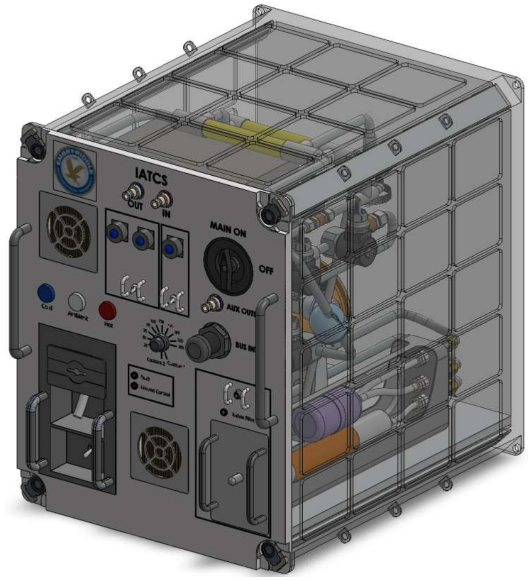
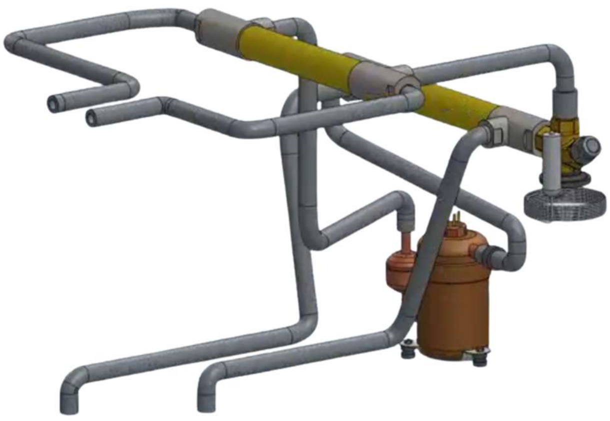
Advanced Quality Orbital Rehydration Assembly (AQUORA)

2026 Human Lander Challenge Technical Paper

Embry-Riddle Aeronautical University
Advanced Space Technologies Research Applications (ASTRA) Lab



Full Potable Water Dispenser, AQUORA



Cold Water Assembly

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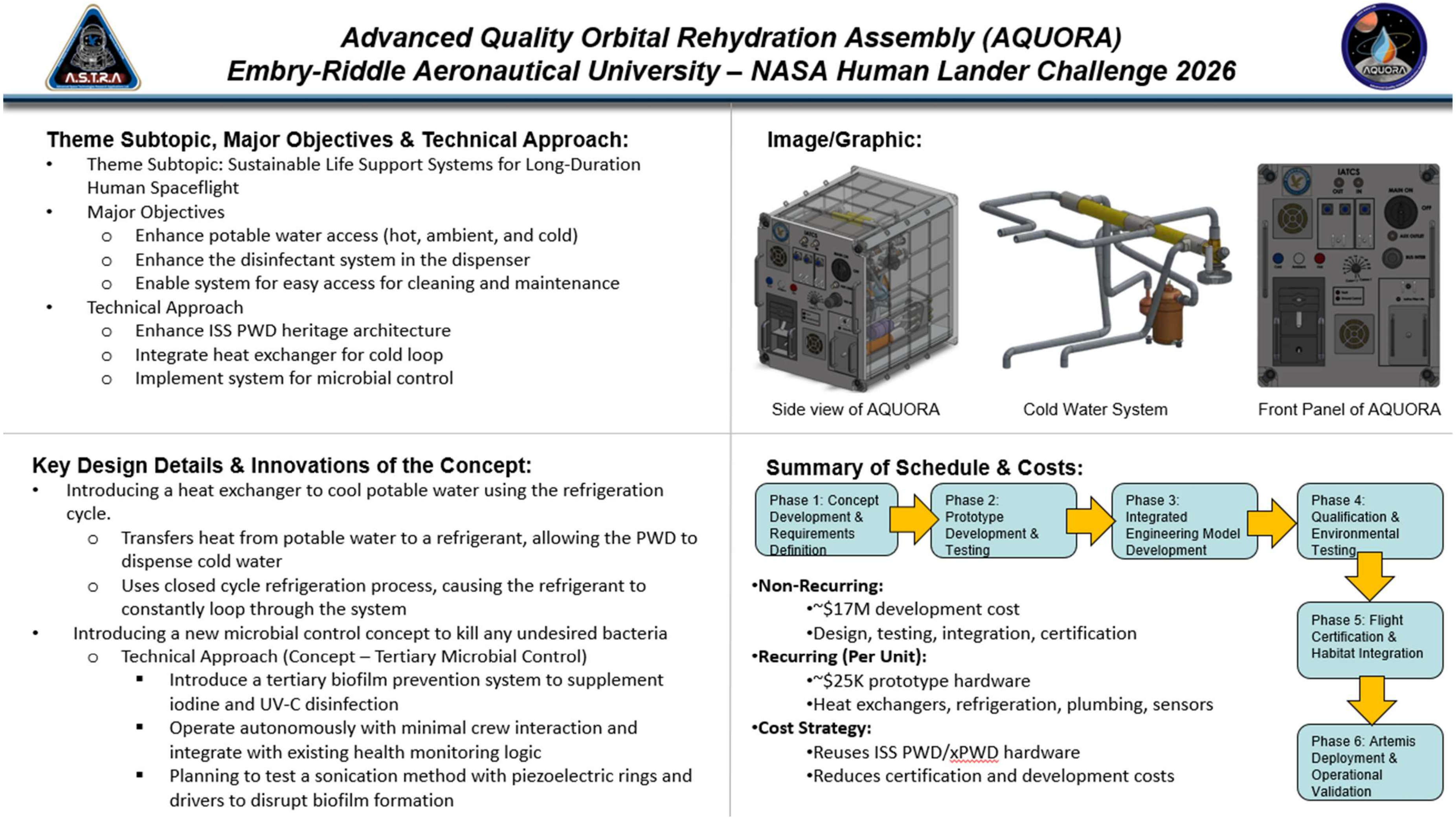
Quad Chart



Advanced Quality Orbital Rehydration Assembly (AQUORA)
Embry-Riddle Aeronautical University – NASA Human Lander Challenge 2026

Theme Subtopic, Major Objectives & Technical Approach:

- Theme Subtopic: Sustainable Life Support Systems for Long-Duration Human Spaceflight
- Major Objectives
  - Enhance potable water access (hot, ambient, and cold)
  - Enhance the disinfectant system in the dispenser
  - Enable system for easy access for cleaning and maintenance
- Technical Approach
  - Enhance ISS PWD heritage architecture
  - Integrate heat exchanger for cold loop
  - Implement system for microbial control

Image/Graphic:

Side view of AQUORA

Cold Water System

Front Panel of AQUORA

Key Design Details & Innovations of the Concept:

- Introducing a heat exchanger to cool potable water using the refrigeration cycle.
  - Transfers heat from potable water to a refrigerant, allowing the PWD to dispense cold water
  - Uses closed cycle refrigeration process, causing the refrigerant to constantly loop through the system
- Introducing a new microbial control concept to kill any undesired bacteria
  - Technical Approach (Concept – Tertiary Microbial Control)
    - Introduce a tertiary biofilm prevention system to supplement iodine and UV-C disinfection
    - Operate autonomously with minimal crew interaction and integrate with existing health monitoring logic
    - Planning to test a sonication method with piezoelectric rings and drivers to disrupt biofilm formation

Summary of Schedule & Costs:

Phase 1: Concept Development & Requirements Definition

Phase 2: Prototype Development & Testing

Phase 3: Integrated Engineering Model Development

Phase 4: Qualification & Environmental Testing

Phase 5: Flight Certification & Habitat Integration

Phase 6: Artemis Deployment & Operational Validation

- **Non-Recurring:**
  - ~$17M development cost
  - Design, testing, integration, certification
- **Recurring (Per Unit):**
  - ~$25K prototype hardware
  - Heat exchangers, refrigeration, plumbing, sensors
- **Cost Strategy:**
  - Reuses ISS PWD/xPWD hardware
  - Reduces certification and development costs

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Table of Acronyms

AQUORA	Advanced Quality Orbital Rehydration Assembly
HuLC	Human Lander Challenge
ASTRA Lab	Advanced Space Technologies Research Applications Lab
ISS	International Space Station
PWD	Potable Water Dispenser
xPWD	Extended Potable Water Dispenser
ECLSS	Environmental Control and Life Support System
FRIDGE	Freezer / Refrigerator / Incubator Device for Galley and Experimentation
IATCS	Internal Active Thermal Control System
CFM	Colony Forming Units
MTBM	Mean Time Between Maintenance
MTBF	Mean Time Between Failures
ROM	Rough Order of Magnitude
COP	Coefficient of Performance
PDR	Preliminary Design Review
CDR	Critical Design Review
FRR	Flight Readiness Review
CAD	Computer-Aided Design
R-134a	Tetrafluoroethane Refrigerant

Technical Paper

I. Executive Summary

Advanced Quality Orbital Rehydration Assembly (AQUORA) addresses the HuLC Potable Water Dispenser subtopic by enhancing temperature-controlled water delivery for long-duration lunar missions. As NASA transitions to sustained Artemis surface operations, potable systems must support extended crew presence without increasing risk or complexity.

