

Enhanced Potable Water Dispenser (EPWD)

Purdue University

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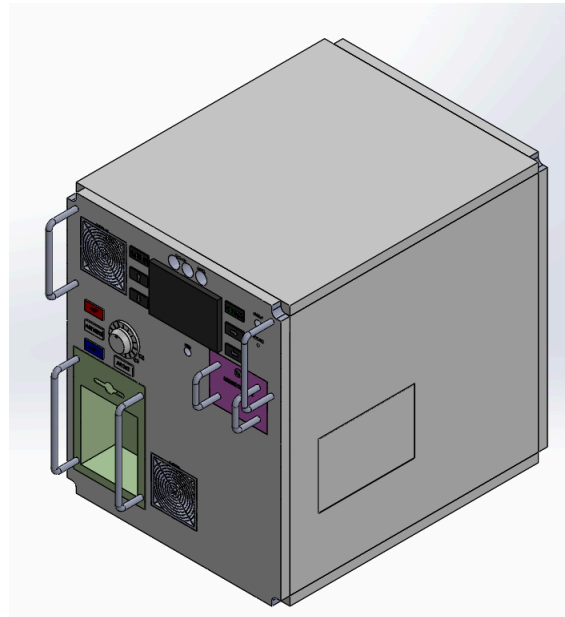


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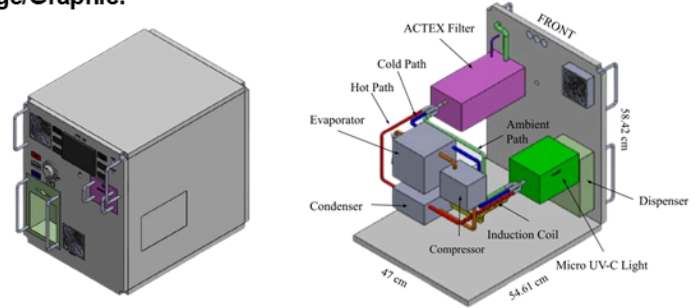
Quad Chart

Theme: Potable Water Dispenser

Major Objectives
Add a Cooling Element while Maximizing Throughput and Ensuring Safety and Reliability

Design Approach
Trade cooling and heating elements based on reliability, cost, throughput, mass, maintenance usage, TRL, and power consumption. Further improve upon the xPWD by minimizing dead spots, minimizing bubble formation, and enhancing user compatibility.

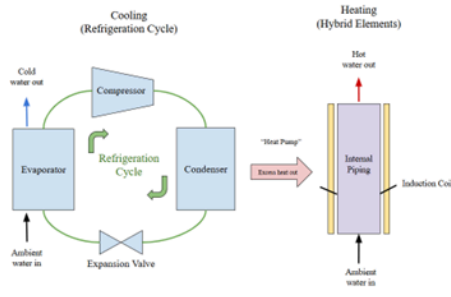
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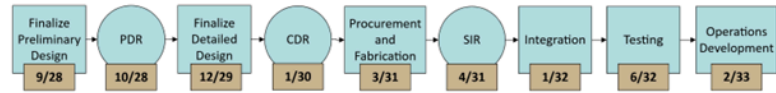
Design Details	
Mass [kg]	30.633
Dimensions [cm]	47w x 58.42h x 54.61d
Energy Draw [W]	~468W
Hot Water Throughput	765.3 mL/min
Cold Water Throughput	756.0 mL/min
Ambient Throughput	754.7 mL/min

Innovation

- Mini refrigeration cycle and hybrid heating element
- System status display panel



Schedule



Budget

Budget Category	Estimated Costs (Millions of \$)
Design and Development	9.1
System Test Hardware	3.4
Recurring	2.6
Personnel	4.472
Manufacturing	7.55
Margin (30%)	8.1366
Total Cost	35.2586

1. Executive Summary

Human exploration missions to the Moon and Mars will require a potable water dispenser to fulfill astronauts' food and beverage needs. Existing systems provide a limited amount of hot water and lack the ability to deliver chilled water. A unified solution capable of supplying both hot and cold water on demand would increase crew comfort and operational efficiency. The team proposes the Enhanced Potable Water Dispenser (EPWD) to be incorporated with a Human Lander System (HLS), providing a crew of up to four astronauts on-demand hot and cold water. EPWD utilizes a hybrid heating approach and a miniature refrigeration cycle to efficiently regulate water temperature. An Activated Carbon / Ion Exchange (ACTEX) filter and a micro UV-C light treat the water, meeting potable water quality standards. EPWD's role as an efficient, safe, and reliable potable water dispenser will provide astronauts with comfort, allowing them to put more focus on exploration goals.

