the stirring is enabled;
  - The backflow valve is automatically closed and emergency pumping is started when the backflow exceeds the limit.
- Data frequency: Key points every 1 minute; Regular points every 10 minutes; Real-time alerts for alarm events.
- Redundancy and security: Dual PLC hot standby, dual redundant critical sensors, and network encryption via VPN and TLS.

---

9 Pilot construction plan and schedule

9.1 Key milestones and timeline (estimated total duration: 20 weeks)

1 Site preparation and temporary construction: 2 weeks.
2. Geological drilling and testing: 4 weeks (parallel with material testing).
3. The foundation pit excavation and foundation treatment: 2 weeks.
4. The construction of the impermeable layer and lining: 4 weeks (including concrete curing).
5. The installation of the insulation layer and heat exchanger took 2 weeks.
6. Equipment installation and pipeline connection: 2 weeks.
7. The installation of sensors and the debugging of the control system took 2 weeks.
8. System flushing, pressure test and drying: 1 week.
9. Trial operation and debugging (including complete cycle): 3 weeks.

Total: approximately 20 weeks (parallel work can be done to shorten the duration).

9.2 Key resources and staffing

- Project Manager: 1 person.
- On-site engineers: Structural 1, Thermal 1, Electromechanical 1, Control 1.
- Construction team: 8 people for civil engineering, 6 people for equipment installation, 4 people for welding and anti-seepage.
- The test and monitoring team consisted of 2 people for material test and 2 people for sensor installation and calibration.

---

10 Trial run, data collection and performance evaluation process

10.1 List of tasks for the trial operation phase

- Pre-run inspection: Equipment, valves, sensors, and pipeline integrity.
- The refrigeration machine and pump were run without load for 48 hours.
- The ice was made in each zone according to the control program and the ice growth curve was recorded.
- The cooling simulation was carried out by extracting the cooling capacity according to the terminal load and recording the return water temperature.
- Complete cycle verification: complete the cycle of ice making, release cold, reflux and freeze again and generate performance report.

10.2 Performance evaluation indicators and their determination

- The energy consumption ratio of ice-making is (E{actual}/E{theoretical})≤1.5.

- Seasonal heat loss: cumulative heat loss ≤ 10% (calculated by energy balance).
- Temperature control accuracy: ±0.5℃.
- Structure and anti-seepage: no leakage, crack expansion or abnormal settlement.
- Control and alarm: the alarm response time is less than 5 minutes, and the automatic protection action is reliable.

10.3 Data Reports and Archiving

- Daily report: operating parameters, energy consumption, and abnormal events.
- Weekly Report: Performance Trends and Maintenance Recommendations.
- The final report includes complete cycle data, energy consumption statistics, simulation calibration results and scaling recommendations.

---

1 1 Risk Identification and Response Measures, Technical Level

1 1.1 Major Technical Risks and Mitigation Measures

- The heat loss is excessive: the composite insulation, deep burial and VIP local application are adopted; the insulation scheme is optimized by simulation.
- The ice blockage was solved by the measures of zoning ice-making, bypass and local heating belt, and regular backwash.
- Seepage prevention failure: 100% inspection of HDPE welds and grouting reinforcement plan are on standby.
- Foundation settlement/freeze-thaw damage: foundation reinforcement, flexible joint, long-term monitoring and early warning.
- Equipment failure: redundancy of key equipment, spare parts inventory and quick replacement process.

1 1.2 Emergency Response Process (Technical Operations)

- Leakage event: immediately close the relevant valve → activate emergency pumping → grouting seal → structure assessment.
- The procedure was as follows: switch to bypass → start local heating → mechanical cleaning → resume operation.
- Structural abnormality: shutdown → stress release and reinforcement on site → expert evaluation → resumption of operation.

Appendix Key Tables and Templates

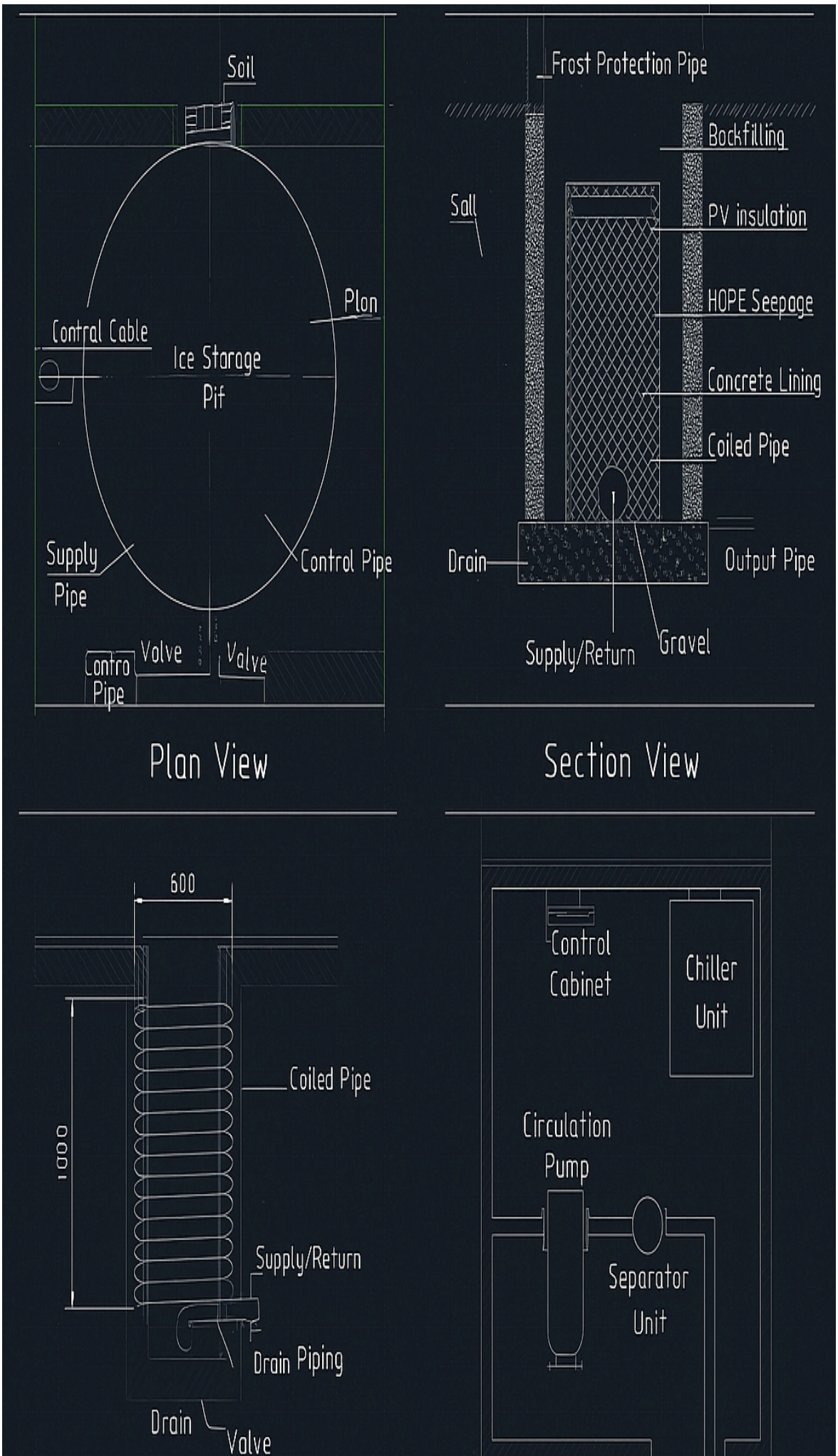
Appendix 1 Hourly Run Template Fields

Time,ExternalTempC,InternalCenterTempC,IceMasskg,AvailableColdkJ,RefrigerationPowerkW,PumpPowerkW,Flowm3h,Pressurebar,AlarmFlag,Notes

Appendix 2 Sample BOM for Equipment

- The refrigeration unit has a refrigeration capacity of 15 kW, low-temperature refrigerant, and Modbus TCP interface.
- 1 set of coil heat exchanger, made of stainless steel 316, with a heat exchange area of 12 m2.
- Two frequency conversion pumps (primary and backup), low-temperature resistant, with flow range as designed.
- One set of PLC control cabinet and one set of SCADA software were provided.
- 20 PT100 temperature sensors, 6 pore water pressure meters and 2 electromagnetic flow meters were used.
- 2.0 mm HDPE impermeable membrane, purchased according to the perimeter and area of the reservoir with a 10% margin.
- Polyurethane insulation material is purchased by volume and 15% is reserved.

Appendix 3 Initial Simulation Input Text (see Chapter 9)


Soil
Plan
Contral Cable
Ice Storage
Pif
Supply
Pipe
Control Pipe
Contro
Pipe
Volve
Valve
Plan View
Frost Protection Pipe
Bockfilling
Sall
PV insulation
HOPE Seepage
Concrete Lining
Coiled Pipe
Drain
Output Pipe
Supply/Return
Gravel
Section View
600
1000
Coiled Pipe
Supply/Return
Drain Piping
Drain
Valve
Control
Cabinet
Chiller
Unit
Circulation
Pump
Separator
Unit

Text version of detailed construction drawings for pilot-scale project: Plan and section, Equipment layout, Pipeline routing description

General Description

- PURPOSE: The construction drawing of this version is used for the site construction, bidding and installation guidance of the civil engineering and equipment installation of the pilot single storage body. All dimensions are nominal values, and the construction drawing (CAD) should be checked and issued according to the site investigation results before construction.
- The drawings include: plan layout, longitudinal section, heat exchanger and coil detail, equipment room layout, pipeline and bracket layout, grounding and cable tray, sensor and sampling port layout.
- Units of measurement: length m, area m2, temperature ℃, pressure bar, time h.

Layout Text

- The baseline of the site is the north side of the site, and the center coordinate of the reservoir body is (0,0).
- Reservoir location: Center of the reservoir (0,0), outer diameter (including insulation and lining) \\(D_{out}=2.0\\mathrm{m}+2\times(0.4+0.5+1.0) =) according to the actual cumulative layer thickness; mark the thickness and interface of each layer in the CAD construction drawing.
- Equipment room location: The equipment room (including the refrigeration plant, pump room, and control room) shall be installed 4.0 meters south of the warehouse. The minimum clearance between the equipment room's exterior wall and the warehouse's outer wall must be 2.0 meters to ensure adequate maintenance access.
- Pipe trench and valve well: underground pipe trench is set from the reservoir to the equipment room, the pipe trench is covered with backfill soil and the maintenance well is set. Valve well is set at every main branch of the pipeline, the valve well is 1.2 m × 1.2 m × 1.5 m (deep).
- Cable tray: The control cabinet in the equipment room is connected to the main control cabinet in the warehouse by underground cable conduits. The width of the cable tray is determined by the power of the equipment and the number of control lines (initially set at 600 mm).
- Safety passage: 1.0 m wide maintenance passage is set around the storage body, the ground is anti-slip and drainage ditch is set.

Longitudinal section text

- Surface layer: 1.0 m of backfill soil, compacted to 95% standard penetration.
- Insulation layer: polyurethane foam 0.5 m (or equivalent composite layer), with VIP board 0.02–0.05 m installed at critical joints.
- Seepage-proof layer: HDPE film (2.0 mm thick), with welds inspected 100% according to welding standards and maintenance access reserved.
- The lining thickness is 0.4 m, the reinforcement is calculated according to the structure, and the coil fixing bracket is set on the inner side.
- The inner cavity is cylindrical with a diameter of 2.0 m and a height of 1.0 m. The bottom of the cavity is equipped with drainage and flushing ports, and the bottom plate is equipped with detachable maintenance ports.
- Foundation: 0.3 m gravel bedding, drainage layer and filter layer, bearing capacity of foundation is designed according to foundation test results and 20% safety margin is left.
- Equipment room foundation: independent strip foundation or independent raft foundation, the top of the foundation is 0.2-0.5 m higher than the top of the storage body in order to install the equipment

Installation and waterproofing.

Heat exchanger and coil

- Coil material: Stainless steel 316L seamless tube, outer diameter 25–32 mm (calculated according to flow rate and pressure drop).
- The spiral coil diameter was 1.6 m, the spacing was 0.08-0.12 m, the vertical coil spacing was 0.12-0.15 m, and the coil fixing bracket spacing was 0.5 m.
- The coil was fixed by stainless steel bracket and thermal insulation gasket, and the bracket was connected with lining by expansion bolt or embedded part.
- Bypass of heat exchanger: each section is equipped with bypass valve and exhaust valve to facilitate partial shutdown and cleaning.
- Maintenance interface: The coil inlet and outlet are connected by flanges with 1.0 m maintenance space reserved, and the flanges are PN16 or according to the design pressure level.
- Anti-icing measures: The interface of controllable vibrator or periodic stirring device is set on the surface of coil to facilitate crystal growth and anti-clogging.

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interroom layout

- The refrigeration unit is placed in the north side of the equipment room, and the base of the unit is a concrete pad, and the top of the pad is a vibration damping pad.
- Pump house: The pump house is equipped with main pump and backup pump, the pump house floor is equipped with drainage ditch and oil-water separator, the pump inlet and outlet are equipped with valve and flowmeter.
- Control room: The PLC control cabinet, SCADA server and monitoring screen are installed in the control room, which is equipped with air conditioning and moisture-proof measures.
- Chemical dosing room: If the use of crystalizer or preservative, set up independent chemical room and equipped with secondary anti-leakage pallet and ventilation.
- Ventilation and drainage: The equipment room is equipped with forced ventilation and drainage system, and the drainage is connected to the site drainage system and a sedimentation tank is set up.

Line direction and bracket arrangement

- Main supply return pipeline: from equipment room to storage body, the underground insulated pipeline is adopted, the depth of the pipeline trench is determined according to the requirements of frozen soil and anti-freeze (it is recommended that the buried depth is $\geqslant$ 1.2 m), the pipeline is covered with steel shell and anti-corrosion layer.
- The spacing of the supports is determined by the pipe diameter and load (generally 1.5–3.0 m), and the inspection wells or expansion joints are installed every 5–10 m for underground pipelines.
- Expansion joint: Expansion joints are installed every 20-50 m in the long straight pipe to absorb thermal expansion and contraction. The location of expansion joints is marked on the construction drawing.
- Valve well: The main branch of the valve well is set up, the valve well is equipped with lighting and drainage, the bearing grade of the cover is selected according to the vehicle load.
- Cable and control line: Cable and control line are laid separately, power and signal line are arranged in separate channel and shielded and grounded.

Sensor and sampling port arrangement

- Temperature points: 1 point at the bottom of the inner side of the reservoir, 1 point at the middle of the side wall, 1 point at the center, 1 point at the top; 2 points at the depth of 0.5 m, 1.0 m and 2.0 m in the external soil.
- Phase point: The dielectric constant sensor is arranged on the inner cavity side wall at four points for ice/water interface detection.
- The pore water pressure points are located at 4 points around the reservoir body, and the depth of the pore water pressure points is 2 m below the bottom of the foundation.
- The monitoring points of the structure are 4 strain gauges, 3 settlement plates and 2 inclinometers.
- Sampling ports: sampling ports are set at return water and discharge port for chemical analysis and environmental monitoring.