AQUORA builds upon the flight-proven International Space Station Potable Water Dispenser (PWD/xPWD) architecture, preserving iodine-based microbial control, deiodination, heating, and real-time monitoring systems to minimize certification risk [1,2]. The primary innovation is a modular cold-water subsystem integrated within the existing locker envelope. This compact vapor-compression system incorporates a sealed compressor and evaporator heat exchanger, rejecting waste heat through the Internal Active Thermal Control System (IATCS) while maintaining strict isolation between refrigerant (R-134a) and potable loops [3].

By leveraging heritage hardware and introducing targeted thermal and biofilm resilience enhancements, AQUORA improves crew hydration capability, operational flexibility, and long-duration Environmental Control and Life Support System (ECLSS) performance for sustained lunar habitation.

II. Problem Statement

The PWD/xPWD currently operating aboard the International Space Station is designed for reliable potable water delivery in a microgravity environment and has demonstrated successful long-duration performance. However, NASA's Artemis missions introduce new operational challenges, including extended lunar surface habitation, partial gravity effects, increased crew autonomy, and reduced resupply opportunities.

The current PWD/xPWD architecture provides hot and ambient potable water but does not support chilled water capability [1,2]. While sufficient for ISS operations, future lunar missions may benefit from increased hydration flexibility and improved crew comfort during long-duration habitation.

Additionally, extended mission durations increase concerns related to microbial growth and biofilm formation within potable water systems [4,5]. Future lunar life support hardware must therefore prioritize long-term reliability, microbial resilience, and compatibility with existing ECLSS infrastructure.

To support sustained Artemis operations, the PWD architecture must be adapted to improve thermal flexibility and long-duration operational capability while preserving the reliability and heritage functionality of the current flight-proven system.

III. Adherence to Design Constraints

AQUORA is designed to meet Human Lander Challenge requirements while maintaining compatibility with the existing ISS Potable Water Dispenser architecture. The system preserves heritage hardware and operational procedures to reduce technical risk and certification complexity [1,2].

The cold-water subsystem is designed to fit within the existing PWD/xPWD locker envelope while maintaining separation between the refrigerant and potable water loops to preserve water quality and crew safety. Waste heat generated by the refrigeration cycle is rejected through the IATCS, allowing compatibility with existing thermal management infrastructure. Currently, there are systems onboard, like the Freezer / Refrigerator / Incubator Device for Galley and Experimentation (FRIDGE), that use the coolant loop of the ISS's Internal Active Thermal Control System, which is used to cool electronics and give air conditioning, to reject heat from their refrigeration cycle. Therefore, AQUORA does the same, using the IATCS coolant loop as a condenser using a shell-and-tube heat exchanger. A second shell-and-tube heat exchanger is used as the evaporator, which is significant as this type of heat exchanger isolates both fluids that transfer heat, curbing any possibility of contamination.

IV. Changes from Proposal

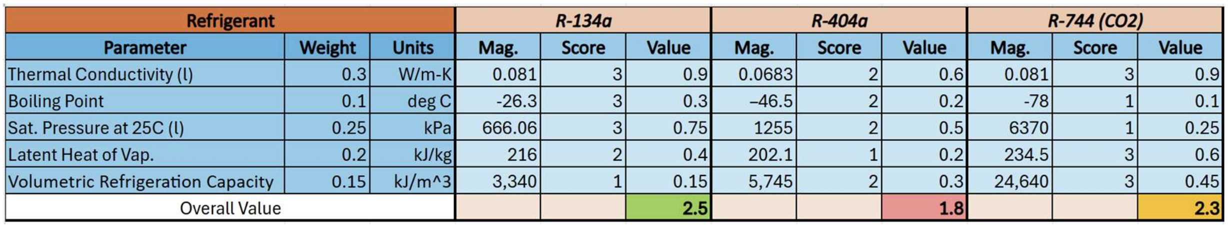
The technical paper expands the proposal by adding component-level trade studies for the refrigerant, compressor, heat exchangers, expansion device, piping, valves, and temperature sensing hardware. These trade studies compare component options against packaging, pressure, thermal-performance, material, power, mass, and cost criteria. AQUORA's operational concept is expanded through cold-path isolation, cold-path flushing, cold water quality hold, and return-to-service verification procedures. These procedures show how off-nominal chilled-water conditions can be contained within the added cold subsystem while preserving hot and ambient dispensing. An additional microbial solution of a sonication system is also introduced for potential future testing. The timeline and budget are also updated to represent longer testing, qualification, and integration path required to mature AQUORA toward flight-ready implementation.

V. Trade Studies

AQUORA's components are selected by first evaluating parameters specific to each type of component. After weighing the parameters based on their importance models are compared to finding which would best match criteria necessary for AQUORA. Additional weight is given to components with a history of use for previous space applications or missions, especially if one has been implemented on the International Space Station (ISS) [1,2]. The overall ratings, from best to worst, in the trade studies are listed in the following order: green, orange, red.

The selection process begins with comparing common refrigerants, as shown in *Table 1*. Between R-134a, R-404a, and R-744, some vital considerations are thermal conductivity, saturation pressure, and latent heat of vaporization. These parameters are chosen because they define the main purpose of refrigerants, being the ability to absorb and expel large amounts of heat before changing state, which allows for maximum energy transfer. Additionally, while not vital factors of consideration, both boiling point and volumetric refrigeration capacity can still influence the effectiveness of a refrigerant in transferring heat to and from different water sources.

Table 1: Refrigerant Trade Study



Refrigerant			R-134a			R-404a			R-744 (CO2)		
Parameter	Weight	Units	Mag.	Score	Value	Mag.	Score	Value	Mag.	Score	Value
Thermal Conductivity (l)	0.3	W/m-K	0.081	3	0.9	0.0683	2	0.6	0.081	3	0.9
Boiling Point	0.1	deg C	-26.3	3	0.3	–46.5	2	0.2	-78	1	0.1
Sat. Pressure at 25C (l)	0.25	kPa	666.06	3	0.75	1255	2	0.5	6370	1	0.25
Latent Heat of Vap.	0.2	kJ/kg	216	2	0.4	202.1	1	0.2	234.5	3	0.6
Volumetric Refrigeration Capacity	0.15	kJ/m^3	3,340	1	0.15	5,745	2	0.3	24,640	3	0.45
Overall Value					🟩 2.5			🟥 1.8			🟧 2.3

Based on the results of the study, R-134a is selected as the most viable refrigerant option for AQUORA. With this selection in mind, a major consideration with the following components would be compatibility with R-134a refrigerant [6].

The next major component in the selection process is the heat exchanger, as shown in *Table 2*. It is desirable to select a single type of heat exchanger that is optimal to use as both an evaporator and a condenser. Therefore, the parameters are compared while considering each component as an evaporator and a condenser separately. The most pressing guidelines are the maximum pressure, maximum temperature, and material yield strength the component can withstand as well as its longest dimension. The highest max pressure, max temperature, and yield strength are desired while the shortest longest dimension is also highly considered. The final parameter reviewed is the maximum internal surface area, in which the highest value is the most favorable. Through the study, Exergy's Shell & Tube 10 Series heat exchanger is selected for both an evaporator and compressor [7].

Table 2: Heat Exchanger Trade Study

Heat Exchanger			***VPE A22-2 HX-01041***			***Exergy Shell & Tube 10 Series***			***ChillX Stainless Steel (10 Ton)***		
Parameter	**Weight**	**Units**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**
Max Pressure	0.2	bar	124.1	3	0.6	104	2	0.4	36	1	0.2
Max Internal Surface Area	0.1	m^2	0.3849	3	0.3	0.016	1	0.1	0.15	2	0.2
Material Yield Strength	0.2	MPa	240	3	0.6	170	2	0.4	170	2	0.4
Max Temperature	0.25	deg C	200	2	0.5	425	3	0.75	30	1	0.25
Longest Dimension	0.25	mm	508	1	0.25	226	3	0.75	360.7	2	0.5
Overall Value					**2.25**			**2.4**			**1.55**

For selecting a compressor, displayed in *Table 3*, important considerations included cooling capacity, maximum variable speed, and operating voltage. Being the loudest component during operation, all three compressor options are selected while considering the need to be quiet for the sake of the crew. The lowest operating voltage is the most desired while the highest cooling capacity and variable speed are needed as well. For remaining parameters, the lowest mass and lowest minimum evaporator temperature (within range) are sought after. The best-suited component for the system requirements is RIGID's HVAC QX1901VDL mini compressor [8].

Table 3: Compressor Trade Study [9,10]

Compressor			***RIGID HVAC QX1901VDL***			***Aspen A-9***			***Lando Chillers LD-MC 024***		
Parameter	**Weight**	**Units**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**
Cooling Capacity	0.2	W	450	2	0.4	455	2	0.4	625	3	0.6
Mass	0.15	kg	0.72	2	0.3	0.68	3	0.45	1.3	1	0.15
Max Variable Speed	0.25	rpm	6500	3	0.75	6500	3	0.75	6300	2	0.5
Min Evaporator Temperature	0.15	deg C	5	3	0.45	-22	1	0.15	5	3	0.45
Operating Voltage	0.25	V	12	3	0.75	24	1	0.25	12	3	0.75
Overall Value					**2.65**			**2**			**2.45**

Additional component trades support the selection of the expansion valve, refrigeration piping, solenoid valve, temperature sensor, and flow-control valve, with detailed scoring provided in the appendix. These supporting trades focus on compatibility with the selected R-134a refrigeration loop, pressure containment, packaging, control response, material compatibility, power consumption, mass, and cost. The expansion valve regulates refrigerant flow into the evaporator, while the 316L stainless-steel piping provides corrosion resistance and pressure capability for the refrigeration loop [11-13]. The solenoid and flow-control valves support cold-path isolation and controlled dispensing, and the immersion temperature sensor provides cold-water temperature feedback for safe operation [14-18]. Together, these supporting component selections complete the cold-water subsystem configuration summarized in *Table 4*.