2. Problem Statement

There are three primary challenges to implementing cooling in a PWD: resource constraints, microbial control, and environmental considerations. NASA missions require systems to minimize mass, volume, and power while maintaining safety and reliability. Adding a cooling function increases mass, energy use, and complexity, so the design must balance thermal performance with spaceflight limitations. Maintaining potable water quality is the second challenge. Although a biocide disinfects water upstream, it must be removed before dispensing due to crew health risks. Past systems experienced biofilm growth from dormancy and dead spots in the plumbing, leading to microbial contamination. Minimizing stagnation and ensuring effective decontamination are therefore critical. Finally, cislunar, lunar, and Martian environments introduce radiation exposure, variable gravity, and dormancy periods, requiring shielding, contingency protocols, and gravity-independent fluid management.

3. Solution

The EPWD delivers rapid, hot and cold water with heat recovery, high efficiency, and simultaneous multi-temperature output via a hybrid heating approach and a miniature refrigeration cycle. Water is deiodinated through the use of an ACTEX filter and disinfected by a micro UV-C light. 316L stainless steel tubing and a controlled positive pressure gradient from upstream of the EPWD ensures smooth and reliable fluid flow. An LCD screen is incorporated for user-friendly status updates. The EPWD is estimated to have a launch mass of 30.623 kg, dimensions of 47 cm width x 58.42 cm height x 54.61 cm depth, and a peak power draw of 488 W after Phase B margins are applied.

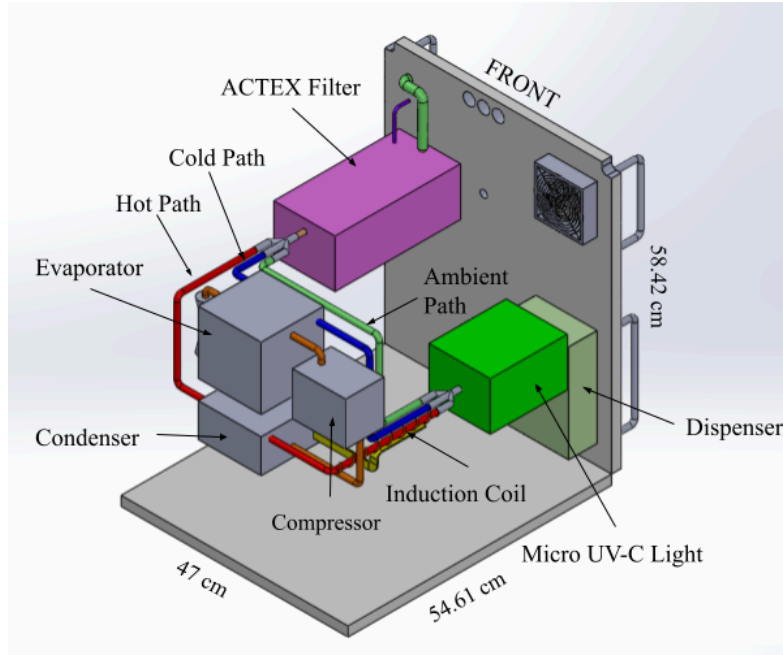


Figure 1. Isometric View Inside EPWD

To facilitate the design of the EPWD, the system is divided into six distinct subsystems: Thermal Control, Water Quality and Filtration, Fluid Transporting, Command and Data Handling, User Interface, and Power Handling. Each subsystem used a mixture of requirement traceability, analyses, trade studies, and lessons learned from heritage systems to address the challenges and arrive at a robust solution. Importantly, the team assumed that the chosen HLS will be similar to the ISS in that the EPWD can assume the same incoming water properties that are supplied to the dispenser onboard the ISS.

3.1. Changes Since Proposal

Since the proposal, the team made a primary architectural revision to the thermal system involving the implementation of an integrated heat pump configuration, which significantly enhances overall efficiency through active waste heat recovery. By reconfiguring the thermal loops, the heating water line is now placed in direct thermal contact with the vapor-compression condenser. This integration yields a dual synergistic effect: the sensible heat rejected by the condenser accelerates the temperature ramp-up of the hot water cycle, while the cooler heating water simultaneously acts as a heat sink to subcool the refrigerant, thereby increasing the cooling cycle's coefficient of performance. Furthermore, this continuous thermal coupling, when regulated by closed-loop controllers, mitigates the risk of localized thermal overheating in both the condenser and the hot water lines, ensuring precise thermal management across the subsystem.