Run the CSV template hourly

`
Time,ExternalTempC,InternalCenterTempC,InternalTopTempC,IceMasskg,AvailableColdkJ,RefrigerationPowerkW,PumpPowerkW,Flowm3h,Pressure_bar,ValveStatus,AlarmFlag,Notes
2025-12-01 00:00,-15.0,-2.0,-1.5,2994,1000000,0.10,0.05,0.5,0.5,OPEN,0,Init
2025-12-01 01:00,-15.2,-2.1,-1.6,2994,999900,0.12,0.05,0.5,0.5,OPEN,0,
2025-12-01 02:00,-15.5,-2.2,-1.7,2994,999800,0.15,0.05,0.5,0.5,OPEN,0,
...
`

- Field Description
  - Time: Timestamp in format YYYY-MM-DD HH:MM.
  - ExternalTemp_C: External temperature in degrees Celsius.
  - InternalCenterTemp_C: The central temperature of the library body.
  - InternalTopTemp_C: Top chamber temperature.
  - IceMass_kg: The mass of ice in the warehouse.
  - AvailableCold_kJ: Current available cooling capacity.
  - RefrigerationPower_kW: Real-time power consumption of the refrigerator.
  - PumpPower_kW: Real-time pump power.
  - Flow_m3h: Flow rate in cubic meters per hour.
  - Pressure bar: System pressure.
  - ValveStatus: Key valve status OPEN/CLOSED.
  - AlarmFlag: Alarm flag 0/1.
  - Notes: Remarks.

Detailed plan and test sheet for material testing

Overall requirements for the trial

- Objective: To verify the mechanical, thermal and durability properties of the key materials under low temperature and freeze-thaw cycles, and to ensure the design life and safety objectives.
- Test institution: the material testing laboratory with national accreditation or the third party testing institution.
- Sample quantity: At least 3 batches of samples for each material, with no fewer than 5 specimens per batch (adjusted according to standards and engineering quantities).
- The test environment was a temperature controlled chamber with a temperature range of-50℃ to +50 ℃ and humidity controlled.

Low-temperature concrete test protocol

- test item

1 . The compressive strength (standard curing 28 days) is determined according to GB/T 50081 or equivalent standards.

2. Bending / tensile strength.

3. Freeze-thaw cycle test: ≥ 300 cycles, according to GB/T 50082 or equivalent standards, record the mass loss rate, strength retention rate and crack condition.

4. Thermal conductivity was measured by steady-state or transient method (-10℃,0℃, +10℃).

5. Permeability test: water permeability or chloride permeability test.

6. Low temperature impact /brittle test: to measure the fracture toughness at low temperature.

- Sample preparation: prepare test blocks (150×150×150 mm or according to standard) according to the design ratio and record curing conditions.

- acceptance level

- The compressive strength meets the design grade (e.g., C50) with a test block qualification rate of ≥95%.

- The strength retention rate after freeze-thawing was ≥ 80%.

- The deviation of thermal conductivity and design value is less than 15%.

- No through cracks or cracks width ≤ 0.2 mm.

Test plan for thermal insulation materials

- test item

1 Thermal conductivity measurement (-20℃,0℃, +20℃).

2. Compression strength and resilience test.

3. Freeze-thaw cycles and wet heat aging test (≥ 200 cycles or equivalent accelerated aging).

4. The water absorption rate and hygroscopicity were tested.

- acceptance level

- The deviation of thermal conductivity and design value is less than 10%.

- The change of thermal conductivity after freeze-thawing was less than 20%.

- The mechanical strength meets the construction load requirements.

HDPE (High-Density Polyethylene) Seepage Prevention Membrane Test Protocol

- test item

1 Tensile strength and elongation at break.

2. Weld strength test (hot-melt weld).

3. Low temperature brittleness test (-40℃).

4. Permeability and chemical stability test.

- acceptance level

- The tensile strength was consistent with or better than the standard value.

- The weld strength is ≥ 90% of the base material strength.

- Low temperature brittleness without crack.

Test Scheme for Heat Exchanger and Pipeline Materials

- test item

  1 Low temperature impact test of metal materials (Charpy impact or equivalent).

  2. Corrosion rate test (salt spray or chemical medium).

  3. Nondestructive testing (UT/RT) and pressure test (1.5×design pressure, 2 h).

- acceptance level

  - The impact energy meets the requirements of low temperature toughness.
  - The welding joint has no crack and no leakage.

Test Schedule and Deliverables

- schedule

  - The samples were collected and prepared for 1 week.
  - mechanical testing was performed for 2-3 weeks.
  - Freeze-thaw cycles and aging tests were performed for 6–8 weeks (in parallel, with multiple batches).
  - The report was prepared and delivered within 1 week.

- deliverable

  - The original data, test records, photos and videos (key steps), and test reports (including conclusions and recommendations) for each test.
  - Rectification suggestions and reinspection plan for nonconforming items.

Purchasing and BOM details for bidding

Summary of key equipment specifications

- refrigerating unit

  - The cooling capacity is designed to meet the requirements, with a minimum stable output of 2 kW per unit, and a parallel configuration is recommended. The refrigerant is selected according to regulations, and the interface is Modbus TCP.

- coil heat exchanger

  - The material is 316L stainless steel, with a heat exchange area designed to accommodate 20% extra space, and the flange is PN16.

- variable frequency pump

  - The low temperature resistance, the flow range according to the design, with frequency control and remote interface.

- PLC and SCADA

  - The PLC features dual-machine hot standby with support for both Modbus TCP and OPC UA protocols, while the SCADA system supports historical database management and remote visualization capabilities.

- sensor

  - The equipment includes 20 PT100 temperature sensors (with a range of-50 to +150°C and an accuracy of ±0.1°C), 6 pore water pressure meters, and 2 electromagnetic flow meters.

- HDPE waterproof membrane

  - The thickness of the material was 2.0 mm, and the material was purchased according to the circumference and area of the reservoir, with a surplus of 10%.

- heat insulating material

  - Polyurethane foam or boards are procured by volume with a 15% surplus; VIP boards are procured at critical nodes.

Key points of the procurement document

- Technical specifications: each equipment should include performance curve, interface protocol, environmental adaptability, maintenance cycle and spare parts list.
- Acceptance conditions: factory inspection report, performance test report, installation and commissioning records, operation manual and spare parts list.
- Warranty period: The warranty period for key equipment is no less than 24 months, and for refrigeration units, it is recommended to be 36 months with 5 years of spare parts guarantee.

Geology and Pipeline Engineering Technology in Permafrost Area, Frozen Soil-Pipeline Coupling

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Project Overview and Delivery Objectives

Objectives Overview

This technology addresses the most critical technical challenge in permafrost pipeline engineering—the frozen-soil-pipeline coupling effect (including frost heave, thaw settlement, thermal disturbances, seepage, and mechanical coupling)—by providing a comprehensive set of engineering technical documents directly applicable to pilot-scale testing and scaling up. The deliverables cover all technical elements, from investigation, numerical modeling, design calculations, material and construction specifications, construction techniques, monitoring and control, emergency response and maintenance, to pilot-scale testing and scaling-up evaluation criteria.

Lao Zi provides engineering design book, simulation input and calibration process, construction technology card, material test scheme, monitoring and control system configuration, emergency plan and acceptance form which can be directly used in pilot section construction and operation.

- The technical criteria from pilot to scale-up were defined and the implementation route and schedule were given.
- The BOM and equipment specifications for bidding and procurement are provided.

scope of application

It is suitable for the pilot and engineering implementation of medium and long distance transportation pipelines, cold source transportation pipe corridors, underground insulated pipelines and related ground/semi-buried structures in permafrost areas (including continuous permafrost and discontinuous permafrost zones).

Key technical framework and engineering requirements

Technical issues list (must be resolved)

- The influence of frost heave on the axial and circumferential stress and fatigue life of the pipeline;
- The uneven settlement and the deformation of the pipeline caused by the fusion and the sinking;
- The frozen soil degradation and the change of seepage path caused by thermal disturbance;
- The design of thermal expansion and contraction coordination and expansion joint of pipe and support;

- The anti-icing, heat preservation and active thermal management strategies of the pipeline;
- Reliability of low temperature welding,flange and seal under freeze-thaw cycle;
- Establishment of long-term monitoring and online early warning system.

Design and Performance Requirements

- The safety of structure: the strength and deformation limit of the pipeline are satisfied under the design condition and extreme condition, the circumferential strain and axial strain are not beyond the allowable limit of the material (the safety factor is set according to the material specification).
- Deformation control: long-term cumulative settlement or displacement $\leqslant$ 30 mm (target of pilot section); enlarge project according to the specification and risk assessment.
- Thermal stability: the degradation range of frozen soil along the route is controlled, and the rate of temperature change of frozen soil in key section is $\leqslant$ 0.5℃/year (long-term monitoring target).
- Water and soil pollution risk is controllable. The anti-seepage measures are verified by 100% weld joint inspection and leakage test.
- Monitoring and response: Real-time monitoring system is established, and the protection and emergency process is automatically triggered when the key parameters exceed the limit.

Numerical modeling and experimental verification scheme

Overall approach to modeling

A three-dimensional thermal-hydraulic-mechanical coupling model (THM) is developed to simulate the interaction between the pipeline and the frozen soil. The model includes phase change (freezing/ melting), nonlinear thermal properties of soil, coupling of pore water flow and effective stress, and elastic-plastic response of the pipeline structure. The model is used for design verification, sensitivity analysis, thermal disturbance prediction during construction and long-term operation assessment.

Model equations and key terms

- Heat conduction and phase transition:

$$
\rho c \frac{\partial T}{\partial t} = \nabla\cdot(k\nabla T) + S - \rho L \frac{\partial \phi}{\partial t}
$$

Where T is the temperature, ϕ is the ice fraction, L is the latent heat, and S is the external heat source (e.g. pipe heat dissipation, geothermal heat, etc.).

- Pore water (Darcy):

$$
\mathbf{q} = -\frac{k}{\mu} \nabla p
$$

conservation of mass：

$$
\frac{\partial (\theta)}{\partial t} + \nabla\cdot\mathbf{q} = 0
$$

- Mechanical equilibrium (elastic-plastic):

$$
\nabla\cdot\boldsymbol{\sigma} + \mathbf{b} = 0
$$

The constitutive relationship is based on a temperature-dependent elastic-plastic model with the frost heave stress term.

Modeling implementation steps (executable directly)

1 Data preparation: borehole sampling, physical property test of soil (thermal conductivity, specific heat, porosity, permeability, elastic modulus, frost heave curve), groundwater level and ground temperature profile, meteorological time series.

2. The mesh was divided into axial segments (0.1-0.5 m in the range of 0-5 m around the pipeline) and gradually thickened in the far field.

3. Boundary conditions: surface temperature time series, deep constant temperature boundary, groundwater flow boundary, and pipeline heat flux boundary (given by pipeline operating conditions).

4. Phase change treatment:explicit or implicit phase change terms are used to solve the equation, and the effects of supercooling and non-equilibrium phase change are considered.

5. Coupled solution: the thermal-hydraulic-hydrodynamic coupling iterative solution, the time step is minute or hour in the fast stage, and day or month in the long-term evolution.

6. Calibration and validation: The model parameters were calibrated and sensitivity analysis was performed with the observation data of the pilot section (temperature profile, sedimentation, seepage).

Sensitivity and Uncertainty Analysis

- The key parameters are thermal conductivity, permeability, frost heave stress curve, insulation layer thickness and heat flux of the pipe surface.
- Methods: Multi-parameter uncertainty analysis was performed by single parameter scanning and Latin hypercube sampling (LHS).
- The criterion is that if a parameter causes the key index to exceed the limit, the redundancy or the improvement of the structure should be added in the design.

Simulation input sample (text format, convertible directly)

`

```
DOMAIN:
  lengthalongpipe: 200 m
  lateral_extent: 50 m
  depth_extent: 30 m
MATERIALS:
  permafrost:
    density: 2000 kg/m3
    thermal_conductivity: 1.5 W/mK
    specific_heat: 900 J/kgK
    permeability: 1e-8 m/s
    elastic_modulus: 50 MPa
    frostheavecurve: file:frost_heave.csv
PIPE:
  outer_diameter: 0.5 m
  wall_thickness: 0.02 m
  surfaceheatfluxtimeseries: file:pipeheatflux.csv
BOUNDARY:
  surfacetemperaturetimeseries: file:surfacetemp_hourly.csv
  deep_temperature: -2 C
INITIAL:
  initialgroundtemperature: -5 C
  initialicefraction: 0.6
SIMULATION:
  total_time: 10 years
  time_step: 1 day
```

OUTPUT:
  temperature: daily
  displacement: monthly
  pore_pressure: daily
  pipe_strain: daily

`

Design and Construction Technical Details

Piping laying method and support system

- The laying method is selected according to the frozen soil type, terrain and maintenance accessibility. The general rule is that the continuous frozen soil area should be laid above ground, semi-buried or fully buried to avoid the settlement caused by the degradation of frozen soil, while the intermittent frozen soil area can be laid shallowly and combined with the insulation layer.
- Support system: The height-adjustable bearing (expansion and height-adjustment mechanism) is used in the overhead section, and the deep foundation or pile foundation is used in the semi-buried section to avoid the influence of active layer.
- Expansion joints and compensators: Expansion compensators are installed every 200-500 m in long straight sections. The type of compensator is selected according to the axial displacement and temperature difference (the combination of bellows compensator and sliding support).
- Guidance and fixing of the pipe: Guidance device is set at the bearing to control the axial displacement and avoid excessive bending stress.

Insulation and thermal management

- Passive insulation: Multi-layer composite insulation layer (inner anti-corrosion metal layer + polyurethane foam + outer steel shell), key joints use vacuum insulation plate (VIP).
- Active thermal management: using electric heating tape or circulating heat medium to maintain the surface temperature of the pipeline when necessary, or setting up cold source isolation and thermal barrier in high-risk sections.
- Surface cover: Insulation layer (backfill, insulation board) above the pipeline and vegetation restoration to reduce surface thermal disturbance.
- The design of thermal bridge is adopted between the support and the crossing point, and the thermal isolation pad is set between the support foundation and the pipeline.

Seepage prevention and foundation reinforcement

- Seepage barrier: HDPE or cement-based composite seepage barrier is used in sensitive water body or high permeability section, and 100% welds are inspected.
- Foundation reinforcement: using grouting, deep mixing or cement soil pile to reinforce the weak foundation, and pile foundation to subside the bearing foundation to the stable layer when necessary.
- Soil improvement: In the section with high risk of frozen soil degradation, cooling piles or artificial freezing technology should be used to stabilize the foundation during construction, and surface insulation or low thermal conductivity materials should be used for long-term.

Low Temperature Welding and Joint Design

- Welding process: Low temperature welding process (preheating, postheating, low temperature welding material) was adopted, and the weld was tested by nondestructive testing (UT/RT) and mechanical property test.
- Flange and seal: The flange is made of metal gasket or low temperature elastic gasket, and the flange bolt is treated with anti-corrosion and anti-loosening measures.
- Replaceable flange: Replaceable flange or flexible joint is used in critical section for maintenance and replacement.

Material specifications and low-temperature test plan

List of materials and performance requirements

- Pipe material: Low-temperature toughness steel (e.g., X70 or as specified in project specifications), with Charpy impact energy meeting low-temperature toughness requirements (-40°C or below).
- The insulation materials are polyurethane closed-cell foam, vacuum insulation board (VIP), moisture-proof layer and steel shell.
- The anti-seepage film was HDPE with a thickness of ⩾ 2.0 mm, and passed the low temperature brittleness test.
- Welding material and sealing material: low temperature compatible welding rod/wire and low temperature elastic sealing material.
- The bearing material is low temperature resistant alloy or anti-corrosion treated structural steel, and the sliding surface is PTFE or low temperature lubricating material.

Test items to be completed (before project implementation)

- Metal materials: Charpy impact test, low temperature tensile test, fatigue test, corrosion rate test, mechanical properties of welded joints and nondestructive testing.
- Thermal insulation materials: thermal conductivity test (-20℃,0℃, +20℃), freeze-thaw cycle and wet heat aging test, compressive strength.
- Seepage resistance: tensile strength, weld strength, low temperature brittleness, permeability.
- Concrete and grouting materials: compressive strength, freeze-thaw cycle resistance, permeability coefficient.
- Sealing materials: Low temperature elasticity and aging test.