Table 4: Component Selection Summary

Component	Selection
Refrigerant	R-134a
Evaporator	Exergy Shell & Tube 10 Series
Condenser	Exergy Shell & Tube 10 Series
Compressor	RIGID HVAC QX1901VDL
Pipes	Stainless Steel 316L
Solenoid Valve	STC 2S050
Temperature Sensor	ATC Semitec BTS5
Flow Control Valve	Bürkert Type 2875

VI. System Overview & Architecture

The vapor-compression refrigeration cycle uses R-134a as the working fluid and consists of four primary components: compressor, condenser, expansion device, and evaporator. R-134a is selected due to its established operational heritage aboard the International Space Station (ISS), demonstrated reliability in spaceflight thermal control applications, and compatibility with a compact refrigeration architecture [19]. The potable water loop and associated heat exchanger components are constructed from 316 stainless steel to provide corrosion resistance, microbial compatibility, and long-term structural durability within potable water systems intended for spaceflight environments.

The refrigeration cycle operates through controlled variations in refrigerant pressure, temperature, and phase to facilitate thermal energy transfer. The primary thermodynamic objective is to deliver the refrigerant to the condenser as a high-pressure, high-temperature vapor and to the evaporator as a low-pressure, low-temperature two-phase mixture. Maintaining appropriate saturation conditions at both the condenser and evaporator is critical to maximizing latent heat transfer efficiency during condensation and evaporation processes [20].

Figure 1 presents the full AQUORA system flow architecture. Potable water enters from the habitat water bus, passes through the treatment section, and is routed through the selected hot, ambient, or cold dispensing path before reaching the common dispensing needle. The hot and ambient paths preserve the heritage PWD/xPWD functionality, while the added cold path sends potable water through an isolated heat exchanger before dispensing. The refrigeration loop remains separate from the potable water path and uses the condenser to reject heat to the coolant interface. This layout keeps potable water, refrigerant, and thermal-control coolant physically isolated while showing how the cold-water subsystem integrates into the existing dispenser architecture.

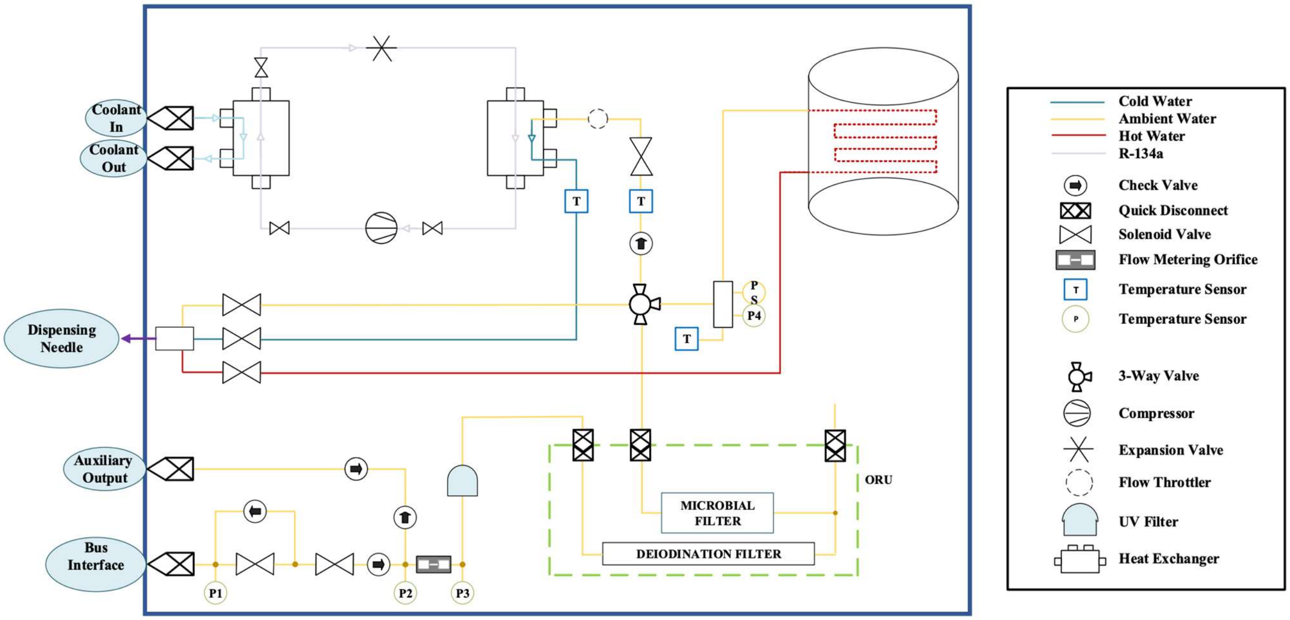


Figure 1: Flow Diagram

The cycle begins at the compressor inlet, where the refrigerant enters as a low-pressure, low-temperature vapor, typically in a slightly superheated state. The compressor increases the refrigerant pressure and temperature, producing a high-pressure, high-temperature vapor suitable for downstream heat rejection. Increasing the saturation pressure raises the corresponding condensation temperature. This enables thermal energy rejection to the surrounding thermal sink.

The high-pressure vapor then enters the condenser, where heat is rejected to the IATCS loop. During this process, the refrigerant is first cooled as a saturated vapor and subsequently condensed into a high-pressure liquid at approximately constant pressure and temperature. The condenser therefore functions to remove thermal energy from the refrigerant to complete the vapor-to-liquid phase transition.

Following condensation, the high-pressure liquid refrigerant passes through the expansion valve. The expansion process produces a significant pressure reduction while occurring at approximately constant enthalpy. Due to the rapid decrease of pressure, partial flash evaporation occurs, resulting in a low-pressure, low-temperature two-phase mixture at the expansion valve outlet. This two-phase condition is an expected and necessary characteristic of the refrigeration cycle and directly supports consistent evaporator performance.

The refrigerant then enters the evaporator, where it absorbs thermal energy from the potable water loop. Heat absorption causes the refrigerant to boil at approximately constant temperature and pressure, transitioning toward a saturated vapor state while reducing the potable water temperature to the desired dispensing range. This evaporation process leverages the refrigerant’s latent heat of vaporization to provide stable and efficient thermal transfer. The refrigerant vapor subsequently exits the evaporator and returns to the compressor inlet, completing the cycle.

VII. Engineering & Technical Analysis

Table 5: Functional Requirements [1, 2, 21]

Requirement	Description	Target Value(s)
Three water delivery modes	Provide hot, ambient, and cold potable water	Hot: 66 – 93°C Ambient: 18 – 51°C Cold: 4 – 8°C
Potable water delivery amount	Total volume provided by system	25 mL increments up to 250 mL
Potable water quality and microbial safety	Preserve potable water quality by supporting microbial control and biofilm mitigation.	50 CFM/mL CFM = Colony Forming Units Iodine concentration: 0.2 mg/L - 6.0 mg/L
Compatibility with legacy PWD/xPWD envelope	Fit within existing packaging and interface constraints.	WxHxD: 18.5” x 22.5” x 21.5”
Efficient Heat Rejection [3]	Rejects waste heat to the IATCS thermal sink.	95% refrigerant condensation performance

The engineering analysis for AQUORA focuses on selecting a cold-water architecture that meets performance needs while preserving the heritage PWD/xPWD design. A subsystem-level trade study compared candidate cooling concepts based on thermal performance, packaging within the existing dispenser envelope, separation between the refrigerant and potable water loops, reliability, and compatibility with IATCS heat rejection. From this process, a closed-loop vapor-compression cycle is selected as the most practical solution.

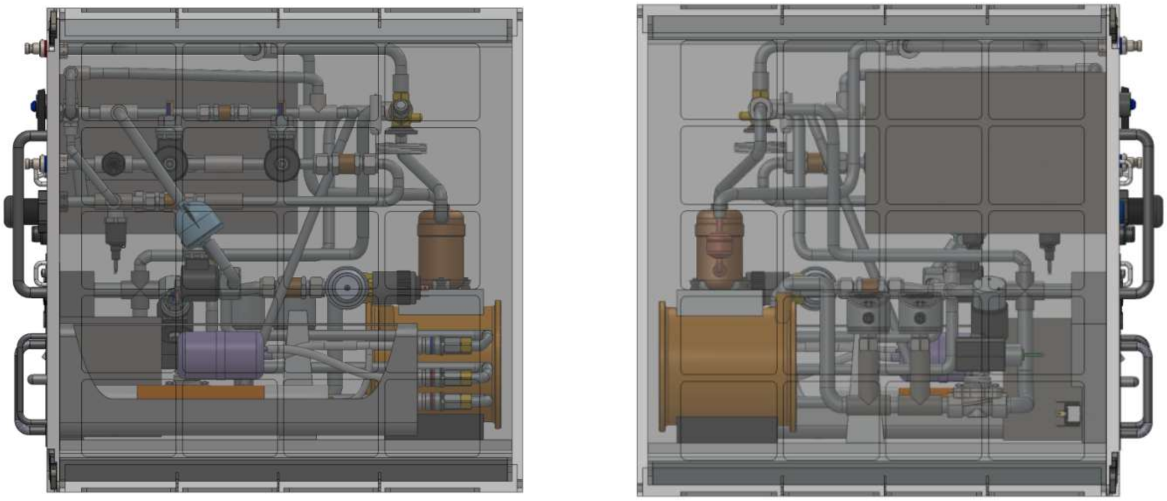


Figure 2: AQUORA CAD view. (a) Port-side view (b) Starboard-side view

Thermodynamic and heat transfer analysis then focused on the cooling duty required to reduce potable water to the desired cold-water range. As discussed in the system architecture section, the evaporator-side heat exchanger is the key thermal interface in the system. It transfers heat from the potable water stream to the refrigerant while maintaining physical separation between the loops to preserve water quality and system safety. These results support the feasibility of a compact refrigeration-based subsystem for delivering cold potable water.