In addition to this revision, the components inside the EPWD were reordered to minimize pipe volume, further reducing dead spots where bacteria can grow. Other additions include a fireport to mitigate the consequences of fire within the system, the water inlet was moved to the front panel to better align with existing systems, and the iodine inlet was moved to be more inline with the main water stream.

3.2. Thermal System

The thermal subsystem (Figure 2) enables on-demand water delivery across a temperature range of 4°C to 93°C through a novel no-tank design that conditions water directly within insulated stainless-steel piping, minimizing microbial growth and thermal lag. The heating architecture employs a hybrid approach combining a high-frequency induction coil wrapped around stainless steel piping for primary heating, supplemented by Mineral Insulated (MI) cable tracing for thermal maintenance. This configuration achieves rapid heating at 7.5°C per minute, requiring a peak transient power draw of 1.05 kW to reach target temperatures within 600 seconds (see Appendix F1). The cooling system utilizes a compact vapor-compression refrigeration cycle with a miniature direct current (DC) compressor pumping refrigerant at -2°C through copper coils wrapped around the cold water line, achieving 1.4°C cooling per minute with 236 W power consumption. Notably, waste heat rejected at the condenser is recovered via an updated heat pump system approach and conducted into the heating loop to improve overall efficiency. All piping will be protected with TEEK-based FPF-44 multi-layer insulation to minimize thermal losses throughout. The subsystem is designed to meet all temperature, pressure, and safety requirements while enabling simultaneous cold, ambient, and hot outputs as shown in Appendix F1.

The induction and MI cable hybrid heating system was selected because it maximizes efficiency and precision through the induction's high weighted score while leveraging the extreme durability and high-temperature capabilities of MI cable to outperform standard silicone options as shown in Appendix C. The Mini Refrigeration Cycle was selected as the optimal cooling solution due to its high weighted score, is driven by superior speed and a lightweight design, and outperforms both immersion and contact plates in rapid thermal response and overall mass efficiency as shown in Appendix D.

A thermal resistance network analysis determined that indirect condenser heat recovery (via external conductive pads) created a severe thermal bottleneck, requiring an unsustainably high ΔT . Instead, routing the ambient water directly through the secondary fluid channels of a Brazen Plate Heat Exchanger (BPHE) eliminates external contact resistance. This allows for 315 W of rejected heat transfer with a Log Mean Temperature Difference (ΔT_{LMTD}) of 5.88 K. This direct coupling maintains compressor efficiency and minimizes system dry mass, making the overall system more efficient as shown in Appendix F2.