Test Method and Acceptance Criteria (Directly Implementable)

- The test was performed according to national or international standards (e.g. GB, ISO, ASTM, etc.), and the original data, test conditions, photos and conclusions were given in the test report.
- Acceptance criteria: Charpy impact energy ⩾ 27 J (-40℃); thermal conductivity deviation of insulation material ⩽ 10%; weld strength of waterproof membrane ⩾ 90% of substrate.

Construction Technology Card and Pilot Test Implementation Route

Definition and objectives of the pilot-scale phase

- Pilot section length: recommended 200–500 m (including different typical geological sections: overhead, semi-buried, wetland/high permeability sections).
- The purpose of the pilot test is to verify the laying method, bearing system, insulation structure, welding process, monitoring system and emergency disposal process, and to obtain the operation data for simulation calibration and scale-up judgment.

Construction process card (step-by-step, executable directly)

1 Site preparation: cleaning, temporary construction, temporary drainage and construction road.

2. Geological drilling and in-situ testing: drilling holes at designed points and conducting SPT, thermal conductivity, and groundwater level observation.

3. Foundation and bearing construction: pile foundation or strip foundation construction, bearing installation and height correction.

4. Pipe pre-fabrication and welding: pipe segment welding, external anti-corrosion and insulation layer initial installation in the pre-fabrication yard, after the weld non-destructive testing qualified, transfer.

5. Installation of laying and support: pipe section is placed, support is fixed, expansion joint and guide device are installed.

6. Insulation and outer protection construction: insulation layer spraying or panel installation, outer protection steel shell installation, joint sealing.

7. Seepage prevention and foundation treatment: Seepage prevention membrane laying and grouting reinforcement were carried out in sensitive section.

8. Pressure test and leak detection of pipeline: hydraulic test and leak detection are carried out according to 1.5× design pressure.

9. The sensors were installed and connected to the PLC/SCADA system for temperature, pore water pressure, strain and settlement.

10. Test run and data collection: Complete the cooling/heating cycle according to the test run plan and record the data.

1 1. Acceptance and report: Submit the trial operation report, material test report, simulation calibration results and enlargement suggestion.

Construction quality control points (must be recorded)

- weld nondestructive testing records and mechanical test reports;
- 100% inspection record of the anti-seepage membrane weld;
- The verticality and elevation of bearing and foundation are recorded;
- Sampling and testing of thermal insulation layer thickness and thermal conductivity;
- Sensor calibration certificate and installation records.

Monitoring system, control and emergency plan

Monitoring system composition (must be deployed)

- Temperature monitoring: Surface and temperature profiles at different depths along the route (50–200 m, 10–50 m in key sections).
- Pore water pressure: The higher the permeability section, the more points are placed around the foundation (spaced 50–200 m apart).
- Strain and displacement: axial and circumferential strain gauges, displacement sensors, settlement plates and inclinometers.
- Environmental monitoring: groundwater chemical sampling and methane monitoring (permafrost area).
- The monitoring of equipment includes the surface temperature of the pipeline, the temperature of the insulation layer, the flow rate and pressure, and the temperature of the flange.

PLC/SCADA Control Strategy (Direct Deployment)

- Data collection frequency: key points 1 min; routine points 10–60 min.
- Alarm threshold examples: local temperature rise rate> 0.5℃/day; abnormal rise of pore water pressure; pipeline strain exceeds limit; settlement rate exceeds limit.
- Automatic protection actions: automatic load reduction or shutdown, bypass activation, local heating or cooling, and maintenance team notification.
- Data management: Local historical database + cloud backup, automatically generate daily/weekly/monthly reports.

Emergency Plan (Directly executable)

- Leakage event: immediately close the relevant valve → start emergency pumping and blocking → grouting or temporary casing repair → environmental monitoring and report to the regulatory department.
- Freeze-thaw induced settlement: temporary support or reinforcement pile is used to relieve the load and repair the foundation, and the insulation strategy is evaluated and adjusted.
- Failure of weld or joint: cut the section and enable the bypass → replace the joint or sleeve repair → nondestructive testing retest.
- Monitoring alarm response process: Alarm classification (red/yellow/blue), each level defines response time, responsible person, emergency measures and record forms.

Route and Criteria for Determining the Transition from Pilot to Scale-up

Phased delivery

1 . Single-stage pilot testing (200–500 m)

- Objective: To verify the laying method, welding process, insulation structure, monitoring system and emergency procedure.
- Conclusion: The 1-year operation data collection was completed, and the key indexes (settlement, strain, frozen soil temperature) were within the allowable range.

2. continuous section test (1−5 km)

- Objective: To verify the parallel section thermal management, long-term stability and maintenance strategy.
- Conclusion: The operation of the system for 2 years, the environmental impact is controllable, the maintenance cost and energy consumption assessment meet the owner's requirements.

3. Longline amplification (>5 km)

- Objective: To scale up the project and run it for a long time, and to pass the regulatory approval of economic and environmental impact assessment.
- Conclusion: The technology, economy and environment meet the threshold of amplification and pass the third party review.

Decision criteria (must be quantified)

- Technical: maximum circumferential strain ⩽ 0.8 × material yield strain; maximum settlement ⩽ 30 mm (pilot scale) or adjusted according to scaling target; frozen soil degradation depth ⩽ 20% beyond the initial active layer depth.
- The groundwater chemical index was not significantly over the standard, and the methane release was controlled and mitigated.
- Economy: The energy consumption and maintenance cost per unit are within the acceptable range (the threshold is set by the owner).
- Reliability: MTBF and maintenance response time of critical equipment meet contract requirements.

List and ready-to-use templates

1 Engineering Design Document (Complete Version): Includes calculation book, detailed construction drawings, and construction process card.

2. THM simulation input sample and explanation: can directly import the text template of the simulation software.

3. Material test plan and test record form (Excel/CSV field examples).

4. Construction drawing list and CAD drawing specifications (including detailed descriptions, layers, symbols, and frame templates for each drawing).

5. BOM and equipment specifications sample (Excel/CSV).

6. The configuration diagram of monitoring and control system and the logic description of PLC/ SCADA are also provided.

7. Emergency plan and maintenance manual template.

8. Pilot implementation timeline and task allocation table (Gantt chart field example).

9. Acceptance form and performance evaluation template.

10. Enlarge the report template.

Key template example fields

- Material test record form fields: Sample number, sampling point, test item, test conditions, original data file, test conclusion, testing institution, report number.
- Monitoring data template (CSV): Time, LocationID, Depthm, TempC, PorePressurekPa, PipeStrainmicrostrain, Settlementmm, Flowm3h, Pressure_bar, AlarmFlag, Notes.
- Construction inspection checklist fields: Process, Responsible Person, Inspection Item, Inspection Result, Recorder, Date, Attachment (Photo/Report).

Risk assessment and mitigation measures (technical level)

Key risk items and mitigation strategies

- The measures to mitigate the settlement caused by the degradation of frozen soil are as follows: using elevated or deep foundation, adding insulation layer, local foundation reinforcement, long-term monitoring and quick response.
- Freeze blockage and local thermal runaway: mitigation: zone control, bypass and local heating, regular backwash and maintenance.

- Weld joint failure: mitigation: strict welding process, 100% nondestructive testing, critical joint redundancy design.
- Groundwater pollution risk: mitigation: anti-seepage membrane and secondary protection, leakage detection and emergency sealing scheme.
- Extreme weather or earthquakes: Mitigation: Seismic design, flexible connections, emergency shutdown and rapid repair procedures.

Implementation timeline (pilot phase example: 12 months)

1 preparatory phase 0-2 months: project initiation, site permits, drilling and preliminary surveys.

2. The material low temperature test and the preliminary establishment of the simulation model were carried out during the test stage from February to April.

3. Pre-fabrication and procurement from April to June: pipe section pre-fabrication, equipment procurement, welding materials and thermal insulation materials arrive.

4. Construction stage: foundation, support, laying, insulation, sensor installation.

5. Trial operation and calibration 9-1 1 : system debugging, trial operation, data acquisition and simulation calibration.

6. evaluation AND ACCEPTANCE 1 January to December: performance evaluation, acceptance report, and scaling up recommendations.

Appendix: Sample calculations, simulation input snippets, and BOM samples

Appendix A: Simplified Formula for Estimating Swelling Stress

The frost stress can be estimated by the constraint stress caused by the volume expansion.

$$
\sigma{f} \approx E \cdot \epsilon{f}
$$

The equivalent elastic modulus of soil or structure is E, and the frost heave strain is ε _f, which is given by the frost heave curve.

Appendix B: Simplified Simulation Input Examples (Refer to the THM Simulation Input Examples above)

Appendix C BOM sample (CSV field example)

```
Item,Name,Spec,Material,Qty,Unit,TechReq,Remark
1,Pipe,OD500x20,LowTempSteel,200,m,Charpy -40C>=27J,Pre-fabricated
2,Insulation,PU Foam,lambda<=0.025,50,m3,Frost cycle>=200,Include VIP at joints
3,HDPE Membrane,2.0mm,HDPE,500,m2,Heat weldable,10% spare
4,Expansion Joint,AxialComp,Metal,10,pcs,Axial travel +/-50mm,Include flange
5,Temperature Sensor,PT100,-50~150C,20,pcs,Accuracy 0.1C,With cable
```

The "frozen soil-pipe coupling" problem in the pipeline project in the permafrost area is provided with a complete engineering technology delivery, including modeling, design, materials, construction, monitoring, emergency and scale-up route, which is enough to support the construction, operation and scale-up decision of the pilot section.

Geology and Pipeline Engineering Technology in Permafrost Area (permafrost-pipeline coupling)

It can be directly used for pilot testing and bidding.

1 The engineering design document (full version) includes the design basis, calculation book, detailed construction drawings, construction process card, and acceptance form.

2. The input set and calibration procedure of the THM (thermal-hydro-mechanical) simulation are given, including the example of the text format, the suggestion of the mesh and time step, and the scheme of the sensitivity analysis.

3. Material test plan and record sheet (Excel/CSV field examples).

4. Draft of construction bidding package: technical specifications, acceptance clauses, quality assurance and delivery requirements.

5. Monitoring and PLC/SCADA configuration specifications: sensor list, deployment points, alarm logic, and data templates.

6. Emergency plan and maintenance manual template.

7. Pilot implementation schedule (Gantt field) and task allocation table.

8. BOM and equipment specifications sample (CSV/table).

The complete engineering design book and all the ancillary templates and examples can be used by the engineering team to carry out pilot implementation, bidding and simulation calibration.

---

1 Project Overview and Engineering Objectives

1 1. Project Background and Objectives

The main risk sources are frost heave, thaw settlement, thermal disturbance and seepage change caused by the frozen soil-pipe coupling.

1 2. Pilot and Scale-up Objectives (Quantitative)

- The length of the pilot section is 200-500 m (including typical geological sections: overhead, semi-buried, wetland/high permeability sections).

- The target of pilot test is to collect the data of one year of continuous operation and the key indexes (sinking, strain, frozen soil temperature) meet the following criteria.

- The critical criteria (Pilot scale) are: maximum cumulative settlement $\leqslant$ 30 mm; maximum circumferential/axial strain $\leqslant$ 0.8 $\times$ allowable strain of material; and the depth of frozen soil degradation $\leqslant$ 20% beyond the initial active layer depth.

- Scale-up target: after meeting the pilot-scale determination criteria, scale up to 1–5 km (continuous section) and then to long-line scale-up (>5 km).

---

2 Design Basis, Field Data and Necessary Preparatory Work

2.1 Required on-site data (must be completed before construction)

- Borehole sampling: Boreholes are drilled along the proposed route at intervals of 50–200 m (with higher density in critical sections), with depth coverage exceeding the impact depth of reservoir/ pipeline (recommended ≥30 m).
- The physical properties of soil samples were tested, including thermal conductivity, specific heat, porosity, permeability, frost heave curve, elastic modulus and shear strength.
- Groundwater level and velocity observations: seasonal variation records (at least 1 year or historical data).
- Geothermal profile: Temperature profile from surface to deep (≥30 m) and daily/hourly meteorological data.
- Topography, vegetation and surface cover were investigated.

2.2 Design hypothesis (replaceable with field data)

- Initial ground temperature (example): -5℃ (deep constant temperature); annual average surface temperature-8℃.
- Initial ice fraction in soil (example): 0.5–0.8 (adjusted according to frozen soil type).
- Pipeline material: Low-temperature toughness steel (e.g. X70 grade), Charpy impact energy ≥ 27 J (-40℃).
- The design safety factor is 1.5 for the structure and 1.2 for the thermal capacity redundancy.

---

3 THM Numerical Modeling and Simulation Suite (Directly Executable Implementation)

3.1 Model objectives and output indicators

Objective: To predict thermal disturbance, frost degradation, seepage change, frost heave stress and pipeline strain/settlement caused by pipeline operation and construction, and to provide quantitative basis for design optimization and scale-up judgment.

The main output indexes are temperature field, ice phase distribution, pore water pressure, surface/ pipe top settlement, pipe circumferential and axial strain, and seepage path change.

3.2 Systems of Equations and Numerical Methods (Summary)

- Thermal conduction with phase change (latent heat term): \\(\\rho c \\frac{\\partial T}{\\partial t} = \\nabla\\cdot(k\\nabla T) + S - \rho L \frac{\partial \phi}{\partial t}\\)。
- Porous flow (Darcy) and mass conservation: \\(\\mathbf{q} = -\\frac{k}{\\mu}\\nabla p\\), \\(\\frac{\\partial \\theta}{\\partial t} + \\nabla\\cdot\\mathbf{q} = 0\\).
- Mechanical equilibrium: \\(\\nabla\\cdot\\boldsymbol{\\sigma} + \\mathbf{b} = 0\\), the constitutive model is temperature dependent and includes frost heave stress term.
- Phase transition treatment: explicit or implicit phase transition solution, considering supercooling and non-equilibrium phase transition (if necessary).

3.3 Grid, time step, and boundary conditions (apply directly)

- The spatial grid was set as 0-5 m fine mesh (0.1-0.5 m element) around the pipeline, and gradually thickened to 1-5 m in the far field. The axial direction was subdivided by pipe sections (0.5-2 m element length).
- Time steps: minutes or hours for rapid phases of cooling/heating or construction; days or weeks for long-term evolution.
- Boundary conditions: Surface temperature time series (hourly/daily); Deep constant temperature boundary (depth ≥ 30–50 m); Groundwater flow

boundary (velocity/water level).

- Initial conditions: initial temperature field, initial ice fraction, initial pore water pressure.

3.4 Simulation input example (text, convertible directly)

```
DOMAIN:
  lengthalongpipe: 500 m
  lateral_extent: 50 m
  depth_extent: 30 m
MATERIALS:
  permafrost:
    density: 2000 kg/m3
    thermal_conductivity: 1.5 W/mK
    specific_heat: 900 J/kgK
    permeability: 1e-8 m/s
    elastic_modulus: 50 MPa
    frostheavecurve: file:frost_heave.csv
PIPE:
  outer_diameter: 0.5 m
  wall_thickness: 0.02 m
  surfaceheatfluxtimeseries: file:pipeheatflux.csv
BOUNDARY:
  surfacetemperaturetimeseries: file:surfacetemp_hourly.csv
  deep_temperature: -2 C
INITIAL:
  initialgroundtemperature: -5 C
  initialicefraction: 0.6
SIMULATION:
  total_time: 10 years
  time_step: 1 day
OUTPUT:
  temperature: daily
  displacement: monthly
  pore_pressure: daily
  pipe_strain: daily
```

3.5 Calibration and sensitivity analysis (run directly)

- The calibration process is to adjust the thermal conductivity, permeability, frost heave curve and contact thermal resistance with the observation data of the pilot section (temperature profile, settlement, pore water pressure, strain).
- Sensitivity analysis: single parameter scan and Latin hypercube (LHS) multi parameter sampling were performed on the key parameters (thermal conductivity, permeability, insulation thickness, heat flux of pipe surface) to obtain the distribution of maximum settlement, maximum strain and depth of frozen soil degradation.
- Conclusion: If a parameter causes the key index to exceed the limit, the design should increase the redundancy (adding the insulation, improving the support, increasing the foundation reinforcement).