Previous studies from spacecraft and potable water systems show that several bacterial groups are capable of forming biofilms, impacting long-term water quality [4, 5]. These organisms include *Burkholderia cepacia* complex organisms, *Ralstonia pickettii* (previously classified under *Pseudomonas*), *Sphingomonas paucimobilis*, *Sphingomonas yanoikuyae*, *Sphingomonas stygialis [23]*, and indicator organisms such as *Escherichia coli* (*E. coli*) [4]. These organisms are primarily Gram-negative bacteria capable of surviving under low-nutrient conditions and attaching to wetted surfaces to establish biofilms [2, 24].

Biofilm formation within AQUORA may reduce effectiveness of the iodine treatment and limit direct interaction with ultraviolet disinfection methods. To supplement these existing microbial control systems, AQUORA proposes evaluating sonication through piezoelectric ring actuators to introduce mechanical disturbance within the water pathway and reduce conditions favorable for early-stage biofilm formation. Piezoelectric rings are chosen because medical equipment technology has demonstrated that sonication-based cleaning methods can reduce bacterial biofilms by approximately 10,000-fold, showing strong potential for biofilm mitigation in spacecraft water systems [25]. The actuators, powered by one or more ultrasonic drivers, would be externally mounted onto selected tubing sections, manifolds, and other regions susceptible to biofilm development. The rings will receive energy from the drivers, which will generate ultrasonic vibrations through the tubing walls to give localized mechanical disturbance and reduce favorable conditions to biofilm formations [26]. These vibrations would occur for approximately 30 seconds every 20 minutes based on the rapid growth rate of *E. coli*, which has a doubling time of about 20 minutes [27].

Since ultrasonic mitigation has not been validated for AQUORA, implementation will have to go through testing before full system integration. Initial testing will integrate the sonication subsystem into the AQUORA water dispenser on the ISS. This testing would evaluate biofilm reduction, water quality, temperature rise, pressure drops, free gas generation, and power consumption. If testing demonstrates measurable improvements without negative system impacts, the piezoelectric subsystem could be added to future AQUORA models.

VIII. Verification and Validation Plan

Table 6 outlines the set of procedures necessary to move AQUORA from a conceptual design to a flight worthy system. Because the design preserves the heritage PWD/xPWD hot and ambient architecture, early V&V focuses on the added cold-water subsystem and the risks introduced by that subsystem: cold-water delivery, IATCS heat rejection, potable/refrigerant isolation, cold-path stagnation, and integrated flightworthiness. Full NASA certification and flight testing is deferred to later qualification [28, 29].

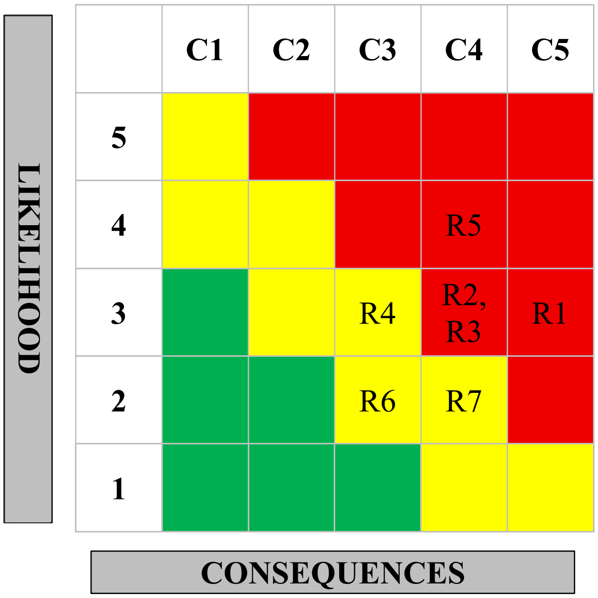
Table 6: Validation and Verification Objectives

Objective	Proposed Method	Evidence of Success
Verify cold-water delivery	Develop a breadboard cold-water loop and test repeated 25–250 mL dispense cases, including worst-case warm inlet water and repeated crew-use cycles.	Outlet temperature meets the cold-water requirement, nominally 4–8°C, within instrument uncertainty; dispense volume remains within defined limits.
Close the thermal balance	Measure potable-water heat removal, compressor power, and condenser heat rejection during cold-mode operation.	Measured heat removal and heat rejection agree within instrument uncertainty, supporting the calculated condenser load of approximately 196.4 W.
Demonstrate thermal-interface compatibility	Test the condenser against an IATCS-representative coolant loop while recording coolant flow rate, inlet/outlet temperature, pressure, and heat rejection.	The subsystem rejects the calculated heat load without exceeding interface temperature, pressure, or flow limits. Results can be generalized to equivalent spacecraft thermal-control loops.
Verify fluid isolation and containment	Perform pressure-hold, leak-detection, and post-cycle inspection of all fluid boundaries: potable water, refrigerant, and thermal-control coolant. Repeat after thermal cycling.	No measurable pressure decay, leakage, or evidence of cross-contamination between potable water, refrigerant, and coolant loops.
Evaluate cold-path water-quality recovery	Conduct dormancy-and-flush testing using the proposed cold-path flush sequence, with water-quality checks before return to service. Treat sonication as a future risk-reduction test, not a baseline requirement.	Cold path is returned to service only after water quality is verified within allowable limits; stagnation does not require full dispenser shutdown.

IX. Risk Analysis

AQUORA’s preliminary risk analysis is developed from the selected subsystem architecture, component trade results, and added cold-path contingency procedures. Each risk is assessed using a 1-5 likelihood scale and a 1-5 consequence scale, where higher values indicate greater probability or greater mission impact [28, 29]. The highest-priority risks are associated with potable water quality, refrigerant containment, heat rejection, cold-path control, component qualification, valve reliability, and crew habitability impacts from added compressor operation.

Table 7: AQUORA Risk Matrix



LIKELIHOOD

	C1	C2	C3	C4	C5
5	🟨	🟥	🟥	🟥	🟥
4	🟨	🟨	🟥	🟥 R5	🟥
3	🟩	🟨	🟨 R4	🟥 R2, R3	🟥 R1
2	🟩	🟩	🟨 R6	🟨 R7	🟥
1	🟩	🟩	🟩	🟨	🟨

CONSEQUENCES

Risk 1, cold-path microbial growth or biofilm formation, is the primary water-quality risk. The added chilled-water path increases wetted hardware and may introduce additional stagnant regions if the system is not flushed or operated regularly. AQUORA mitigates this risk by minimizing dead-leg geometry where possible, maintaining smooth wetted flow paths, and extending Flush Iodine and Flush Water recovery procedures through the cold path before chilled service is restored.

Risk 2, refrigerant leakage or loss of charge, could reduce chilled-water performance or require cold-mode shutdown. This risk is mitigated through a sealed refrigeration loop, minimized service fittings, pressure and leak testing, and cold-mode lockout if refrigeration-loop behavior becomes off-nominal.

Risk 3, insufficient heat rejection, could occur if the assumed spacecraft thermal-control interface cannot reject the condenser heat load at the required sink temperature, flow condition, or duty cycle. AQUORA mitigates this risk by defining condenser heat-rejection requirements, monitoring condenser-side thermal performance, and isolating chilled mode if the cold subsystem cannot maintain the required heat-rejection margin.

Risk 4, cold throughput error, could result from sensor drift, expansion-device instability, or compressor-control issues. This risk is mitigated through temperature feedback control, operating limits, and fault detection based on disagreement between commanded and measured cold-water performance.

Risk 5, integrated hardware qualification uncertainty, addresses the gap between preliminary component selection and final flight implementation. The selected hardware configuration requires additional subsystem-level verification to confirm that the assembled cold-water loop maintains structural integrity, leak-tightness, and functional performance after exposure to the expected flight environment.

Risk 6, valve or flow-control failure, could prevent proper cold-path isolation, reduce dispense accuracy, or route water through an unintended path. AQUORA mitigates this risk through fail-safe valve positioning, valve cycle testing, flow verification, and mode logic that allows the cold subsystem to be isolated without disabling hot and ambient dispensing when those functions remain nominal.

Risk 7, compressor acoustic or vibration impact, is a crew habitability and integration risk introduced by the vapor-compression subsystem. This risk is mitigated through low-noise compressor selection, vibration isolation, duty-cycle control, and acoustic and vibration testing during subsystem validation.