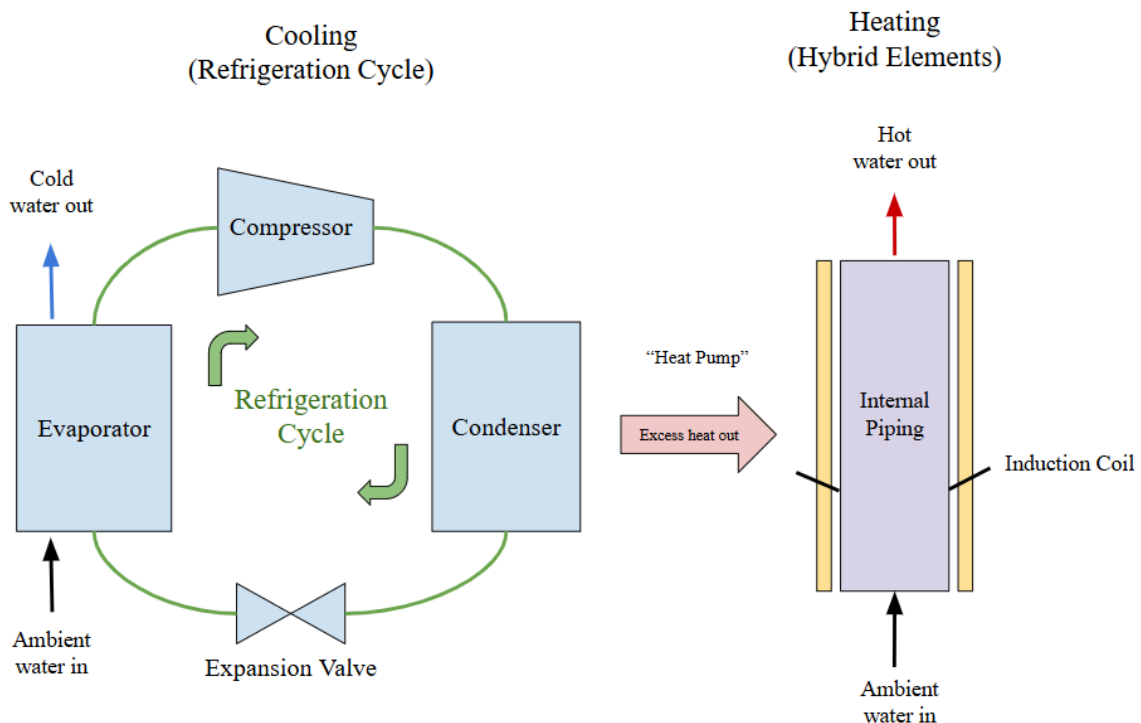
For a standard thermal cycle delivering water at 4°C and 93°C, the baseline decoupled system required 241.2 Wh, vastly exceeding the 25 Wh peak power budget constraint. The integrated heat pump architecture improves efficiency across both fluid loops. Specifically, the implementation of a high-efficiency Brushless Direct Current compressor ($COP_C = 3.0$) reduces cooling energy consumption by 77% (from 46.8 Wh to 10.8 Wh), while recovering 157.3 kJ of thermal energy from the condenser reduces the primary induction heater's electrical demand by 25%, dropping the heating requirement from 194.4 Wh to 145.9 Wh. Ultimately, this integrated heat pump configuration yields a net savings of 35% per cycle, effectively mitigating transient surges on the vehicle's power bus and validating subsystem feasibility within strict mission constraints as shown in Appendix F3.

In addition to power constraints, the system must deliver two liters of appropriate temperature water within a strict 600-second window. A lumped capacitance transient thermal analysis was utilized to model the time-to-temperature performance of the fluid loops. Under the baseline decoupled design, the standalone induction heater operating at maximum allowable power was calculated to reach the 93°C target in 11.1 minutes, failing the delivery requirement. Increasing the heater wattage to shorten this

duration was prohibited by the peak power budget. The new integrated architecture resolves this timeline deficiency. By injecting the 315 W of recovered condenser heat directly into the water stream, the baseline temperature of the fluid entering the primary induction heater is significantly elevated. The transient analysis demonstrates that this pre-heating assist accelerates the thermal ramp rate, allowing the system to reach the 93°C target in 8.5 minutes. This provides a adequate safety margin for the 10-minute delivery requirement without requiring an increase in electrical draw as shown in Appendix F3.

An environmental thermal load analysis was conducted to evaluate the reduction in ambient heat emissions achieved by transitioning from the baseline open-loop dumping configuration to the integrated closed-loop design. By capturing the cooling loop's rejected heat to preheat the water reservoir, the cumulative thermal energy expelled into the surroundings was reduced by 81%, dropping from 252 kJ to 47.3 kJ per cycle. This net mitigation of 204.7 kJ ensures a low-impact, nearly thermal-neutral footprint within the sensitive cabin environment as detailed in Appendix F4.

Additionally, during periods when the cooling loop is inactive, the reconfigured heating subsystem successfully achieves its target temperature within the mandated 10-minute operational window. This transient performance is primarily attributed to enhanced thermal insulation and a significant reduction in contact resistance via the direct-fluid coupling within the condenser assembly. By maximizing this internal thermal communication, the system minimizes ambient parasitic thermal losses and ensures that a greater fraction of the input energy is directed toward the fluid stream, thereby maintaining compliance with the designated time-to-temperature constraints.