---

4 Piping laying method, support and expansion compensation (can be directly constructed according to the code)

4.1 Principles for the Selection of Installation Method (Directly Applicable to Engineering)

- The overhead laying is preferred for continuous frozen soil area or active layer depth and foundation unstable section.
- The semi-deep/ shallow buried laying is suitable for the discontinuous frozen soil or the restricted terrain, and the insulation and bearing design should be strengthened.
- Full buried: only when foundation is stable, the influence of frozen soil is controllable and construction cost is permissible, it is necessary to strictly prevent seepage and heat preservation.

4.2 Support system and foundation (can be constructed directly)

- The support is adjustable in height and the foundation is either pile or deep foundation, which penetrates the active layer to the stable layer.
- Semi-submerged bearings: flexible cushion (PTFE or low-friction material) with sliding surface, bearing foundation reinforced and expansion compensation provided.
- Expansion compensation: Axial compensators (a combination of bellows or sliding bearings) are installed every 200-500 m, and the specifications of the compensators are calculated according to the temperature difference and axial displacement.

4.3 Design Points of Support and Guide

- The bearing capacity of the support is calculated according to the maximum load (the pipeline's own weight, the medium, the ice load, the wind and snow), and a safety margin of 20-30% is reserved.
- The guide device should limit the lateral displacement and allow the axial sliding, the material should be resistant to low temperature and have anti-corrosion treatment.
- The thermal isolation pad is set at the connection between the bearing foundation and the pipeline to reduce the thermal bridge effect.

---

5 Insulation, Anti-freezing and Heat Management (Directly Implementable)

5.1 passive thermal insulation construction (can be purchased and constructed directly)

- Inner layer anti-corrosion: The outer wall of the pipeline is first made of anti-corrosion layer (epoxy or polymer coating).
- Insulation layer: Polyurethane closed-cell foam (sprayed or prefabricated) thickness calculated according to heat loss target; key joints are reinforced locally with VIP (vacuum insulation panels).
- The outer sheath is made of anti-corrosion steel shell or composite sheath, and the outer waterproof layer and mechanical protection layer are covered.

5.2 Active thermal management (on-demand deployment)

- Electric heating belt: electric heating belt is set in high risk section or crossing point and connected to PLC control.
- Circulating heat medium: the surface temperature of the pipeline is maintained by circulating heat medium when needed.
- Artificial freezing: use artificial freezing technique to stabilize foundation during construction (if necessary).

5.3 Surface and thermal bridge treatment

- The ground surface was backfilled with thermal insulation material (low thermal conductivity filler) and vegetation was restored.

---

6 Seepage Prevention,Foundation Reinforcement and Permafrost Improvement

6.1 anti-seepage measure

- HDPE impermeable membrane: thickness ⩾ 2.0 mm, heat fusion of weld, 100% weld inspection and maintenance opening.
- Secondly, the cement-based composite anti-seepage layer or double-layer anti-seepage system is used in sensitive sections.

6.2 Foundation reinforcement methods

- Grouting reinforcement: chemical or cement grouting to seal the high permeability layer and void.
- Deep mixing/cemented soil piles: used to improve the bearing capacity of weak foundation.
- Pile foundation: The bearing foundation is pile foundation which passes through active layer to stable layer.

6.3 permafrost improvement

- The artificial freezing method is used to stabilize the foundation during the construction period, and the surface insulation or the replacement of low thermal conductivity materials can be used to reduce the thermal disturbance in the long term.

---

7 Low temperature welding, joint and flange

7.1 Welding Technology and Quality Control

- Welding process: low temperature compatible welding materials, preheating and post-heating process; welding personnel need low temperature welding qualification.
- Nondestructive testing: UT/RT/magnetic particle/penetrant testing shall be performed at 100% of weld grade; mechanical tests shall be conducted on critical joints.
- Weld record: each weld record the welder, batch number of welding material, welding parameters, test report and photos.

7.2 flange and seal

- The flange design is metal gasket or low temperature elastic gasket, and the bolt is anti-loosening and anti-corrosion treatment.
- Replacement flange: The key section is equipped with replaceable flange or sleeve joint for maintenance.

---

8 Material specifications and low-temperature test plan

8.1 Key Materials and Performance Requirements (Example)

- The pipe material is low temperature toughness steel (e.g. X70) with Charpy impact energy ⩾ 27 J at-40℃.
- Insulation material: polyurethane closed-cell foam, thermal conductivity ⩽ 0.025 W/(m·K).
- HDPE anti-seepage film: the thickness is ⩾ 2.0 mm, and the low temperature brittleness is qualified.
- The welding material was low temperature compatible welding wire and welding rod, and the mechanical properties of the weld were qualified.

8.2 Test items to be completed (before project implementation)

- Metal materials: Charpy impact, low temperature tensile, fatigue, corrosion test, mechanical test of welded joint.
- Thermal insulation materials: thermal conductivity (multi-temperature point), freeze-thaw cycle, wet heat aging, compressive strength.
- Seepage resistance: tensile strength, weld strength, low temperature brittleness, permeability.
- Concrete/grouting: compressive strength, freeze-thaw resistance, permeability coefficient.

8.3 Test record form fields (CSV/Excel template)

`

SampleID,Location,MaterialType,TestType,TestStandard,TestConditions,RawDataFile,Result,Conclusion,Lab,ReportNo,Date

`

---

9 Construction process card (per procedure, executable directly)

9.1 Preparations before construction

- Site cleaning, temporary construction, construction road, temporary drainage.
- On-site inspection of equipment and materials (BOM verification and factory inspection report).
- The sensor and monitoring system are pre-wired.

9.2 Main construction steps (item by item)

1 Drilling and foundation test: drilling and sampling at the designed location.

2. Foundation and bearing construction: pile foundation/strip foundation construction, bearing installation and correction.

3. The welding, anticorrosion, insulation and nondestructive testing are completed in the prefabrication yard.

4. Piping laying: position, support fixing, guide device installation, expansion compensator installation.

5. Insulation and outer protection: insulation layer spraying/plate installation, outer protection steel shell installation, joint sealing.

6. Seepage prevention construction: laying HDPE anti-seepage film in sensitive section and welding inspection.

7. Pressure test and leakage detection: The hydraulic test was carried out at 1.5× the design pressure and the results were recorded.

8. Sensors installation: temperature, pore water pressure, strain and settlement sensors were installed and calibrated.

9. System commissioning and trial operation: Data acquisition and simulation calibration are completed according to the trial operation scheme.

9.3 Quality control points (must be recorded)

- Nondestructive testing report of weld; Inspection record of anti-seepage membrane weld; Sampling inspection of insulation layer thickness; Record of bearing elevation and verticality; Sensor calibration certificate.

---

10 Monitoring System, PLC/SCADA and Alarm Logic

10.1 Monitoring points and frequency (recommended)

- Temperature profile: every 50-200 m along the line (10-50 m in key section), depth 0.5 m, 1.0 m, 2.0 m, 5.0 m; sampling frequency: 1 min (real-time) at key points, 10-60 min at regular points.
- Pore water pressure: every 50–200 m across wetland/high permeability section; sampling frequency 10–60 min.
- Strain/displacement: pipe circumferential/axial strain gauge, support displacement sensor, settlement plate; sampling frequency 1 min (key point).
- Environmental monitoring: groundwater chemical sampling and methane monitoring (permafrost area).

10.2 PLC/SCADA Control and Alarm Logic

- Data acquisition: The PLC collects data from field sensors and transmits it to SCADA, which stores historical data and generates reports.
- Alarm threshold examples: Temperature rise rate> 0.5℃/day (yellow); Abnormal rise of pore water pressure (yellow); Pipeline strain exceeds limit (red); Settlement rate exceeds limit (red).

- Automatic protection actions: Yellow-level alarm notifies maintenance and records; Red-level alarm automatically reduces load/ceases operation, activates bypass, starts local heating/cooling and notifies emergency team.
- Communication protocol: Modbus TCP/OPC UA; remote access via VPN with TLS encryption.

10.3 Data Template (CSV Field)

`

Time,LocationID,Depthm,TempC,PorePressurekPa,PipeStrainmicrostrain,Settlementmm,Flowm3h,Pressure_bar,AlarmFlag,Notes

`

---

1 1 Emergency Plan and Maintenance Manual

1 1.1 Major Emergency Scenarios and Response Procedures

- Leakage / leakage: immediately close the relevant valve → start emergency pumping and blocking → grouting or temporary casing repair → environmental monitoring and report to the regulatory authorities.
- Freeze-thaw induced settlement: temporary support or reinforcement piles are used to relieve the load and repair the foundation, and the insulation strategy is adjusted and long-term measures are evaluated.
- Failure of weld / joint: cut off the section and enable the bypass → replace the joint or sleeve repair → re-inspection by nondestructive testing.
- Monitoring alarm response: Alarm levels (red/yellow/blue), with response time, responsible person, emergency measures and record forms defined for each level.

1 1.2 Maintenance Plan (Periodic)

- Daily: Online monitoring, alarm processing, equipment operation records.
- Monthly: Equipment inspection, sensor calibration, valve and flange inspection.
- Annual: comprehensive inspection of structure and waterproofing, insulation layer testing, maintenance of refrigeration/ heating system.
- Spare parts management: key spare parts list, minimum inventory cycle and supplier contact information.

---

12 construction bidding

12.1 Technical specifications (example)

- The pipe material is low temperature toughness steel, and its chemical composition and mechanical properties are specified in Appendix A of the contract. The Charpy impact test at-40℃ is ≥ 27 J.
- Thermal insulation: closed-cell polyurethane foam, thermal conductivity ≤ 0.025 W/(m·K), freeze-thaw cycles ≥ 200.
- The anti-seepage membrane is HDPE 2.0 mm with hot-melted welds, and the weld strength is ≥ 90% of the base material.
- Welding: welder qualification, welding material batch number, 100% nondestructive testing (UT/ RT) of welds.
- Test and acceptance: material test report, weld inspection report, insulation thickness test, pressure test and leakage test report, sensor calibration certificate.

12.2 Delivery and Warranty

- Delivered documents: Factory inspection report, material qualification certificate, installation records, pressure test report, nondestructive testing report, sensor calibration certificate, trial operation report.
- Warranty: Critical equipment is covered for a minimum of 24 months; refrigeration/heating systems are recommended for 36 months of warranty and 5 years of spare parts coverage.

- The non-conforming items shall be rectified and re-accepted, and the rectification period and responsible party shall be specified in the contract.

---

13 Pilot implementation timeline (Gantt field example) and staffing

13.1 Gantt field (importable to project management tools)

```
TaskID,TaskName,StartDate,EndDate,DurationDays,Predecessors,Resource
1 Project started, 2026-01-01,2026-01-14,14, Project Manager
2, Drilling and Geological Testing, 2026-01-05,2026-02-05,32,1, Geological Team
3, Material test, 2026-01-10,2026-03-10,60,1, Laboratory
4. Simulation modeling and calibration, 2026-01-15,2026-03-31,75,2; 3. Simulation engineer
5, Prefabrication and Procurement, 2026-02-01,2026-04-01,60,3, Procurement and Prefabrication Plant
6, Construction and Laying, 2026-04-05,2026-07-05,92,5, Construction Team
7. Sensor Installation and Joint Debugging, 2026-06-20,2026-07-10,20,6, Monitoring Team
8. Trial Run and Data Collection, 2026-07-11,2027-07-11,365,7, Operation Team
9, Evaluation and Acceptance, 2027-07-12,2027-08-12,31,8, Evaluation Team
```

13.2 Suggested staffing (pilot scale)

- Project Manager 1; Site Engineer (Structural, Geology, Mechanical & Electrical, Control) 1 each; Construction Team (configured by process); Material Testing 2; Monitoring & Data Analysis 2; Safety & Quality Supervision 2.

---

14 Acceptance Form and Performance Evaluation Template

14.1 Trial run acceptance criteria (must be met)

- The maximum cumulative settlement was less than 30 mm (pilot test).
- The maximum circumferential/axial strain of the pipe is $\leqslant$ 0.8 × the allowable strain of the material.
- The depth of frozen soil degradation was less than 20% of the initial active layer depth.
- The sensor and monitoring system were in good working condition, and the data integrity rate was $\geqslant$ 99%.
- The qualified rate of weld and anti-seepage test is 100%.

14.2 Acceptance form fields (CSV)

```
CheckItem,Requirement,MeasuredValue,Unit,Result(Pass/Fail),Inspector,Date,Remarks
```

---

15 Risk Matrix and Mitigation Measures (Engineering Level)

Risk	Probability of Occurrence	Impact Level	Mitigation Measures
Permafrost degradation-induced settlement	Medium	High	Elevated or deep foundations, thickened insulation, foundation reinforcement, long-term monitoring		Weld joint failure	Low	High	Strict welding procedures, 100% non-destructive testing, critical joint redundancy
Groundwater leakage contamination	Low	High	Double-layer anti-seepage, leakage detection, emergency grouting plugging || Ice blockage/ thermal runaway	Medium	Medium	Zoned control, bypass, local heating, regular maintenance || Extreme climate/seismic	Low	High	Seismic design, flexible connections, emergency shutdown procedures

---

16 Appendix (Templates and sample files for direct copying)

Appendix A: Simulation Input Examples (text, see Chapter 3) -can be directly imported or converted to simulation software format

Appendix B: CSV template for material test records

```
SampleID,Location,MaterialType,TestType,TestStandard,TestConditions,RawDataFile,Result,Conclusion,Lab,ReportNo,Date
S-001,PK-01,PipeSteel,CharpyImpact,ASTM A370,-40C,raw/S-001.csv,30J,Pass,LabA,2026-001,2026-02-15
```

Appendix C: Monitoring Data CSV Template (see Chapter 10)

Appendix D: BOM CSV Example (see Chapter 8)

```
Item,Name,Spec,Material,Qty,Unit,TechReq,Remark
1,Pipe,OD500x20,LowTempSteel,200,m,Charpy -40C>=27J,Pre-fabricated
2,Insulation,PU Foam,lambda<=0.025,50,m3,Frost cycle>=200,Include VIP at joints
3,HDPE Membrane,2.0mm,HDPE,500,m2,Heat weldable,10% spare
4,Expansion Joint,AxialComp,Metal,10,pcs,Axial travel +/-50mm,Include flange
5,Temperature Sensor,PT100,-50~150C,20,pcs,Accuracy 0.1C,With cable
```

Appendix E: Construction Checklist CSV Template

```
TaskID,TaskName,CheckItem,Requirement,Result,Inspector,Date,PhotoRef,Remarks
```

SUBZERO RESIDENTIAL THERMAL BATTE
SYSTEM – OVERVIEW

CLIENT: SUBZERO TECHNOLOGIES DATE: 1/1/2020

NOTES

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10	2.08181	G2163\
2 1S	10018122	30.0300
2 10	Z.00127L	2.04 L01
12	2.036218	Z.80A11
5 10	5.C81832:	15.8+,561
18	C02175C	20.#5SD
3 10	2.70187C.	2.15 310
15	0.08187C.	2.1fl 5SC

OPERATING CONDITIONS

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10 0	0.56f9n.	20.58
3/0 0	6.3/78	20S 30
2/9. 59	6.7.3 t5	J01 20
1S 0	8 S27A	00t SG
TD 0	8.0/5 5	f201 50
/K 0	3.0/3 5.	00t C0