Overall, the highest risks are concentrated in the added cold-water subsystem rather than the inherited hot and ambient dispenser functions. AQUORA's risk strategy is therefore based on containment and isolation.

X. Contingency Operation & Failsafe Procedures

AQUORA preserves the existing PWD/xPWD operational framework rather than replacing it. Heritage operating and recovery modes, including Rehydration, Flush Iodine, Flush Water, and Auxiliary, remain unchanged as the baseline dispenser procedures [1,2]. The added contingency procedures below apply only to the new cold-water path and are intended to preserve potable water safety while supporting full-life operation of the integrated cold subsystem.

Table 8: AQUORA Fail Safe Procedures

AQUORA Added Procedure	Trigger	System Response	Purpose
Cold Path Isolation	Cold outlet temperature out of range, cold-loop pressure limit exceeded, sensor disagreement, or unexpected cooling behavior	Disables cold dispensing and places the cold path in a safe state. Hot and ambient dispensing remain available if water quality and containment are nominal.	Prevents an off-nominal cold condition from impacting the full dispenser.
Cold Path Flush	Cold-path dormancy, stagnation concern, or directed water quality recovery	Routes the existing Flush Iodine/Water recovery sequence through the cold path.	Extends the heritage PWD recovery approach to the added cold-water path.
Cold Water Quality Hold	Suspected cold-path contamination, failed water quality sample, or unresolved dormancy condition	Prevents chilled water use until the cold path completes the required flush and verification sequence.	Protects crew consumption while avoiding unnecessary full-system shutdown.
Cold Return-to-Service Verification	After Cold Path Isolation, Cold Path Flush, or Water Quality Hold	Confirms cold-path flow, temperature control, and water quality before cold dispense is restored	Ensures cold service is only restored after the path is confirmed nominal.

The added procedures support AQUORA's cold-safe operating philosophy. Cold-path faults are isolated to the cold-water function. The existing hot and ambient modes remain available when the rest of the dispenser is running as intended. For dormancy or water quality recover, AQUORA extends the heritage Flush Iodine and Flush Water sequence through the cold-water hardware prior to returning cold water to service.

XI. Realistic Technology Assumptions

AQUORA is developed under several realistic technology assumptions to define the scope of the design. Future long-duration transit and surface habitats are assumed to include a centralized potable water supply, such as the potable water bus on the ISS or equivalent spacecraft water distribution architecture [21]. AQUORA is therefore designed as an end-use dispenser rather than a standalone water processor. Here, upstream water recovery, storage, and primary water quality management are handled at the spacecraft ECLSS level.

The dispenser is assumed to remain compatible with crew food and beverage preparation operations. Hot and ambient dispensing are retained as baseline functions while chilled water is added to improve crew hydration, habitability, and food preparation flexibility for Lunar and Martian mission applications. This framing allows the cold-water function to be treated as an added capability without changing the dispenser's core role within the ECLSS framework.

AQUORA also assumes that the spacecraft provides an available heat rejection interface through the internal thermal control system. The ISS IATCS uses water loops inside habitable modules to collect and transport waste heat thus making water-based internal cooling a reasonable analog for future habitat integration [3]. AQUORA's heat rejection approach is therefore scoped around transferring heat from the potable cold-water path to an available spacecraft thermal control interface while maintaining isolation between potable water and non-potable thermal fluids.

Additionally, to reduce hindrance to the crew, each AQUORA component is selected to ensure as quiet operation as possible. The loudest unit in the system is normally the compressor, so all compressor options considered are first filtered by quietest operation. All three components are rated at about the same low noise level. Also, just like the compressor, the solenoid valve is chosen between direct current (DC) options rather than alternating current (AC), as AC coils hum constantly while DC coils do not [30]. The rest of the components are chosen under these similar frameworks.

The design is scoped to minimize crew burden, reduce stagnant wetted regions where possible, and retain heritage PWD/xPWD operating and recovery logic where applicable for long-duration operation.

XII. Mass, Volume, and Power Estimates

Table 9 summarizes mass, volume, power, and heat-rejection estimates for the AQUORA cold-water subsystem [7, 8, 12]. These values represent the major refrigeration-loop components only and are intended as first-order sizing estimates. The evaporator is sized to remove approximately 163.7 W from the potable water stream for the bounding cooling case, while the condenser must reject approximately 196.4 W to the spacecraft thermal-control interface after accounting for compressor work [3, 6, 20]. The compressor is the only active power-consuming component in the cold loop, with the remaining components treated as passive thermal-fluid hardware [8]. The negative heat-rejection value for the evaporator indicates heat absorbed from the potable water, while the positive condenser value represents heat that must be rejected to the IATCS. The reader is directed to the Appendix for calculations related to this analysis.

Table 9: Mass, Volume, and Power Estimates

Component	Mass (kg)	Volume (cm^3)	Power (W)	Heat Rejection (W)
Evaporator	0.15 kg	102	0W	-163.7 W

Compressor	0.72 kg	200	75W-150W	164 W
Condenser	0.15 kg	102	0W	196.4 W
Expansion Valve	0.64 kg	25	0W	0W

XIII. Proposed Path-to-Flight Project Timeline

AQUORA follows a proposed six-year Development, Test, and Evaluation (DT&E) timeline aligned with NASA human-rated system development practices and projected Artemis surface mission schedules [31]. Because the system retains much of the existing PWD/xPWD architecture, development efforts are primarily focused on validating the new cold-water subsystem, thermal integration, and long-duration operational reliability

Table 10: Project Timeline

Phase	Timeline	Major Activities
Phase I: Concept Development & Requirements Definition	Year 1	Finalize mission requirements, perform component trade studies, complete preliminary thermal and fluid modeling, and conduct Preliminary Design Review (PDR).
Phase II: Prototype Development & Testing	Year 2	Fabricate initial cold-water subsystem prototypes, perform refrigeration testing, validate heat exchanger performance, and evaluate microbial mitigation strategies.
Phase III: Integrated Engineering Model Development	Year 3	Integrate the cold-water subsystem into a full engineering model of the dispenser, conduct thermal-fluid performance testing, and complete Critical Design Review (CDR).
Phase IV: Qualification & Environmental Testing	Year 4	Perform vibration, thermal vacuum, and reliability testing to simulate launch and lunar surface operational environments.
Phase V: Flight Certification & Habitat Integration	Year 5	Complete flight qualification testing, software validation, crew operations assessments, and integrated habitat compatibility testing prior to Flight Readiness Review (FRR).
Phase VI: Artemis Deployment & Operational Validation	Year 6	Deploy AQUORA within a lunar surface habitat architecture for operational validation during Artemis missions and long-duration crew habitation scenarios.

XIV. Cost and Budget Assessment

The estimated prototype hardware cost for the AQUORA cold-water subsystem is approximately $25,000, with major cost drivers including the heat exchangers, refrigeration loop hardware, plumbing components, structural packaging, and thermal control interfaces. Additional hardware margin is included to account for subsystem redesigns and prototype iterations during development.

The estimated total non-recurring development cost is approximately $17 million and includes subsystem development, prototype manufacturing, environmental qualification testing, personnel labor, systems integration, and certification support. A significant portion of the projected budget is associated with thermal vacuum testing, vibration testing, and operational evaluations required to verify system performance and survivability under launch and lunar surface conditions. Personnel estimates are based on Bureau of Labor Statistics salary data for aerospace engineers, engineering managers, and aerospace engineering technicians, scaled appropriately for a small subsystem development team [32]. Recurring production costs are expected to remain relatively low due to the reuse of heritage ISS PWD/xPWD hardware and operational architecture. Overall, AQUORA provides a cost-effective and lower-risk upgrade path for future Artemis potable water systems by integrating new cooling capability within an already flight-proven architecture. The use of heritage ISS technologies helps reduce certification complexity, development overhead, and overall system integration risk while improving crew comfort and operational flexibility for long-duration lunar missions.

Table 11: AQUORA Program Budget Breakdown
(All Values in Millions of FY2029 USD)

Cost Element	FY26	FY27	FY28	FY29	Total
1. AQUORA Hardware / Cold-Water Subsystem					
Cold-Water Subsystem Components	0.3	0.5	0.3	0.1	1.2
Heat Exchangers & Thermal Hardware	0.2	0.4	0.2	0.1	0.9
Fluid System Components & Plumbing	0.1	0.2	0.1	0.1	0.5
Sensor & Monitoring Systems	0.1	0.2	0.1	0.0	0.4
Prototype Manufacturing	0.4	0.7	0.5	0.2	1.8
Subtotal	**1.1**	**2.0**	**1.2**	**0.5**	**4.8**
2. Manufacturing & Test Facilities					
Clean Room Operations	0.1	0.2	0.2	0.1	0.6
Thermal Vacuum Testing	0.2	0.4	0.5	0.2	1.3
Vibration & Environmental Testing	0.1	0.3	0.4	0.1	0.9
Integration Facilities	0.1	0.2	0.2	0.1	0.6
Subtotal	**0.5**	**1.1**	**1.3**	**0.5**	**3.4**
3. Personnel Costs					
Aerospace Engineers	0.5	0.7	0.9	1.1	3.2
Project Management	0.2	0.3	0.3	0.2	1.0
Technicians & Integration Staff	0.3	0.4	0.4	0.3	1.4
Systems & Safety Review Personnel	0.1	0.2	0.3	0.2	0.8
Subtotal	**1.1**	**1.6**	**1.9**	**1.8**	**6.4**
4. Program-Level Costs					
Documentation & Verification	0.1	0.2	0.2	0.2	0.7
Flight Certification & Validation	0.0	0.1	0.3	0.4	0.8
Risk Reduction & Contingency	0.2	0.3	0.4	0.3	1.2
Subtotal	**0.3**	**0.6**	**0.9**	**0.9**	**2.7**
TOTAL PROJECT COST	**3.0**	**5.3**	**5.3**	**3.7**	**17.3M**