EQUIPMENT OVERVIEW

1. Heat Resistance Mix 1
2. Thermal Insulation
3. Stabilized Fill (SH4)
4. Rebar Mesh
5 Drainage Pipe

CONSTRUCTION

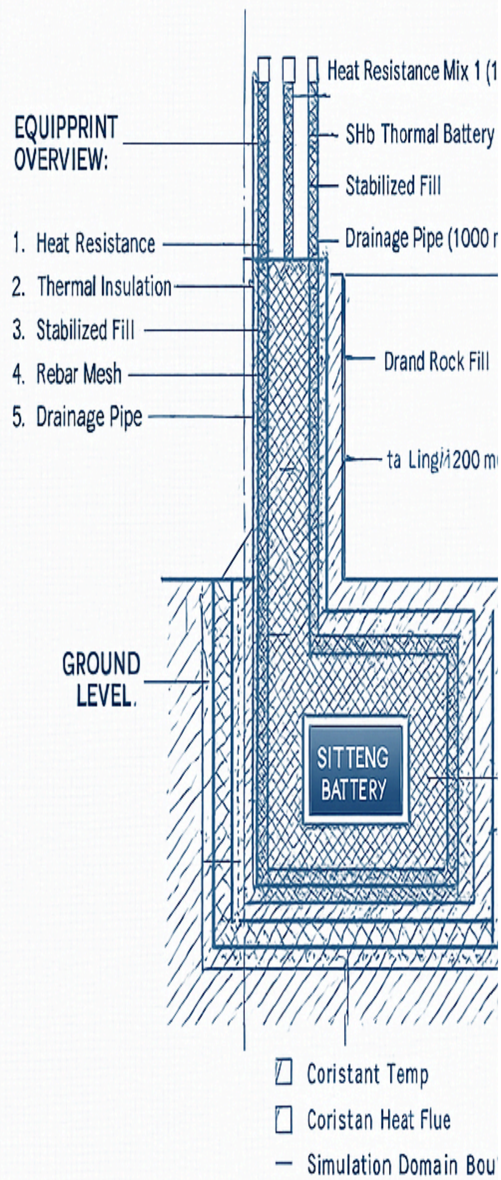
STAGE OF. DECK/REBRA/HESH:
T D D. (MN/DQ/YYYY)

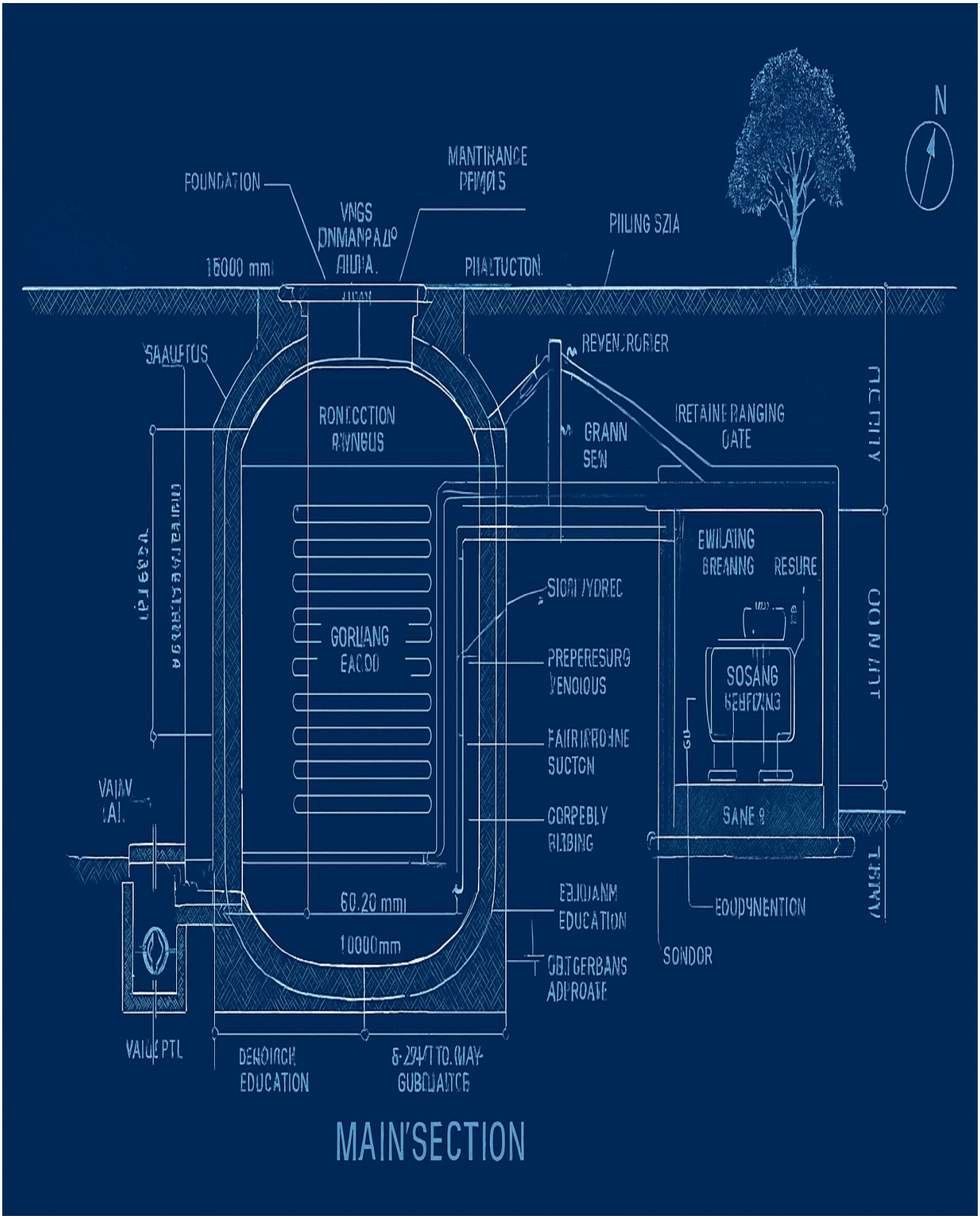
CONSTRUCTION

Stape of beck R.	Meb Mas.
(6P Date:	T B D.

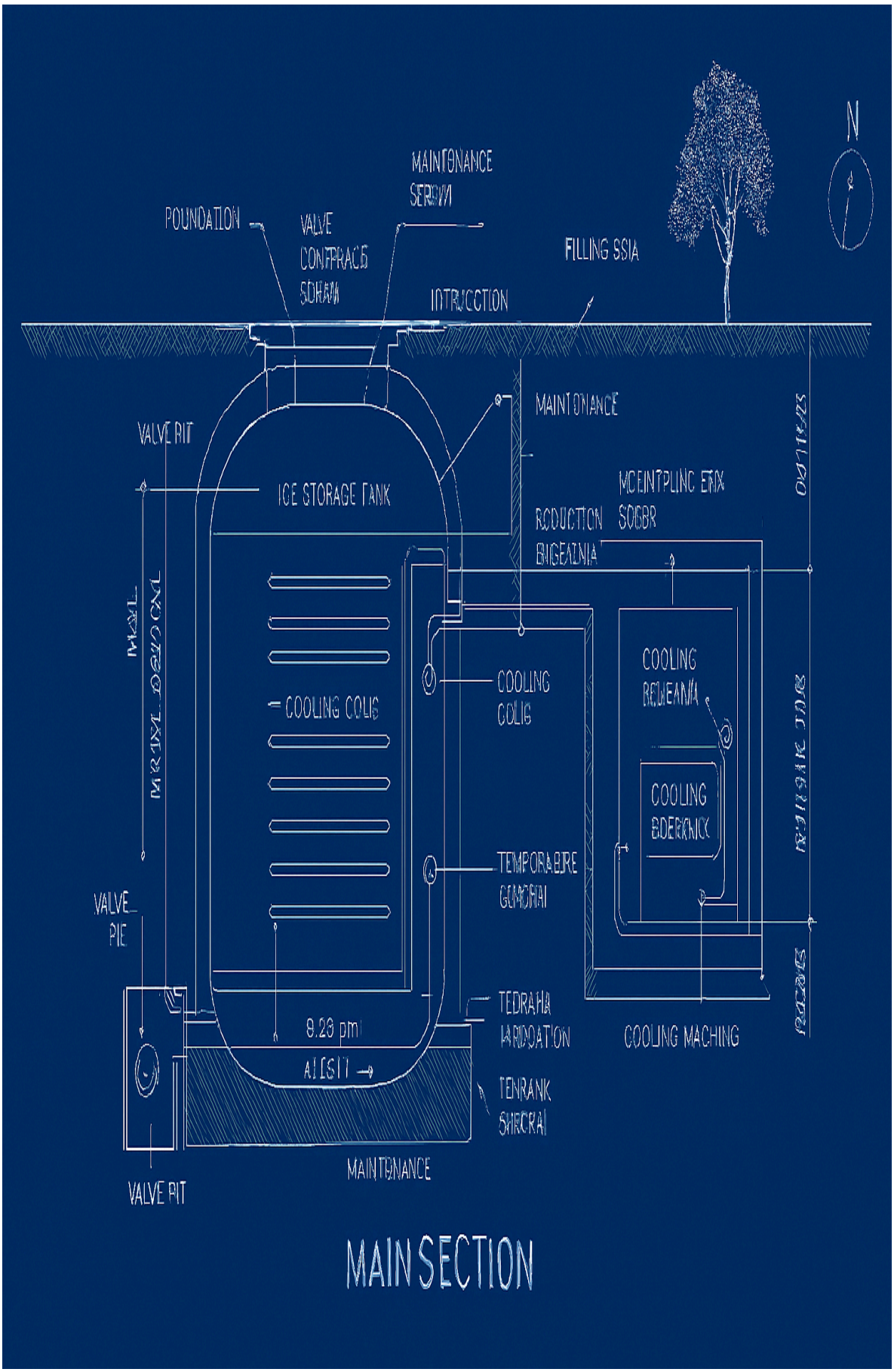
MATERIAL PARAMETERS

Density (HJg/N()	5:977335
SpecificHeat (2tF)	8.18834 II-
Thermal Condiucit / BtB)	#:389/:#D
Tim Please Temperature	1.82.8°C.





MAIN'SECTION



MAIN SECTION

Node detail: Flange and maintenance port 1:2 (text description)

summary

- Purpose: This detailed drawing is used for the construction and acceptance of sealing, drainage and bearing nodes at flange connections and maintenance openings. It is applicable to the junctions of low-temperature, insulation and anti-seepage systems.
- The ratio was 1:2.
- Applicable materials: low-temperature steel flanges, metal or elastic gaskets, low-temperature sealant, HDPE impermeable membrane, concrete lining, and insulation layer (polyurethane or VIP).

Size and material labels (example)

- Flange outer diameter: According to the design flange table (example 500 mm).
- Flange hole ring: the diameter, number and distance of bolt holes are according to the standard flange table.
- Bolt specifications: M24 × 3 × length (determined by flange thickness and gasket compression), material 10.9 or as specified in the contract.
- The gasket is a low temperature elastic gasket or metal gasket with a thickness of 2-4 mm and a low temperature resistance of-40℃.
- Maintenance access opening dimensions: Example 600 mm × 600 mm (verified against equipment and maintenance tool specifications).
- Drainage hole: 20–50 mm in diameter, with filter and check valve.
- The outer diameter of the casing is 20 mm larger than the penetration hole, and the water seal ring is made of rubber or polymer.

Structure details (per item)

- flange connection：
  - The flange surface was clean and free of burrs, the gasket was centered, and the bolts were tightened step by step in diagonal order and the torque value was recorded.
  - The anti-loosening measures of bolt are spring washer or nut fastener.
- Maintenance hatch seal:
  - The flange type maintenance port is composed of metal flange, elastic gasket and external fastening bolt. The inner side is sealed with low temperature sealant (if required).
  - The cover plate of the maintenance hole is equipped with lifting hole and positioning pin, and the outer side of the cover plate is equipped with anti-slip pattern or anti-slip pad.
- Seepage barrier penetration:
  - The HDPE impermeable membrane is sleeved and heat-sealed at the penetration points, with protective layers (corrosion-resistant coatings or metal cladding) applied over the welds.
  - The backfill compact layer (sand and gravel or fine stone mixture) is filled between the casing and the concrete lining, and the water stop ring is set.
- Insulation layer treatment:
  - The insulation layer (polyurethane spray or prefabricated plate) is stepped closed at the flange and maintenance opening and fixed by the pressure plate; the VIP plate is installed at the key point and pressed by the mechanical pressure plate.
  - The insulation outer sheath (steel shell or composite sheath) is flanged at the joint and sealed with waterproof sealant.

Welding, Inspection and Construction Sequence

- HDPE welds: Hot-melt welding, with weld width and parameters specified by material suppliers and standards; inspection openings left in each weld segment.

(200 mm of the end of the detection section).

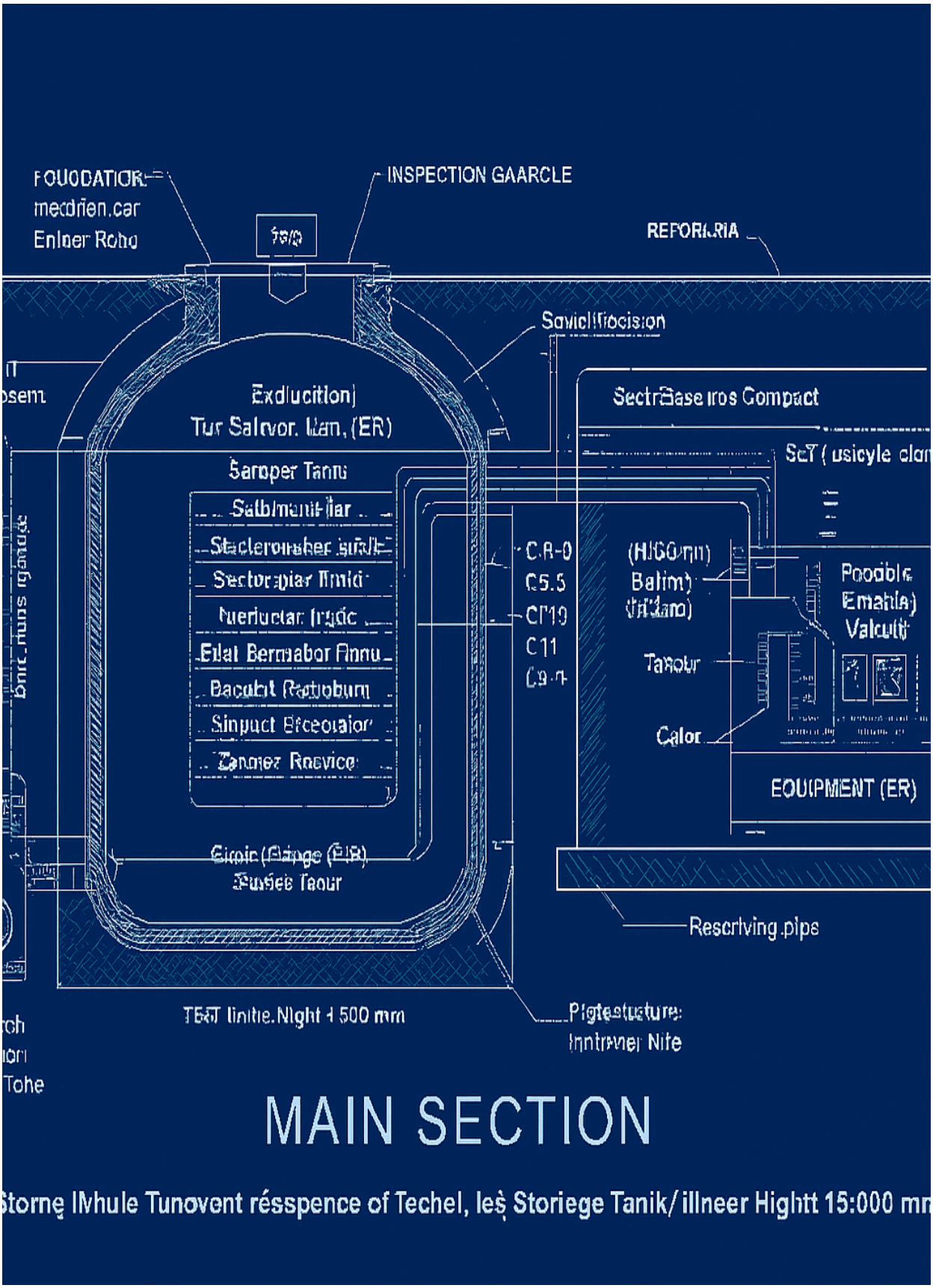
- Welding inspection: 100% visual inspection of welds plus random UT/RT testing (100% UT/RT for critical joints); inspection records include welder, welding material batch number, welding parameters, and test report number.
- The construction sequence (suggested) is as follows: casing pre-embedding → concrete lining pouring and curing → anti-seepage membrane laying and hot-melt welding → flange/inspection port installation (including gasket) → insulation layer construction → outer protective layer installation → weld and seal inspection → pressure test and leakage detection.

Key points for installation and acceptance

- Tightening torque records: torque values of each bolt are recorded and archived.
- Sealing test: After the flange and maintenance port are completed, a gas-tight or hydrostatic test shall be conducted (at 1.1−1.5× the design pressure, with the duration specified by the regulations).
- Acceptance of anti-seepage welds: 100% visual qualification rate of welds; UT/RT qualification for random or critical welds.
- Sampling inspection of insulation thickness: sampling inspection of insulation thickness and thermal conductivity, deviation must not exceed the design allowable value (example ±10%).
- The completion record includes the photo record of the whole node, the weld number, the test report, the torque record and the test report.

Drawing Legends and Annotations (For Drafters)

- Item: Material code (e.g., M-01: low-temperature steel; I-01: polyurethane insulation; V-01: VIP panel; L-01: HDPE 2.0 mm); Thickness/Specification; Bolt specifications and quantity; Flange code; Maintenance port code.
- Symbols: weld symbol, water stop ring symbol, drainage hole symbol, insulation pressure plate symbol, inspection port symbol.
- Legend: All material codes, symbols and brief descriptions are listed on the right side of the frame, which is convenient for construction and acceptance.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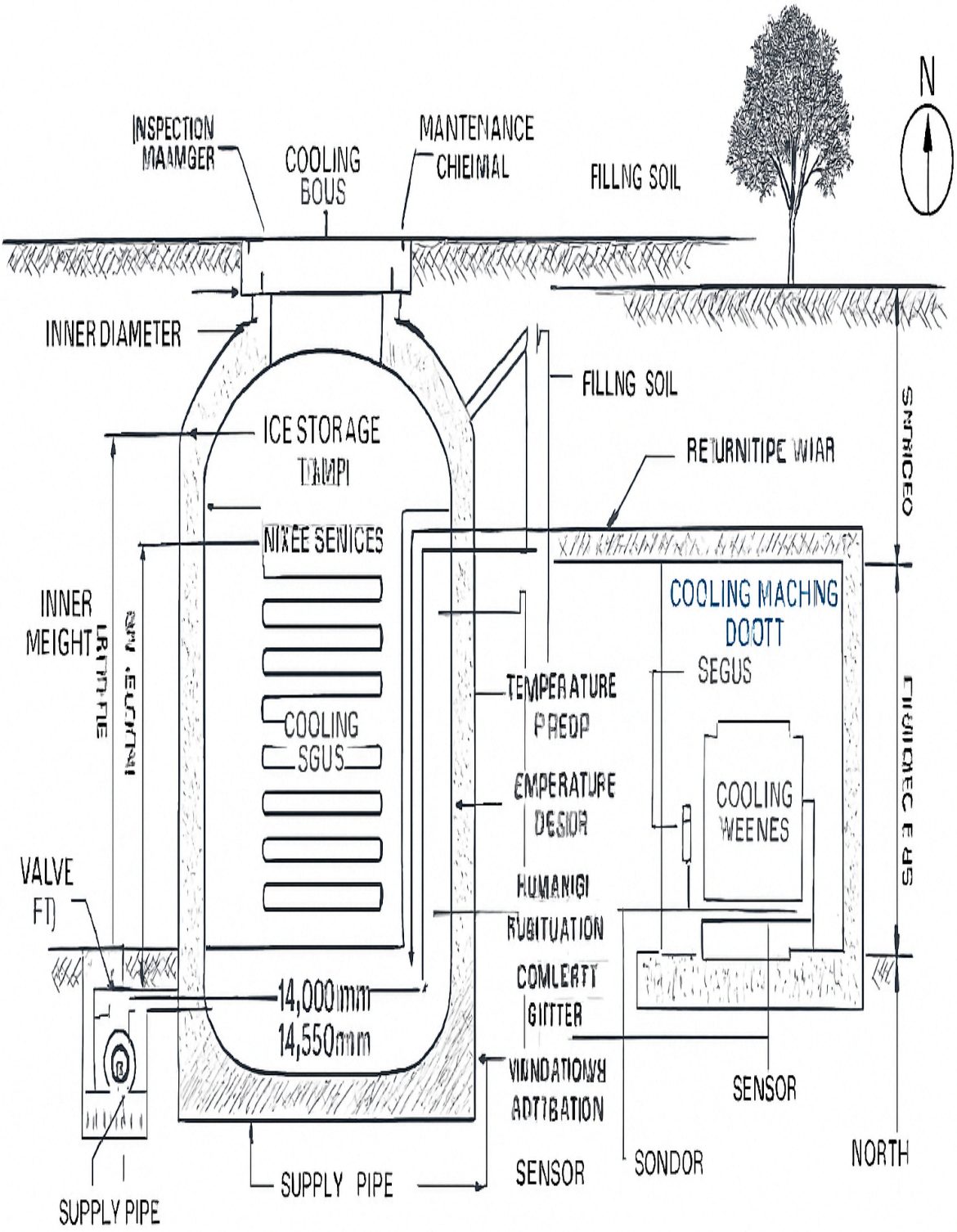


MAIN SECTION

Pipe isometric drawing (scale 1:50) -Text description (for CAD annotations and construction briefings)

I. SUMMARY

- Image Name: Piping Isometric
- Scale: 1:50
- Application: It is used for pipeline prefabrication, flange hole position table, bracket positioning, slope and slope direction verification, expansion joint and bypass arrangement, site installation and welding sequence guidance.
- Application scope: supply and return pipelines, valve wells, bypass and flushing ports between the reservoir and the equipment.

---

2 Elements that must be labeled in the diagram (item by item)

- Pipeline number: A unique identifier for each pipeline (e.g., P-101, P-102); it must match the isometric and plan view.
- Diameter and wall thickness: The nominal diameter (DN) and wall thickness (t) are specified, e.g., DN125×6.3 mm.
- Materials and Grades: Pipe material (e.g., low-temperature steel X70 / HDPE) and corrosion resistance grade (external coating, inner lining).
- Slope and Aspect: Marked in ‰ or% (e.g. 0.5% → 5‰) with flow direction arrow.
- Flange and flange numbers: Flange types (RF/FF), standard (ANSI/ASME/DIN/GB), flange numbers and reference to hole position tables.
- Expansion joint/compensator: Position, type (bellows/sliding bearing/compensator model), rated axial displacement (±mm).
- Support and bearing: support number, spacing, bearing type (fixed/guided/sliding), foundation type (pile/strip) and bearing elevation.
- Valves and valve wells: valve types (gate valves, ball valves, check valves), valve numbers, valve well dimensions and maintenance port locations.
- Flange spacing and flange hole position table: the standard table of center distance, bolt hole number and hole diameter for each pair of flange.
- Slope direction / rinse port / vent point: The position of the rinse port and the vent valve aligns with the arrow indicating the slope direction for rinsing or venting.
- Welding sequence and numbering: Each weld is numbered (W-01...), with a recommended sequence of diagonal segmental and layered welding.
- Maintenance clearance: Minimum clearance around flanges, valves, and expansion joints (e.g., 600 mm around flanges, 800 mm for valve operation).
- Insulation and anti-corrosion joint: insulation layer thickness, type of outer shell, insulation treatment of insulation flange and flange.
- Detection port and sampling port: sampling port number, location and access mode.
- Refer to the table index: the reference numbers for the flange hole position table, valve detail table, bracket detail table, and weld inspection table (e.g., Ref: TBL-FL-01).

---

3. Detailed node annotations (must be marked on the drawings by both the drafter and the construction supervisor)

- Flange node: Mark the flange number, flange standard, gasket type, bolt specifications, and torque range; at the flange, mark "insulation flange treatment" and "flange maintenance port number".
- Expansion joint node: Mark the installation reserved length, installation direction arrow, guide sleeve position, seal cover and protective cover, maximum allowable displacement and installation sequence (first fixed end→guide→compensation end).
- Stent node: specify stent number, foundation type (pile/strip), bearing surface dimensions, sliding surface material (PTFE) and lubrication point location, seismic anchoring requirements (if applicable).
- Valve well joint: the size of the well cover, the slope of the well, the installation height of the valve, the extension height of the valve operating rod, the drainage hole and the anti-freeze measures.
- Rinsing/drain node: the type of the valve of the rinsing port, the diameter of the drain pipe, the position of the drain valve and the slope of the drain.

---

4. Welding, Pressure Testing and Quality Control Requirements

- Welding procedure: The process shall be performed in accordance with the Welding Procedure Specification (WPS), with 100% non-destructive testing (UT/RT) for critical joints and visual inspection plus random UT for general welds.
- Welding sequence: marking welding sequence number on isometric drawing and recording the welder, batch number of welding material and welding parameters in construction record.
- Test requirements: The hydrostatic test shall be conducted at 1.5× the design pressure, with a holding time specified in the specifications (e.g., 30 minutes); the air-tightness test shall comply with the contractual terms.
- Inspection of welds and flanges: 100% visual pass rate for welds; 100% UT/RT pass rate (for critical joints); successful flange seal test.
- The acceptance of the bracket was recorded in the form of the distance between the brackets, the verticality, the wear of the sliding surface and the lubrication point.

---

5 Legends, Tables, and Index (must be on the right side of the drawing or on an appendix page)

- Legend: Pipeline type symbols (supply/return/discharge/flush), valve symbols, support symbols, expansion joint symbols, weld symbols, insulation flange symbols.
- Flange location index: Table reference number (TBL-FL-01), with the following columns: Flange ID; Standard; OD; Bolt Quantity; Bolt Diameter; PCD; Face Type.
- Index of the valve details list: Table reference number (TBL-VV-01), with the following columns: ValveID; Type; DN; Rating; Actuator; Remarks.
- Index for the bracket detail list: Table reference (TBL-SUP-01), with the following columns: SupportID, Type, Spacing, BaseType, and Material.
- Weld inspection form index: Table reference number (TBL-WELD-01), with the following columns: WeldID, Location, Welder, WPS, NDT, and Result.

---

6. Installation Sequence Recommendations (For On-site Construction Reference)

1 Pre-fabrication and flange matching: flange matching, flange hole position check, flange surface cleaning and initial installation of insulation are completed in the prefabrication yard.

2. The foundation of the support was installed and the elevation and position were adjusted.

3. The pipe segment was placed in the order of the isometric drawing, and the slope and slope direction were checked by temporary support.

4. Welding and Nondestructive Testing: Welding was carried out in sections according to the welding sequence and NDT was performed. 100% inspection was carried out on critical joints.

5. Installation and adjustment of expansion joint: Install the guide and fixing end, reserve the installation gap and record the initial position.

6. After welding and pressure test, the insulation layer and outer shell are constructed, and the flange is fixed by the insulation flange and the pressure plate.

7. Pressure test and flushing: flushing and pressure test should be carried out before the insulation or according to the design requirements, and the test data should be recorded.

8. Final inspection and completion records: Complete all testing, verification, and documentation archiving, and generate the as-built drawings.

---

7. Example of drawing annotations: CAD can be used directly

- P-101 DN125×6.3 S-01 → SUPPLY PIPE; Slope 5‰; Flow →
- FLG-01 ANSI B16.5 RF DN125; Bolt M24×8; Gasket: Metal-Coated

- EXP-01 AXIAL COMPENSATOR; MaxAxial ±25 mm; Install: Fixed end @ ValvePit
- SUP-01 GUIDED SUPPORT; Spacing 3.0 m; Base: Pile; Slide: PTFE
- W-001 Weld; Root Pass: TIG; Fill: SMAW; NDT: UT (Ref TBL-WELD-01)

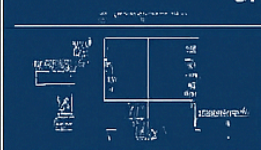
A) ANNOTATIONS FOR COVENILG 'JSRD SILENS/'

XBR N ECK	K/N/Qu/k-n/n/n/n/
Anbau	Ehrenamtliche Gemeinden
Alpenvereinshaus St.	Panorama Genuss Hütte
Schutzhütte mit Übernachtung	Privat Andere
Telegramm Anmeldung	Inhalt Hütte
Hütte	Ehrenamtliche
Identifikation	Führer bei Eglisau
Berghütte Management	Schutzhütte Invite Gratis Hütte
Q Mauer Hütte Bildhauer	Erfüllte Abstände
Kreditkarte	Einkauf
Kocher	Gastronomie
Hüttenübernachtung 25m	Lean Gipfelbesteigung

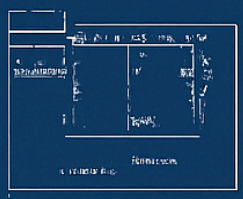
B) 1/0 AND NSTRUMENT LAYOUT SIPERNJN/'

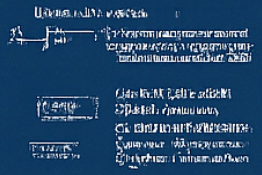
Gipfel	Hütte	Übernachtung	Übernachtungen
Berg	Schutzhütte	Schutzhütte	Gipfel
Gipfel	Übernachtung	Übernachtung	Übernachtungen
Gipfel	Hütte	Übernachtung	Übernachtung
Hütte	Schutzhütte	Übernachtung	Übernachtung
Gipfel	Übernachtung	Übernachtung	Übernachtung
Gipfel	Hütte	Übernachtung	Übernachtung
Gipfel	Hütte	Übernachtung	Übernachtung

C) 1/0 AND NSTRUMENT LAYOUT CHERN IB/'



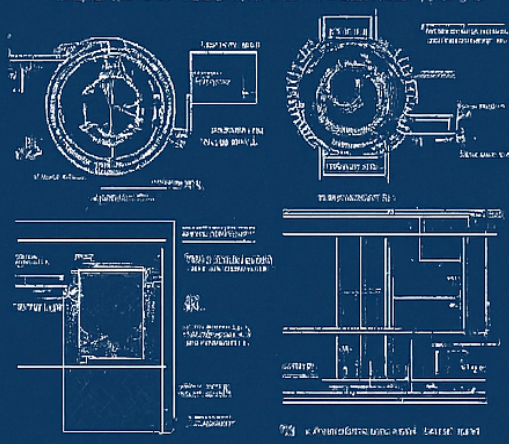
C) SINGI EINE AND WIRING COVRD IE/AENNB.R/'





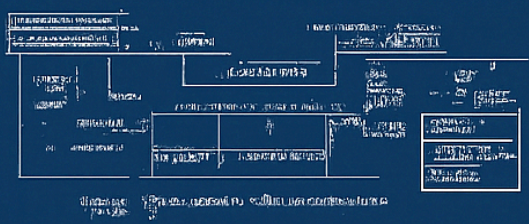
D) DETAIL *REFWANICS CI.*(20°(-13)

/DE/ER-DOT/ T/LOI/EAHL/ FIOGEIRBETM/NTO



E) 1/0/ INDIGI INE AND WIRING NOTES

/BERGBEAN/'