Table 12: Prototype Hardware Cost Estimate

Component	Estimated Cost
Compressor	$210
Expansion Valve	$400
Water Solenoid Valve	$62
Flow Control Valve	$389
Refrigerant	$400
Thermistors & Sensors	$85
Heat Exchangers	$12,000
Tubing, Wiring, & Insulation	$2,500
Structural Packaging	$3,000
Miscellaneous Hardware Margin	$5,000
Estimated Prototype Hardware Total	**$23,557**

XV. Conclusion and Key Findings

AQUORA provides a practical upgrade for potable systems for future long-term space habitats by adding chilled-water capability and preserving core functionality of the heritage of the ISS PWD/xPWD architecture. The proposed design maintains the current hot and ambient dispensing subsystems and introduces an innovative cold-water subsystem with the following characteristics: R-134 vapor-compression, isolated potable cold-water, and refrigerant loops. This architecture supports improvements for crew hydration, food preparation, and habitability without requiring a complete re-design of the existing dispenser network.

The preliminary engineering analysis indicates that the designed cold-water subsystem can be sized within the designated volume dimensions and rejects enough heat waste to the IATCS to maintain nominal operations. The evaporator is sized to remove 163.7 W from the potable water stream, and the condenser is sized to reject 196.4 W after accounting for compressor work. Component trade studies identify R-134a, miniature shell-and-tube heat exchangers, stainless-steel wetted hardware, and a miniature compressor as baseline selections for continued development. This approach concentrates technical risks in the cold-water subsystem, as the ambient and hot systems are flight proven through extensive ISS operation. The highest priority concerns are microbial growth, integrated hardware qualification, refrigerant containment, heat rejection capability, and cold-mode control authority. AQUORA addresses these risks using an isolated cold-path with flush and return-to-duty procedures. The cold path also includes leak testing, water-quality verification, and thermal monitoring. The proposed sonication concept may provide additional biofilm risk reduction, but it shall remain a future validation item until further testing can be completed.

Overall, AQUORA demonstrates a credible concept for extending potable water dispenser capability in long duration surface habitats support of the Artemis program. The strongest advantage of AQUORA is that it preserves heritage operating logic and system interfaces while adding an isolated cold-water capability. Future work should focus on breadboard testing, closing the thermal balance, validating the IATCS heat-rejection interface, testing microbial recovery procedures, and completing environmental qualifications.

XVI. Appendix

References

[1] Barreda, J., and Shaw, L., "International Space Station USOS Potable Water Dispenser Development," NASA, 2008. Available: https://ntrs.nasa.gov/api/citations/20080013432/downloads/20080013432.pdf

[2] Maryatt, B., "Lessons Learned for the International Space Station Potable Water Dispenser," Texas Tech University DSpace Repository, 2018. Available: https://ttu-ir.tdl.org/items/bad446f4-69bd-430f-a879-5f7b09c90f6d

[3] Holt, M., and Morrison, R., "IATCS Coolant Remediation Project," NASA, 2005. Available: https://ntrs.nasa.gov/api/citations/20050210040/downloads/20050210040.pdf

[4] National Aeronautics and Space Administration, "Investigation of Biofilm Formation and Control for Spacecraft: An Early Literature Review," NASA, 2019. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190027342.pdf

[5] "High Extracellular Polymeric Substance Production and Biofilm Formation Potential in Potable Water Produced by the Potable Water Dispenser System," PubMed, 2024. Available: https://pubmed.ncbi.nlm.nih.gov/41641988/

[6] Lemmon, E. W., Bell, I. H., Huber, M. L., and McLinden, M. O., "NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties—REFPROP, Version 10.0," National Institute of Standards and Technology, Gaithersburg, MD, 2018. Available: https://www.nist.gov/srd/refprop

[7] Exergy, LLC, "Model No. 00268-01, 10 Series Shell & Tube Heat Exchanger," Exergy, LLC, n.d. Available: https://heat-exchangers.exergyllc.com/item/shell-tube-heat-exchangers/10-series-shell-tube-heat-exchangers/00268-01

[8] "Mini Compressor QX1901VDL (12V)," Rigid HVAC, Retrieved March 2, 2026. Available: https://www.rigidhvac.com/store/products/mini-compressor-qx1901vdl-12v

[9] Aspen Compressor, LLC, "Miniature Compressor," Aspen Compressor, LLC, n.d. Available: https://www.aspencompressor.com/

[10] Lando Chillers, "Mini Rotary DC Compressor, Miniature Refrigeration Compressor," Lando Chillers, 2025. Available: https://lando-chillers.com/portfolio-items/mini-rotary-dc-compressor-miniature-refrigeration-compressor/

[11] “Thermostatic Expansion Valve — Sporlan — Type SBF,” Parker, Retrieved March 2, 2026. Available: https://ph.parker.com/us/en/product/thermostatic-expansion-valve-sporlan-type-sbf/112195

[12] Danfoss, “Thermostatic Expansion Valves, Type TGE,” Danfoss, n.d. Available: https://www.danfoss.com/en/products/dcs/valves/thermostatic-expansion-valves-txv/thermostatic-expansion-valves/tge-thermostatic-expansion-valves/

[13] MatWeb, “Phosphorus Deoxidized Copper, High Residual Phosphorus, UNS C12200,” MatWeb, n.d. Available: https://www.matweb.com/search/datasheettext.aspx?matguid=aa53d68532b442b39bcf816f19e020da;

[14] “STC 2S050-3/8 NPT Solenoid Valve, Stainless Steel Body, 2-Way, Normally Closed,” VALVEMAN, Retrieved March 2, 2026. Available: https://valveman.com/products/stc2s050-3-8-solenoid-valve-3-8-npt-2-way-normally-closed/

[15] Atlantic Valves, “General Service Solenoid Valves,” Atlantic Valves, n.d. Available: https://atlanticvalves.com/product/general-service/

[16] ATC Semitec Ltd., “BTS5 Fast Response Immersion Temperature Sensor,” ATC Semitec Ltd., n.d. Available: https://atcsemitec.co.uk/product/fast-response-boiler-temp-sensors/

[17] “Proportional Control Valve JSP,” SMC, Retrieved March 2, 2026. Available: https://www.smcworld.com/webcatalog/en-jp/process-valves/proportional-control-valve/JSP-E

[18] Bürkert Fluid Control Systems, “Type 2875: Direct-Acting 2-Way Standard Proportional Valve,” Bürkert Fluid Control Systems, 2026. Available: https://www.burkert.com/en/Media/plm/DTS/DS/ds2875-standard-eu-en.pdf

[19] Skipworth, A., “Zero-Gravity Effects on Vapor Compression Refrigeration,” Thermal and Fluids Analysis Workshop, NASA, 2021. Available: https://tfaws.nasa.gov/wp-content/uploads/TFAWS2021-AT-03-Paper.pdf

[20] Çengel, Y. A., Boles, M. A., and Kanoğlu, M., Thermodynamics: An Engineering Approach, 9th ed., McGraw-Hill Education, New York, 2019.

[21] Chen, T., Ewert, M., and Powell, C., “Life Support Baseline Values and Assumptions Document,” NASA, 2022. Available: https://ntrs.nasa.gov/citations/20210024855

[22] Collaborator Release, “Bacteria on the International Space Station No More Dangerous Than Earthbound Strains,” J. Craig Venter Institute, 2020. Available: https://www.jcvi.org/media-center/bacteria-international-space-station-no-more-dangerous-earthbound-strains

[23] National Center for Biotechnology Information, “Genomic Characterization of Potential Plant Growth-Promoting Features of Sphingomonas Strains Isolated from the International Space Station,” 2021. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC8283171/

[24] “Biofilm Formation Is Correlated with Low Nutrient and Simulated Microgravity Conditions in a Burkholderia Isolate from the ISS Water Processor Assembly,” ScienceDirect, 2023. Available: https://www.sciencedirect.com/science/article/pii/S2590207523000072

[25] Russo, A., Gatti, A., Felici, S., Gambardella, A., Fini, M., Neri, M. P., Zaffagnini, S., and Lazzarotto, T., “Piezoelectric Ultrasonic Debridement as New Tool for Biofilm Removal from Orthopedic Implants: A Study In Vitro,” Journal of Orthopaedic Research, Vol. 41, No. 12, 2023, pp. 2749–2755. https://doi.org/10.1002/jor.25599

[26] “Piezoelectric Ring Chips and Stacks (1.40 mm to 15.0 mm Travel),” Thorlabs. Available: https://www.thorlabs.com/piezoelectric-ring-chips-and-stacks-1.40-mm-to-15.0-mm-travel

[27] Son, M. S., Tuttle, A. R., and others, “Growth and Maintenance of Escherichia coli Laboratory Strains,” Current Protocols, 2021. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC8006063/

[28] National Aeronautics and Space Administration, “NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems,” NASA-STD-8729.1A, 2017. Available: https://s3vi.ndc.nasa.gov/ssri-kb/static/resources/nasa-std-8729.1a.pdf

[29] National Aeronautics and Space Administration, “NASA Systems Engineering Handbook,” NASA/SP-2016-6105 Rev. 2, 2016. Available: NASA Technical Reports Server.

[30] Magnatrol Valve Corporation, “AC Hum, Heat Rise, and General Coil Information,” Magnatrol Valve Corporation, n.d. Available: https://www.magnatrol.com/technical_achum.cfm

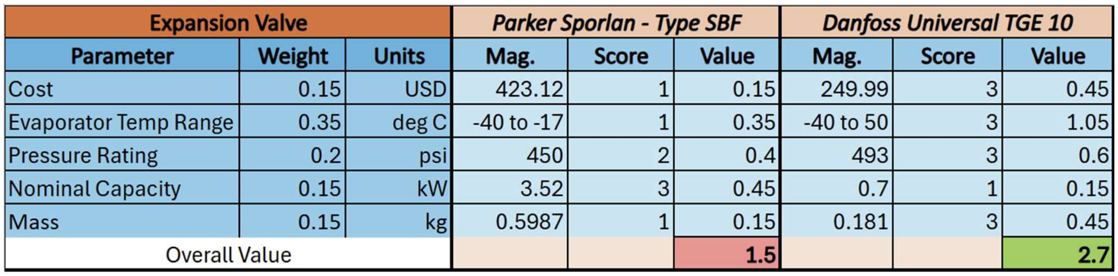
[31] National Aeronautics and Space Administration, “NASA Adds Mission to Artemis Lunar Program, Updates Architecture,” NASA, 2026. Available: https://www.nasa.gov/news-release/nasa-adds-mission-to-artemis-lunar-program-updates-architecture/

[32] U.S. Bureau of Labor Statistics, “Aerospace Engineers,” U.S. Bureau of Labor Statistics, 2025. Available: https://www.bls.gov/ooh/architecture-and-engineering/aerospace-engineers.htm

[33] National Aeronautics and Space Administration, “NASA Cost Estimating Handbook,” NASA, 2024. Available: https://www.nasa.gov/ocfo/ppc-corner/nasa-cost-estimating-handbook-ceh/

Trade Studies:

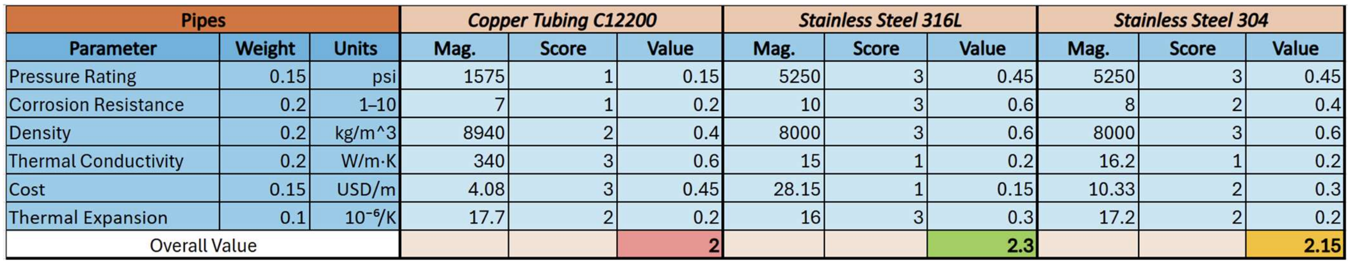
Table 13: Expansion Valve Trade Study



Expansion Valve			Parker Sporlan - Type SBF			Danfoss Universal TGE 10		
Parameter	Weight	Units	Mag.	Score	Value	Mag.	Score	Value
Cost	0.15	USD	423.12	1	0.15	249.99	3	0.45
Evaporator Temp Range	0.35	deg C	-40 to -17	1	0.35	-40 to 50	3	1.05
Pressure Rating	0.2	psi	450	2	0.4	493	3	0.6
Nominal Capacity	0.15	kW	3.52	3	0.45	0.7	1	0.15
Mass	0.15	kg	0.5987	1	0.15	0.181	3	0.45
Overall Value					1.5			2.7

The expansion valve selection trade study is completed in *Table 13*. There are a limited number of available components that matched desired requirements for the mission. Important parameters considered include the evaporator temperature range, pressure rating, nominal capacity, mass, and cost. The ideal temperature range depended on the needed temperatures calculated for the expansion valve, which only one component passed through. Considering the other parameters though, higher pressure rating and nominal capacity are needed as well as lower cost and mass. Out of the two components compared, only Danfoss's Universal TGE thermostatic expansion valve is capable enough.

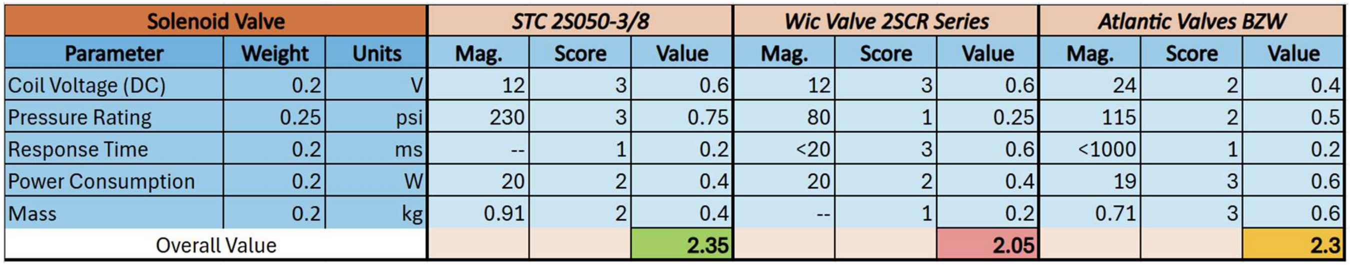
Table 14: Piping Trade Study



Pipes			Copper Tubing C12200			Stainless Steel 316L			Stainless Steel 304		
Parameter	Weight	Units	Mag.	Score	Value	Mag.	Score	Value	Mag.	Score	Value
Pressure Rating	0.15	psi	1575	1	0.15	5250	3	0.45	5250	3	0.45
Corrosion Resistance	0.2	1–10	7	1	0.2	10	3	0.6	8	2	0.4
Density	0.2	kg/m^3	8940	2	0.4	8000	3	0.6	8000	3	0.6
Thermal Conductivity	0.2	W/m·K	340	3	0.6	15	1	0.2	16.2	1	0.2
Cost	0.15	USD/m	4.08	3	0.45	28.15	1	0.15	10.33	2	0.3
Thermal Expansion	0.1	10^{-6}/K	17.7	2	0.2	16	3	0.3	17.2	2	0.2
Overall Value					2			2.3			2.15

Table 14 lists the comparison between three different pipe materials to be used in the refrigeration system connecting each major component together. A wide variety of parameters are considered, including pressure rating, corrosion resistance, density, thermal conductivity, cost, and thermal expansion coefficient. Corrosion resistance is rated on a scale of 1-10 compared with the other materials rather than having a definite parameter. The highest values are desired for pressure rating, corrosion resistance, and thermal conductivity, while the lowest values are needed for the other parameters. All three material types are used commonly in refrigeration systems. The pipe material with the best fit is Stainless Steel 316L.

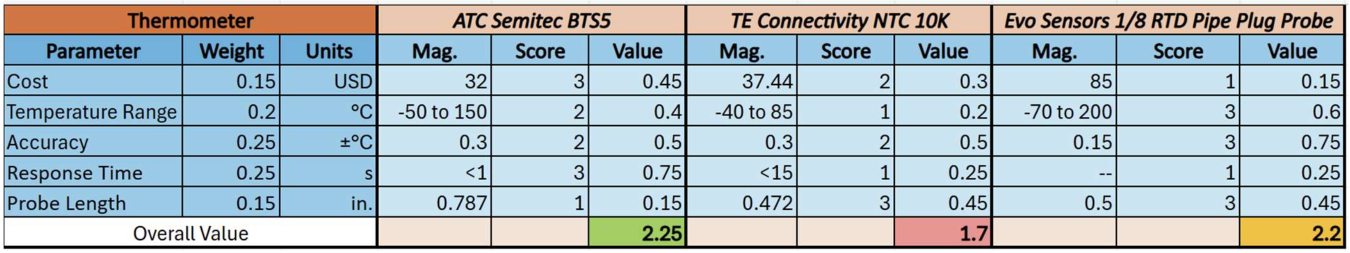
Table 15: Solenoid Valve Trade Study



Solenoid Valve			STC 2S050-3/8			Wic Valve 2SCR Series			Atlantic Valves BZW		
Parameter	**Weight**	**Units**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**
Coil Voltage (DC)	0.2	V	12	3	0.6	12	3	0.6	24	2	0.4
Pressure Rating	0.25	psi	230	3	0.75	80	1	0.25	115	2	0.5
Response Time	0.2	ms	--	1	0.2	<20	3	0.6	<1000	1	0.2
Power Consumption	0.2	W	20	2	0.4	20	2	0.4	19	3	0.6
Mass	0.2	kg	0.91	2	0.4	--	1	0.2	0.71	3	0.6
Overall Value					**2.35**			**2.05**			**2.3**

Different solenoid components are compared in *Table 15*. The parameters compared include DC coil voltage, pressure rating, response time, power consumption, and mass, with pressure rating being the most important factor. High pressure ratings and the lowest of every other parameter are considered best for solenoid valves. The leading component selected is STC Valve's STC 25050-3/8 series.