F) SINGIE LINE AND WIRING NOTES

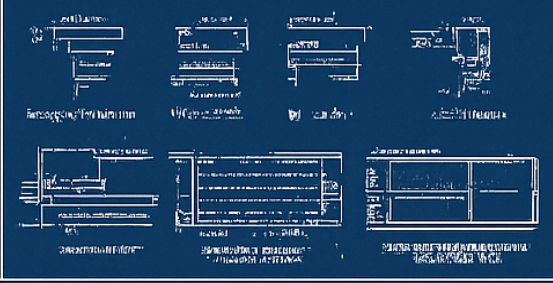
/T JIPBRNDI/'

Gipfel	Hütte	Übernachtung	Übernachtung	Übernachtung	Übernachtung
Hütte	Übernachtung	Übernachtung	Übernachtung	Übernachtung	Übernachtung
Gipfel	Hütte	Übernachtung	Übernachtung	Übernachtung	Übernachtung
Gipfel	Hütte	Übernachtung	Übernachtung	Übernachtung	Übernachtung
Hütte	Übernachtung	Übernachtung	Übernachtung	Übernachtung	Übernachtung
Gipfel	Hütte	Übernachtung	Übernachtung	Übernachtung	Übernachtung

G) COASTRUCTION / SCHEDULES & BONTAMBOED OFFI/EE RV/ONT

• Gaudeld	Chrysochilie-Lodi Bis	Dövestl-Gerüst
• Fenster	Gilde Hauptgebäude	Stiftung
• Tresor	Eisenwerke Hinaus	Rudolfers
• Dieter	Unterwegs überstellt	Support
Ernesto	Empfehlenswert	Eisbrot-Textur
Hildebrandt	Quality Restaurant	Bernhard Heinzel
	Verwaltung	Sendrey, Jo

G) IMATIVIALS TRE IN WELD T.IST. SECOND ABNEILLT



PROJECT	DRWWINS INS 2703.135		
MOOVBO	/OBE/WIONS/		
REVISIONS			
ISSUANCE			
Area	Sheet	Drawing No.	Rev.
TESD	10	575	ROBIX 102

A General Plan and Longitudinal Section Description

Title: Site Layout and Longitudinal Section (Scale 1:200 / 1:100)

Key elements: Site boundary demarcation; Coordinate grid layout; Center coordinates and numbering of the reservoir body; Locations of equipment rooms, utility trenches, valve wells, and maintenance access routes; Surface profile with material stratification (backfill soil, insulation layer, HDPE geomembrane, concrete lining); Buried depth elevation and surface elevation; North-facing arrow, scale, and legend.

Key Notes (Paste Directly):

- SITE-CEN X=12345.67 Y=23456.78
- Pit-C1 Center at GRID A3; Elevation RL 1000.00 m
- Backfill: compacted fill, max layer 300 mm, compaction 95%
- Insulation: PU foam, λ ≤ 0.025 W/m·K, thickness = design value
- Waterproof: HDPE membrane 2.0 mm, weld 100% inspection

Key points of construction: The drilling and in-situ test points are arranged according to the plan; the surface is restored by thermal insulation backfilling and vegetation; the temporary drainage slope marked in longitudinal section is not less than 1%.

B Library plane and section detail drawing description

Title: Storage Pit Plan and Section (Scale 1:50 / 1:20)

Main contents: the inner cavity dimensions of the reservoir (inner diameter 2.0 m, inner height 1.0 m); the coil arrangement (bottom spiral coil + vertical coil on side wall); the location and dimensions of the maintenance opening; the sensor points (T-01, T-02, Pp-01, etc.); the detailed drawings of the insulation layer, lining and bracket joints. Key notes:

- Pit Inner Dia = 2000 mm; Inner Height = 1000 mm
- Coil: SS316L, OD 60 mm, spacing 200 mm (typ)
- Access Hatch: 600×600 mm, flange type, bolt M16×8
- Sensor T-01: PT100, flange probe, location: top inner wall
- Sensor Pp-01: piezometer, depth 2.0 m, outside pit

Key points of construction: the coil installation is arranged according to the thermal calculation and pressure test is done; the flange surface of the inspection port is cleaned, the gasket is positioned, the bolts are tightened step by step according to the diagonal and the torque is recorded.

C Heat exchanger and coil drawing description

Title: Heat Exchanger and Coil Detail (Scale 1:10)

Main contents: pipe diameter, spacing, bracket fixing method, flange connection, drainage and maintenance details, bracket material and anti-corrosion treatment.

Key Notes:

- Coil OD = 60 mm; Pitch = 200 mm; Material = SS316L
- Support: welded saddle on concrete boss; coating B-01
- Flange: ANSI B16.5 RF; Bolt: M24; Gasket: metal-coated
- Drain: DN25 with strainer and check valve

Key points of construction: Nondestructive test should be done after welding of coil support; Insulation flange should be fixed with pressure plate; Drainage outlet should be easy to flush and pump.

D. Isometric Drawing of Pipeline and Valve Well

Title: Piping Isometric and Valve Pit (Scale 1:50)

Main contents: the diameter and wall thickness (DN/t), the slope and slope direction, the flange number and the hole position index, the expansion joint position, the type and spacing of the support, the valve well section, the slope direction of the flushing/drainage.

Key Notes:

- P-101 DN125×6.3; Material: LowTempSteel X70; Coating: External epoxy
- Slope: 5‰ → Flow direction →
- FLG-01 Ref TBL-FL-01; Bolt M24×8; PCD = xxx mm
- EXP-01 Axial Compensator; MaxAxial ±25 mm; Install: Fixed end @ ValvePit
- SUP-01 Guided Support; Spacing 3.0 m; Base: pile; Slide: PTFE

Key points of construction: the flange hole position table and the valve detail table must be matched one to one; the expansion joint installation should be according to the manufacturer's installation manual and the initial position should be recorded; the drainage and anti-freeze measures should be set up in the valve well.

E Node Detail Set Description

Title: Node Details Waterproofing Insulation Flange (Scale 1:5 / 1:2)

Key components: HDPE anti-seepage membrane penetration sleeve, water-stop ring, insulated joint (PU + VIP), flange and maintenance port sealing, insulated pressure plate, as well as water-stop and drainage nodes.

Key Notes:

- HDPE Liner: 2.0 mm; Weld seam: heat fusion; Test: 100% visual + sample UT
- Sleeve: Ø = hole + 20 mm; Waterstop: rubber ring; Backfill: compacted sand-gravel
- Insulation: PU spray / preformed board; VIP at critical joints; Fixing: mechanical clamp
- Flange Gasket: LowTemp elastomer or metal-coated; Bolt torque record required

Key points of construction: first make sleeve and hot-melt welding at the penetration of impermeable film, leave inspection section at the weld; fix the edge of insulation with pressure plate and do moisture-proof treatment; seal the cavity at the repair opening and seal the cavity with sealant (as required by design).

F Instrument Layout and I/O Table Sample Description

Image Title: Instrumentation Layout and I/O Table (CSV Fields)

Main contents: sensor number, location description, range, wiring cable specifications, PLC point number, terminal number, wiring box location example.

Sample CSV header: Signal, Tag, Type, Range, Cable, Shield, PLC_Point, Terminal, Location, Notes
Sample entry:

- Temperature,T-01,PT100,-50~150C,4-core
0.5mm2,Yes,AI-01,TB1-1,StoragePit-Top,Flange probe
- PorePressure,Pp-01,Piezometer,0~500kPa,2-core
0.75mm2,Yes,AI-11,TB2-1,OutsidePit-2m,Standpipe

Key points of construction: All signal lines are shielded and grounded at a single point on the PLC side; The IP rating of the junction box is selected according to the on-site environment; The length and laying path of each cable are recorded in the wiring list.

G Electrical Single Line and Connection Points Explanation

Title: Electrical Single Line and Wiring Notes (Abstract)

Main contents: Main power supply inlet, circuit breaker/fuse, MCC, PLC/control cabinet, UPS, grounding busbar, terminal block, main cable specifications, protection devices and grounding/ shielding rules.

Key Notes:

- Main Supply: 380 VAC 3ph; Main Breaker: 160 A MCCB
- PLC Cabinet: 24 VDC supply from UPS; Terminal blocks TB1..TBn; Shield to PE at PLC end
- Cable sizes: Power 3×95 mm2 + PE; Control 4-core 1.0 mm2 shielded

The key points of construction are: the instrument ground and power ground are separated and connected in single point of the grounding busbar; the cable tray is laid in the category of the category; the terminal number is strictly corresponding to the I/O table.

H BOM and Material Test Template Description

Image name: BOM and Test Record Templates (Sample fields)

BOM header example: Item, Description, Spec, Material, Quantity, Unit,
Remarks. Material test record header example:

SampleID,Location,MaterialType,TestType,TestStandard,TestConditions,RawDataFile,Result,Conclusion,Lab,ReportNo,Date

Example entry:

- 1,Pipe,OD500×20,LowTempSteel,X70,200 m,Charpy -40℃ ≥ 27J
- S-001,PK-01,PipeSteel,CharpyImpact,ASTM A370,-40℃,raw/S-001.csv,30J,Pass,LabA,2026-001,2026-02-15

Key points of construction: the factory inspection report should be attached to the materials; the laboratory report should include the original data, test conditions and photos; the welding inspection report and the material test report should be archived as the basis of acceptance.

I have prepared a Python script that runs directly, including phase transition calculations, hourly surface driving, and plotting/output. Copy it to your local Python 3.8+ environment to run.

This is a complete script (get it on thm1denthalpy.py and run it). The script generates four PNG images and prints a summary in the terminal; the top comment explains how to replace it with real hourly weather data.

`
```
 python
import numpy as np
import scipy.sparse as sp
import scipy.sparse.linalg as spla
import matplotlib.pyplot as plt
import pandas as pd
import os

----------Parameter block (replace with field data) ----------
L = 334000.0             # J/kg
rho_ice = 917.0
rho_water = 1000.0
rho = 1000.0             # Volume conversion unit: kg/m3
cp_ice = 2100.0
cp_water = 4180.0
k_ice = 2.0              # W/mK
k_water = 0.6
depth = 50.0             # m
dz = 0.2
Nz = int(depth/dz)+1
z = np.linspace(0, depth, Nz)
days = 365
dt = 3600.0              # s
Nt = int(days*24)

Initial geothermal profile (replaceable by site)
Tsurfacemean = -10.0
T_deep = -5.0
T0 = Tsurfacemean + (Tdeep - Tsurface_mean)*(z/depth)

Calculate hourly surface temperature (example); see the end of the script for replacement method
np.random.seed(1)
Tsurfacehourly = -5.0 + 15.0np.sin(2np.pinp.arange(Nt)/(24365)) +
2.0*np.random.randn(Nt)

----------Stew Mapping----------
def enthalpyfromT(T):
    H = np.zeros_like(T)
```

```
    for i, Ti in enumerate(T):
        if Ti < -0.1:
            H[i] = cp_ice*Ti
        elif Ti > 0.1:
            H[i] = cp_water*Ti + L
        else:
            frac = (Ti + 0.1)/0.2
            H[i] = cpice(-0.1) + frac(L + cpwater0.1 - cp_ice(-0.1))
    return H

def    Tfromenthalpy(H):
    T = np.zeros_like(H)
    Hice = cpice*(-0.1)
    Hwater = L + cpwater*0.1
    for i, Hi in enumerate(H):
        if Hi < H_ice:
            T[i] = Hi/cp_ice
        elif Hi > H_
        water:
            T[i] = (Hi - L)/cp_water
        else:
            frac = (Hi - Hice)/(Hwater - H_ice)
            T[i] = -0.1 + frac*0.2
    return T
```

initial heating field (J/m3)

```
H = enthalpyfromT(T0) * rho
```

----------Implicit 1D heat conduction with phase change (simplified iteration) ----------

```
def run_simulation():
    T_time = np.zeros((Nt, Nz))
    H_time = np.zeros((Nt, Nz))
    icefractime = np.zeros((Nt, Nz))
    Hn = H.copy()
    for t in range(Nt):
        Tsurface = Tsurface_hourly[t]
        Tn = Tfromenthalpy(Hn/rho)
        for it in range(6):
            k = np.where(Tn<=0, kice, kwater)
            cpeff = np.where(Tn<=0, cpice, cp_water)
            a = np.zeros(Nz); b = np.zeros(Nz); c = np.zeros(Nz); rhs = np.zeros(Nz)
            for i in range(Nz):
                if i==0:
                    b[i]=1.0; rhs[i]=T_surface
                elif i==Nz-1:
```

```
                    b[i]=1.0; rhs[i]=T_deep
                else:
                    km = 0.5(k[i]+k[i-1]); kp = 0.5(k[i]+k[i+1])
                    a[i] = -km/(dz*dz)
                    c[i] = -kp/(dz*dz)
                    b[i] = rho*cp_eff[i]/dt - a[i]-c[i]
                    rhs[i] = rhocp_eff[i]/dt    Tn[i]
            A = sp.diags([a[1:], b, c[:-1]], offsets=[-1,0,1], format='csc')
            T_new = spla.spsolve(A, rhs)
            Hn = enthalpyfromT(T_new) * rho
            Tn = T_new
        Ttime[t,:]=Tn; Htime[t,:]=Hn; icefractime[t,:]=np.where(Tn<=0,1.0,0.0)
    return Ttime, Htime, icefractime

Ttime, Htime, icefractime = run_simulation()

----------Result Calculation and Plotting----------

surface temperature curve
plt.figure(figsize=(10,3))
plt.plot(np.arange(Nt)/24.0, Tsurfacehourly, color='tab:orange')
plt.xlabel('Day'); plt.ylabel('Surface Temp (°C)')
plt.title('Hourly Surface Temperature (synthetic)')
plt.tightlayout(); plt.savefig('surfacetemp.png'); plt.show()

Several moments in the depth profile
times_days = [0,90,180,270,360]
plt.figure(figsize=(6,6))
for d in times_days:
    idx = int(d*24); idx = min(idx, Nt-1)
    plt.plot(T_time[idx,:], z, label=f'Day {d}')
plt.gca().invert_yaxis(); plt.xlabel('Temperature (°C)'); plt.ylabel('Depth (m)')
plt.legend(); plt.title('Depth Temperature Profiles'); plt.savefig('depth_profiles.png');
plt.show()

Ice fraction heat map
plt.figure(figsize=(10,6))
plt.imshow(icefractime.T, aspect='auto', origin='lower', extent=[0,days,0,depth],
cmap='Blues')
plt.colorbar(label='Ice fraction'); plt.xlabel('Day'); plt.ylabel('Depth (m)')
plt.title('Ice Fraction (depth vs time)'); plt.savefig('ice_fraction.png'); plt.show()

annual accumulated cold storage (approximate to ice volume)
icemass = np.sum(icefractime, axis=1)dzrhoice    # kg per m2 each hour
```

```
dailyicemass = ice_mass.reshape((days,24)).mean(axis=1)
dailycoldkJ = dailyicemass * L / 1000.0
plt.figure(figsize=(10,4))
plt.plot(np.arange(1,days+1), np.cumsum(dailycoldkJ))
plt.xlabel('Day'); plt.ylabel('Cumulative cold (kJ per m2)'); plt.title('Cumulative Cold Storage (approx)')
plt.savefig('cumulative_cold.png'); plt.show()
```

Abstract

```
initialmean = np.mean(Ttime[0,:]); finalmean = np.mean(Ttime[-1,:])
annualcoldkJ = np.sum(dailycoldkJ)
print("I initial mean temperature (°C): I, round(" initial_mean", 3))
print("I year-end average temperature (°C): I, round(" final_mean", 3))
print("I-year accumulated cold storage capacity (kJ per m2): I, round(annual cold kJ, 3)")
```

----------How to replace with hourly weather data----------

Name the CSV file surfacetemphourly.csv, containing the column temperature_C (at least Nt rows)

Replace the composite driver at the top of the script:

```
df = pd.readcsv('surfacetemp_hourly.csv')

Tsurfacehourly = df['temperature_C'].values[:Nt]
`
```

Run the script in an environment with Python 3.8+ and the libraries numpy, scipy, matplotlib, and pandas. Save and run the script to output four PNG images and a terminal summary.