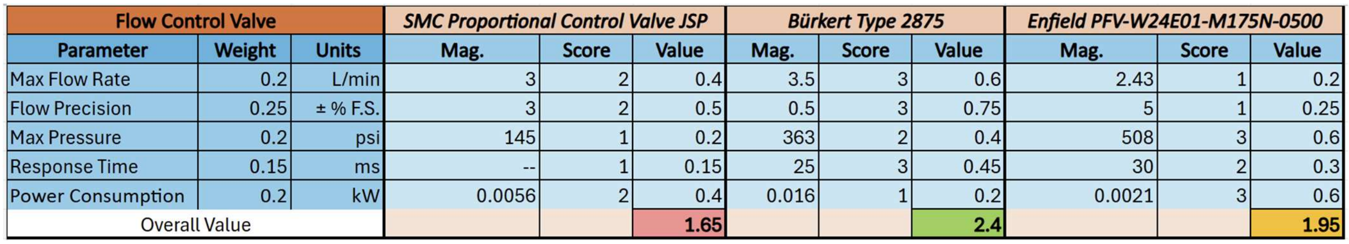
Table 16: Temperature Sensor Trade Study



Thermometer			ATC Semitec BTS5			TE Connectivity NTC 10K			Evo Sensors 1/8 RTD Pipe Plug Probe		
Parameter	**Weight**	**Units**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**
Cost	0.15	USD	32	3	0.45	37.44	2	0.3	85	1	0.15
Temperature Range	0.2	°C	-50 to 150	2	0.4	-40 to 85	1	0.2	-70 to 200	3	0.6
Accuracy	0.25	±°C	0.3	2	0.5	0.3	2	0.5	0.15	3	0.75
Response Time	0.25	s	<1	3	0.75	<15	1	0.25	--	1	0.25
Probe Length	0.15	in.	0.787	1	0.15	0.472	3	0.45	0.5	3	0.45
Overall Value					**2.25**			**1.7**			**2.2**

The temperature sensor used to detect potable water temperature is selected in the trade study of *Table 16*. The parameters considered are cost, temperature range, accuracy, response time, and probe length. Lowest cost, response time, and probe length are most needed, while the highest of the remaining parameters are also needed. The winning component of the trade study is ATC Semitec's BTS5 immersion sensor.

Table 17: Flow Control Valve Trade Study



Flow Control Valve			SMC Proportional Control Valve JSP			Bürkert Type 2875			Enfield PFV-W24E01-M175N-0500		
Parameter	**Weight**	**Units**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**	**Mag.**	**Score**	**Value**
Max Flow Rate	0.2	L/min	3	2	0.4	3.5	3	0.6	2.43	1	0.2
Flow Precision	0.25	± % F.S.	3	2	0.5	0.5	3	0.75	5	1	0.25
Max Pressure	0.2	psi	145	1	0.2	363	2	0.4	508	3	0.6
Response Time	0.15	ms	--	1	0.15	25	3	0.45	30	2	0.3
Power Consumption	0.2	kW	0.0056	2	0.4	0.016	1	0.2	0.0021	3	0.6
Overall Value					**1.65**			**2.4**			**1.95**

The final part of the component selection process is for the flow control valve, as shown in *Table 17*. The parameters noted are maximum flow rate, flow precision, maximum pressure, response time, and power consumption, with flow precision being the most important factor. The highest flow rate and pressure are desired as well as the lowest of the other parameters. Bürkert Fluid Control Systems' Type 2875 are selected as AQUORA's flow control valve.

A summary of the final trade study selections is located in Table 4.

Risk Analysis Calculations:

The AQUORA risk matrix uses a 1-5 likelihood scale and a 1-5 consequence scale. Likelihood represents the estimated probability of occurrence during development, integration, or operation. Consequence represents the estimated impact to crew safety, potable water quality, subsystem performance, or mission operations. The risk score is calculated as:

$$Risk\ Score = Likelihood\ x\ Consequence$$

Risk scores are grouped into three qualitative categories for the matrix:

- **Low Risk**: 1-5
- **Moderate Risk**: 6-12
- **High Risk:** 13-25

Risk ID	**Risk Name**	**Likelihood**	**Consequence**	**Risk Score**	**Risk Category**
R1	Cold-path microbial growth or biofilm formation	3	5	15	High
R2	Refrigerant leakage or loss of charge	3	4	12	Moderate
R3	Insufficient heat-rejection	3	4	12	Moderate
R4	Cold throughput error	3	3	9	Moderate
R5	Integrated hardware qualification uncertainty	4	4	16	High
R6	Valve or flow-control failure	2	3	6	Moderate
R7	Compressor acoustic or vibration impact	2	4	8	Moderate

Based on this scoring approach, the highest-scoring risks are R5 integrated hardware qualification uncertainty and R1 cold-path microbial growth or biofilm formation. R5 receives a high score because the selected hardware configuration requires subsystem-level environmental and structural verification before flight implementation. R1 receives a high score because potable water quality is crew-safety critical, and the added cold-water path increases the importance of microbial control, flushing, and water-quality verification. Risks R2, R3, R4, R6, and R7 remain moderate risks and are controlled through loop isolation, leak testing, thermal monitoring, valve testing, and acoustic/vibration verification.

Givens:

- **Volumetric flow rate of potable water:**
  - $\dot{V} = 0.05$ L/min = 8.33 (10^{-7}) m^3/s
- **Density:**
  - Water: $\rho = 1000$ kg/m^3
  - R-134a:
    - Evaporator:
      - Saturated liquid: $\rho = 1200$ kg/m^3
      - Saturated vapor: $\rho = 5.5$ kg/m^3
    - Condenser: $\rho = 1200$ kg/m^3
      - Saturated liquid: $\rho = 1000$ kg/m^3
      - Saturated vapor: $\rho = 20$ kg/m^3
- **Refrigerant Pressure & Enthalpy:**
  - Leaving evaporator (0° C):
    - Saturated vapor
    - p = 245.1 kPa
    - h = 247.27 kJ/kg
  - Leaving compressor (60° C):
    - Superheated vapor
    - p = 1015.3 kPa
    - h = 280 kJ/kg
  - Leaving condenser (40° C):
    - Saturated liquid
    - p = 1015.3 kPa
    - h = 95.05 kJ/kg
  - Leaving expansion valve (< 0° C):
    - Saturated liquid/vapor mixture
    - p = 245.1 kPa
    - h = 95.05 kJ/kg
- **Heat Exchangers:**
  - Effective transfer area: 0.05 to 0.17 ft^2
  - Overall heat transfer coefficient (evaporator): ~ 500 W/m^2K
  - Overall heat transfer coefficient (condenser): ~ 800 W/m^2K
- **Temperatures:**
  - Potable water inlet: 51° C (maximum)
  - Potable water outlet: 4° C (minimum)
  - IATCS coolant inlet: 1.67° C
  - IATCS coolant outlet: 6-7° C
  - Refrigerant through evaporator: 0° C

  - Refrigerant through condenser: 40° C
- **States:**
  1. Evaporator
  2. Compressor
  3. Condenser
  4. Expansion Valve

Calculations:

1. Mass flow rate of potable water:

$$\dot{m} = \rho \times \dot{V} = 1000 \times 10^{-7} = 8.33 \times 10^{-4}\ kg/s$$

2. Cooling load, Q_{evap}:

$$Q_{evap} = \dot{m} \times c_p \times (T_{in} - T_{out}) = (8.33 \times 10^{-4}) \times 4180 \times (51 - 4) = 163.7\ W$$

3. Log-mean temperature difference for evaporator:

$$\Delta T_{lm,evap} = \frac{\Delta T_{in} - \Delta T_{out}}{\ln(\Delta T_{in}/\Delta T_{out})} = 18.47°\ C$$

4. Required heat transfer area:

$$A_{evap} = \frac{Q_{evap}}{U_{evap} \times \Delta T_{lm,evap}} = \frac{163.7}{500 \times 18.47} = 0.0177\ m^2$$

5. Condenser heat rejection, Q_{cond}:

$$W_{comp} = (0.2) \times 163.7 = 32.7\ W\ \ (assuming\ work\ is\ 20\%\ of\ cooling\ load)$$

$$Q_{cond} = Q_{evap} + W_{comp} = 163.7 + 32.7 = 196.4\ W$$

6. Log-mean temperature difference for condenser:

$$\Delta T_{lm,cond} = \frac{\Delta T_{in} - \Delta T_{out}}{\ln(\Delta T_{in}/\Delta T_{out})} = 35.77°\ C$$

7. Required heat transfer area:

$$A_{cond} = \frac{Q_{cond}}{U_{cond} \times \Delta T_{lm,cond}} = \frac{196.4}{800 \times 35.77} = 0.00686\ m^2$$

8. Refrigeration effect:

$$Q_{in} = h_1 - h_4 = 247.27 - 95.05 = 152.22\,\frac{kJ}{kg}$$

9. Coefficient of performance (COP):

$$COP = \frac{Q_{in}}{W} = \frac{152.22}{32.73} = 4.65$$

10. Refrigerant mass flow rate:

$$\dot{m} = \frac{Q_{evap}}{Q_{in}} = \frac{0.1637}{152.22 \times 10^{-3}} = 1.08 \times 10^{-3}\ kg/s$$