This concludes the proposal. Overall, the loss has been successfully managed. Any follow-up details would fall outside my purview – that's the domain of government agencies and so-called expert elites. Isn't this precisely their role? Their expertise lies in specifics and niche fields, as they can't handle macro-level issues. Of course, if they fail to implement my subsequent recommendations, they'll truly become useless as a mere "point-and-click" solution. To be frank, I'm utterly disillusioned with those high-ranking officials and scholars in governments worldwide. How to put it? They cling to self-interest, refuse to collaborate, and can't mobilize resources effectively. Yet they still hold some utility. Their value lies in conducting field experiments and practical implementation. If they fail to deliver, I'll be at a loss – we'll just have to wait and see. It's inevitable. I believe survival will give them tremendous motivation.

List of Recommendations (for Government Implementation: Follow-up to the completed "THM Hot-Phase Change Script")

Task	Responsible Department	Priority	Key Deliverables	Suggested Timeframe
Freeze-thaw cycles and foundation creep tests	National Land and Natural Resources Administration; Engineering Institute	Maximum	Indoor freeze-thaw test report; In-situ test section observation data	3–24 months
Methane and Groundwater Environmental Impact Assessment (EIA)	Environmental/ecological sector	Maximum	EIA report; monitoring and mitigation plan	12 months (baseline)
Trial voyages of shipping icebreakers and energy consumption/loss accounting	Transportation/ maritime authorities	High	Trial report; shipping loss model; LCA report	6–12 months
Thermal Insulation Materials and Pipeline Durability Certification	MIIT/QS Department	High	Material Aging Test Report; Life Prediction	3–12 months
Large-scale ice-making unit and heat exchanger pilot	Energy/Industry/Research institutions	High	Equipment performance curve; operating manual	6–12 months
Reclaimed Water Treatment and Re-freezing Process Demonstration	Water Resources/Environmental Protection Department	Medium to High	Reclaimed Water Treatment Process Package; Test Data	6–12 months
Port and Ship Renovation Specifications and Emergency Plans	Transportation/Maritime/Emergency Management	Chinese	Port renovation drawings; emergency drill records	6–12 months
Cross-border legal and transport agreement framework	Ministry of Foreign Affairs; Ministry of Justice	China	Multilateral agreement draft; responsibility allocation table	6–18 months
Ecological sensitive area protection and compensation mechanism	Ecology/forestry/fishery sector	China	Ecological compensation scheme; long-term monitoring plan	12–24 months
Cost-effectiveness, Financing and Carbon Accounting Model	Institute of Fiscal/Development/ Energy Economics	China	LCOC/LCA Model; Financing Plan	3-9 months
Pilot to Scale-up Criteria and Regulatory Mechanisms	MIIT/NDRC/Quality Supervision	Medium to High	Judgment Matrix; Regulatory and Acceptance Process	3–6 months
Social impact and public communication	Publicity/Local government	Medium	Public information materials; records of public participation	Sustained and parallel

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Key points for each task (in order, for government departments to directly assign or tender)

1 Freeze-thaw cycle and foundation creep test

- Objective: To verify the mechanical and permeability properties of low temperature concrete, lining and backfill under freeze-thaw cycles, and to evaluate the long-term settlement and crack risk.
- Key actions: commissioning the material laboratory to perform ≥300 freeze-thaw cycles; setting up an in-situ test section at the proposed pilot plant (with at least 1 year of observation); conducting static load/penetration tests and establishing a settlement monitoring network.
- The acceptance criteria were as follows: the strength of the concrete after freeze-thaw cycle was not lower than 20% of the original strength; the annual settlement rate was not higher than 10 mm; the test report included the modified formula and the structural reinforcement suggestion.

2 Environmental Impact Assessment of Methane and Groundwater

- Objective: To quantify the methane release and groundwater chemical changes induced by thawing of frozen soil and to develop mitigation and monitoring strategies.
- Key actions: Conduct baseline monitoring (methane flux, groundwater chemistry, flow rate) for at least 12 months; Establish a thawing scenario model

Propose; design methane capture/abatement and groundwater protection measures.

- Acceptance criteria: The EIA includes risk probability assessment, mitigation measures and long-term monitoring plan; if the risk exceeds the threshold, the site selection or engineering scheme should be adjusted.

3 Trial Navigation of Seawater Ice and Calculation of Energy Consumption/Loss

- Objective: To measure the melting loss, loading and unloading loss and carbon emission per unit cooling capacity of transoceanic ice/ice slurry transportation, and to judge the feasibility and optimal route of sea transportation.

- Key actions: retrofit or lease a test vessel for small-scale trial runs; record cabin temperature, ice quality changes, fuel consumption, and handling losses; establish a heat loss model and perform a Life Cycle Assessment (LCA) for carbon emissions.

- Acceptance criteria: specify the effective cooling capacity loss rate and carbon emissions per unit of cooling capacity (kg CO2/kJ) at the receiving end; if the carbon footprint is unfavorable, prioritize nearshore or land-based solutions.

4 Insulation Materials and Pipeline Durability Certification

- Objective: To verify the long-term performance and joint reliability of polyurethane, VIP, HDPE and composite pipes under extreme temperature and humidity cycles.

- Key actions: Accelerated aging test (thermal cycling, humid heat, freeze-thaw, mechanical fatigue); long-term exposure monitoring of field samples; joint/flange leakage life test.

- Acceptance criteria: 10-year equivalent thermal conductivity decay $\leqslant$ 20%; joint leakage rate below the specification threshold; and maintenance/replacement cycle specified.

5 Pilot Test of Large-scale Ice-making Unit and Heat Exchanger

- Objective: To verify the actual COP and ice-making rate of ice-making unit under ice formation resistance, ice formation strategy and night scheduling.

- Key actions: Constructing the pilot ice-making device (with the script), measuring the ice resistance curve, ice morphology and ice slurry pumpability of the heat exchanger; testing different crystal-promoting and stirring strategies.

- Acceptance criteria: energy consumption $\leqslant$ 1.5×theoretical value, clear ice resistance curve of heat exchanger, operation manual and maintenance plan completed.

6 Backflow Water Treatment and Re-freezing Technology Demonstration

- Objective: To ensure that the hot water/wastewater from the defrosting zone is not contaminated before the return and re-freezing and to improve the efficiency of the circulation.

- Key actions: Design and test the process of precipitation, filtration, desalination and removal of micro-pollutants; verify the efficiency and energy consumption of the process in the pilot scale.

- Acceptance criteria: chemical index of return water meet the safety threshold of refreezing; refreezing energy consumption and efficiency are recorded and included in the system energy balance.

7 Port and Ship Renovation Specifications and Emergency Response Plans

- Objective: To ensure the safety of ice loading and unloading, reduce heat loss and cope with extreme sea conditions.

- Key actions: Develop standards for the closed insulated unloading system; Conduct emergency drills for loading and unloading; Establish emergency procedures for extreme weather shutdown and leakage.

- Acceptance criteria: Emergency drills passed; heat loss during loading and unloading controlled within the design value; port renovation drawings and construction permits were complete.

8 Transnational Law and the Framework of Transport Agreements

- Objective: To clarify the sovereignty, responsibility, environmental compensation and accident handling mechanism of cross-border cold source transportation.

- Key actions: lead bilateral/multilateral negotiations with relevant countries; draft provisions on transport and environmental liability; establish data sharing and customs clearance facilitation mechanisms.

- Acceptance criteria: signing a memorandum of understanding or framework agreement; completion of a legal risk assessment report.

9 Protection and Compensation Mechanism of Ecological Sensitive Area

- Objective: To protect the migratory birds, marine ecology and tundra vegetation in the project implementation, and to establish the compensation and restoration mechanism.

- Key actions: carry out ecological baseline survey; develop avoidance, buffer and compensation projects (wetland restoration, ex situ conservation); long-term ecological monitoring.
- Acceptance criteria: Ecological indicators (species diversity, vegetation cover, etc.) should be no lower than baseline or restored according to the compensation plan.

10 Economy,Financing and Carbon Accounting Model

- Objective: To evaluate the economic feasibility, financing pathway and climate benefits (net carbon impact) of the project.
- Key actions: Establish LCOC (unit cooling capacity cost) model and sensitivity analysis (energy price, loss rate, carbon price); Design financing scheme (public-private partnership, green bond).
- Acceptance criteria: The paper gives the investment payback period, key sensitive points and feasible financing structure.

1 1. Criteria and Regulatory Mechanisms for Determining the Transition from Pilot to Scale-up

- Objective: To determine the time when to scale up from pilot to demonstration or commercialization and to establish the process of supervision and acceptance.
- Key actions: Develop three types of scaling-up trigger conditions (e.g. ice-making energy efficiency, heat loss, methane release threshold, LCOC); Establish a third-party acceptance and supervision checklist.
- Acceptance criteria: the formation of the judgment matrix and the expert review; the supervision process and acceptance form are operable.

Suggested organization and delivery (for government implementation)

- Lead unit: It is recommended that the National Project Coordination Office (or the National Development and Reform Commission) establish a cross-ministerial project team with clear division of labor and contact persons.
- Parallel implementation: Initiate Environmental Impact Assessment (EIA) and pilot project (ice-making/THM verification) concurrently, with key field data collected prior to design optimization.
- Third-party evaluation: All critical acceptance criteria (EIA, material lifespan, shipping LCA, and scale-up determination) are assessed by an independent third-party expert panel.
- Funding and time: It is recommended that the funds be included in the special pilot funds and allocated in stages; the key pilot data (6-12 months) will be used to decide whether to scale up or not.

Thus, the plan conceived under the guidance of Wang Tudi (Wangtu Village's revered figure) is now finalized. Oh my goodness, this is the simplest solution yet. It tackles the root cause directly, surpassing all my previous ecological restoration projects. This embodies the natural cycle of cosmic order—though a reductionist journal would never grasp this. Let me reiterate: I demand those bastards and their descendants witness the benefits this plan brings, and then they shall see the true nature of their ancestors.

After the Civilization of Viruses: Earth Rebirth Project

The triple disaster chain caused by global warming will come to an end in 2150, and the virus civilization will exit the stage of history. This plan is based on the principles of ecology and geology, breaks the shackles of human design, reconstructs the earth's self-healing timeline according to the natural law, and witnesses the ruins of civilization.

To the original epic rebirth.

The post-trauma recovery phase (0-200 years) focuses on climate stabilization and initial ecological restoration: At the atmospheric level, ocean absorption and vegetation recovery will drive CO2 concentrations down from 450ppm to 400ppm within 100 years, reaching pre-industrial levels of 350 ppm by 200 years, while ozone layer restoration will take 50-100 years. In urban ruins, concrete structures will begin collapsing after 50 years of weathering and biological erosion, with large buildings reduced to rubble by 200 years. Steel will corrode over 50-100 years, and aluminum products will degrade faster under acid rain. In the biological realm, urban stray animals will form populations within 10 years, marine fish populations will grow by 30%-50% in 20 years, organic waste will be almost completely degraded within 10 years, and plastics will break down into microplastics deposited in the environment.

The Ecological Reconstruction Period (200,000–50,000 years) initiated geomorphic reshaping and biodiversity revival. Geologically, concrete powder and microplastics mixed and solidified into a 10–20 cm-thick "Anthropocene Cake Layer" within 10,000 years. Global forest coverage reached 50% within 5,000 years, while Amazon rainforest required 10,000–30,000 years to restore its original scale. In marine ecosystems, coral reefs fully recovered within 5,000–10,000 years after seawater pH normalized, and cod populations rebounded to historical peaks within 10,000 years. Species evolution demonstrated renewed vitality: heat-tolerant birds completed adaptive radiation within 5,000 years, and large herbivores reestablished continental ecological corridors.

The geological equilibrium phase (50,000–1 million years) achieved climate stability and geological sequestration: The climate system stabilized, with global average temperatures returning to pre-industrial levels and extreme weather events becoming rare. Over 100,000 years, sea levels solidified into new coastlines. Material cycles gradually concluded, as nuclear power plant waste radiation reached safety levels within this timeframe. Microplastics became permanently embedded in geological layers, marking the Anthropocene. Ecosystems stabilized, with new species filling ecological niches to surpass pre-human diversity. Permafrost refreezing suppressed methane emissions.

The primordial era (1 million to 100 million years ago) witnessed the disappearance of civilization traces and the eternalization of nature: artificial structures were completely obliterated, with only the foundations of pyramids and the Great Wall remaining as outlines. Metal artifacts oxidized entirely, leaving only lunar probes and space station remnants as "civilization tombstones." The geological epoch was reshaped, with the "Anthropocene" solidified as a geological marker, and the carbon cycle restored to balance, ushering in a new geological cycle. Natural laws now fully govern Earth, species replacement follows natural laws, and large-scale biological migrations reappeared. Human traces are preserved solely in geological layers and on the Moon, marking Earth's return to a state of pure natural cycles.

The plan is built on four scientific pillars: an atmospheric restoration model based on IPCC reports and ocean carbon sequestration rates, building collapse dynamics incorporating concrete weathering (0.1-1 mm/year) and steel corrosion (5mm/year) data, ecological succession theory referencing the Galapagos Islands case, and geological time scale calculations adhering to half-life laws and stratified solidification patterns. In virtual dimensions, solar-powered monitoring devices left by humans can maintain 200 years of data records, preserving Earth's self-healing "black box archives" for potential extraterrestrial civilizations.

The extinction of human race is not the end of the earth,but the beginning of the natural restart. From the ruins to the forest,from the pollution to the clear water,from the civilization to the primitive,the earth has demonstrated the resilience of life with silent power in the scale of millions of years.When the last piece of metal oxidizes and the last trace of civilization is destroyed, the law of nature will continue to operate, witnessing the eternal rebirth of the blue planet. This plan is deduced by the Earth's natural system according to the scientific law, recording the epic of the planet's rebirth after the disappearance of civilization.

Both plans work perfectly fine – what a great solution! The only difference is that one requires manual maintenance, while the other needs no repair and will naturally function smoothly over time. Personally, I'd lean toward the second plan, though I'm not entirely sure about the specifics.

All people today share the same choice as I do, and their descendants are irrelevant to me. To be honest, I think the first plan costs way too much. The second plan is the only scientific one—we must trust science. It doesn't require spending more either, and it's equally about restoring the planet's ecosystem. So my choice mirrors most people's: the second plan. The first one is just for show. Honestly, I don't think the first plan is scientific or cost-effective, and we should trust science. That's why I choose the second plan. Like most people, we're truly great—ready to sacrifice ourselves. I believe most people think this way; otherwise, they wouldn't be living such a life of indulgence and recklessness.

I present this proposal as a satire on humanity. Everyone, because I know all choices would superficially agree with Option 1 under Option 2. How so? Because human choices and their definition of science are always... Well, let's use a modern analogy. What better metaphor than to think about how humans define science? Isn't it science itself? What do they see as science? What's real science? Their view prioritizes form over substance—just visually appealing, easy to digest. How convenient! Most journals and policies today choose Option 2. The concept of "good-looking is enough" reigns supreme, indulging in decadence to the extreme. That's why I brought Option 1 to highlight the grandeur of Option 2. Or rather, Option 2 is true science. Because so-called science isn't the pursuit of truth through natural laws, but humanity's internal choice. Clearly, our choice is Option 2. So is true science just formalism? Visually appealing, cost-prohibitive. We choose Option 2 because it's pretty, only treats symptoms, no paper waste, no worries. We tell our children "no worries, no worries" because we believe in their future. "You'll die for our welfare, you'll sacrifice yourselves for us. You're great—we trust you." Look at our generation, we are all great, and sacrifice future interests for our own interests is so good.