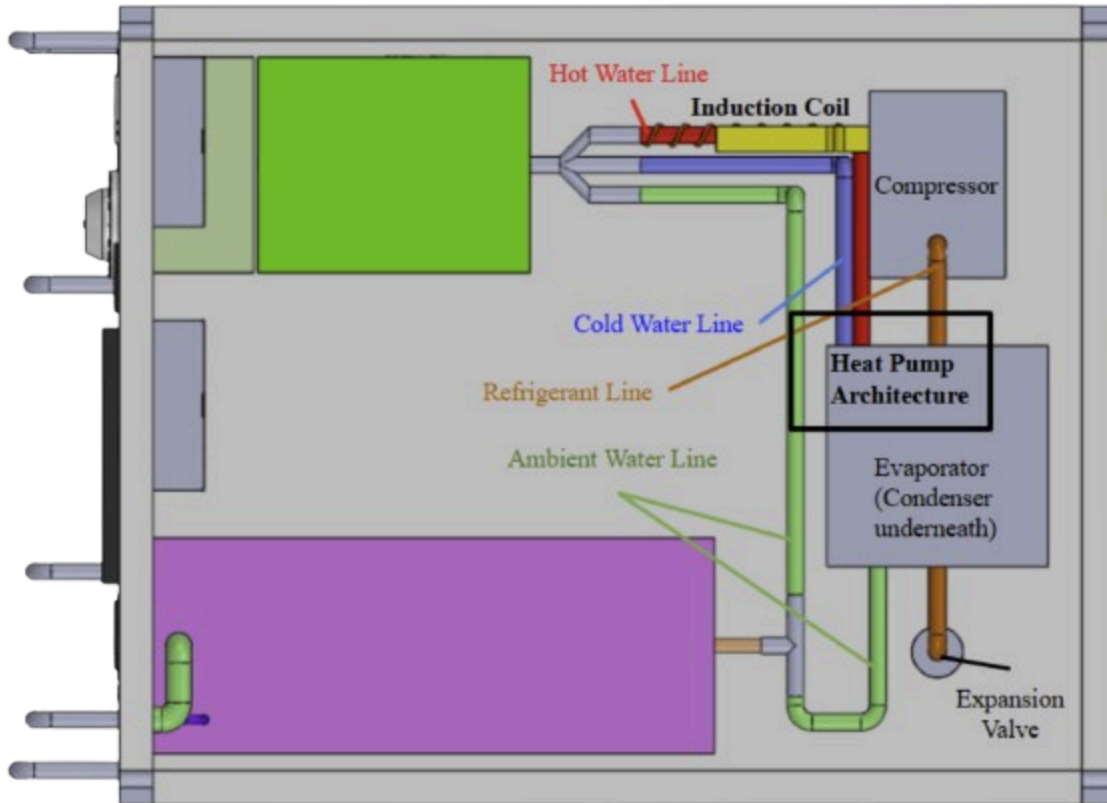


Figure 2. Updated Thermal Control Cycle

3.3. Water Quality and Filtration System

The Water Quality and Filtration System is responsible for filtering out the 1–4 ppm of I_2 used as a biocide upstream of the EPWD and ensuring the dispensed water has a bacteria concentration of less than 50 CFU, in accordance with the ISS Medical Operations Requirement Document. To achieve this, an Activated Carbon / Ion Exchange (ACTEX) filter will be installed at the inlet of the system, ensuring internal hardware is not constantly exposed to high concentrations of iodine. The ACTEX filter is certified to deiodate 4,320 lbm of water, which is typically reached after 7 months of use, assuming a crew of three to four astronauts.

To reduce microbial contamination, water will pass through a UV-C light capable of achieving an NSF Class B rating for water quality just before the dispenser. Past systems were susceptible to biofilm generation and microbial growth exceeding 50 CFU during periods of dormancy. The system will be in a period of dormancy for six months at the Kennedy Space Center, as well as during transit and orbit times to the Moon (~102 hours) and Mars (~200 days). To maximize crew and system safety, a 40 ppm iodine solution in a one-liter Teflon bag will be available for the crew to input into the system, allowing for a full system flush. For this case and the use of the 40 ppm I_2 flush, a “dummy” ACTEX filter will be installed to ensure the entire system is flushed.

3.4. Fluid Transporting System

The Fluid Transporting System utilizes a total of 265 cm of 6.35 mm diameter 316L stainless steel pipes which was selected because of its low surface roughness, mechanical robustness, and iodine compatibility which minimizes the risk of biofilm formation. The fluid transport is controlled using a positive pressure gradient from the upstream Water Recovery System at 230-280 kPa, eliminating the need for pumps. Using the Hagen Poiseuille (Eq. 1 in Appendix H) and orifice flow equation (Eq. 2 in Appendix H), the team estimates the ideal orifice flow rate as 1080 mL/min. Accounting for pressure loss and capillary effects using historical data (approximately 30% loss), the estimated ambient orifice flow rate is 756 mL/min, which represents an approximate 9.24% increase over the current system. A basic flow map of the EPWD is shown in Figure 3, where the water is supplied by the Potable Water Bus (PWB).

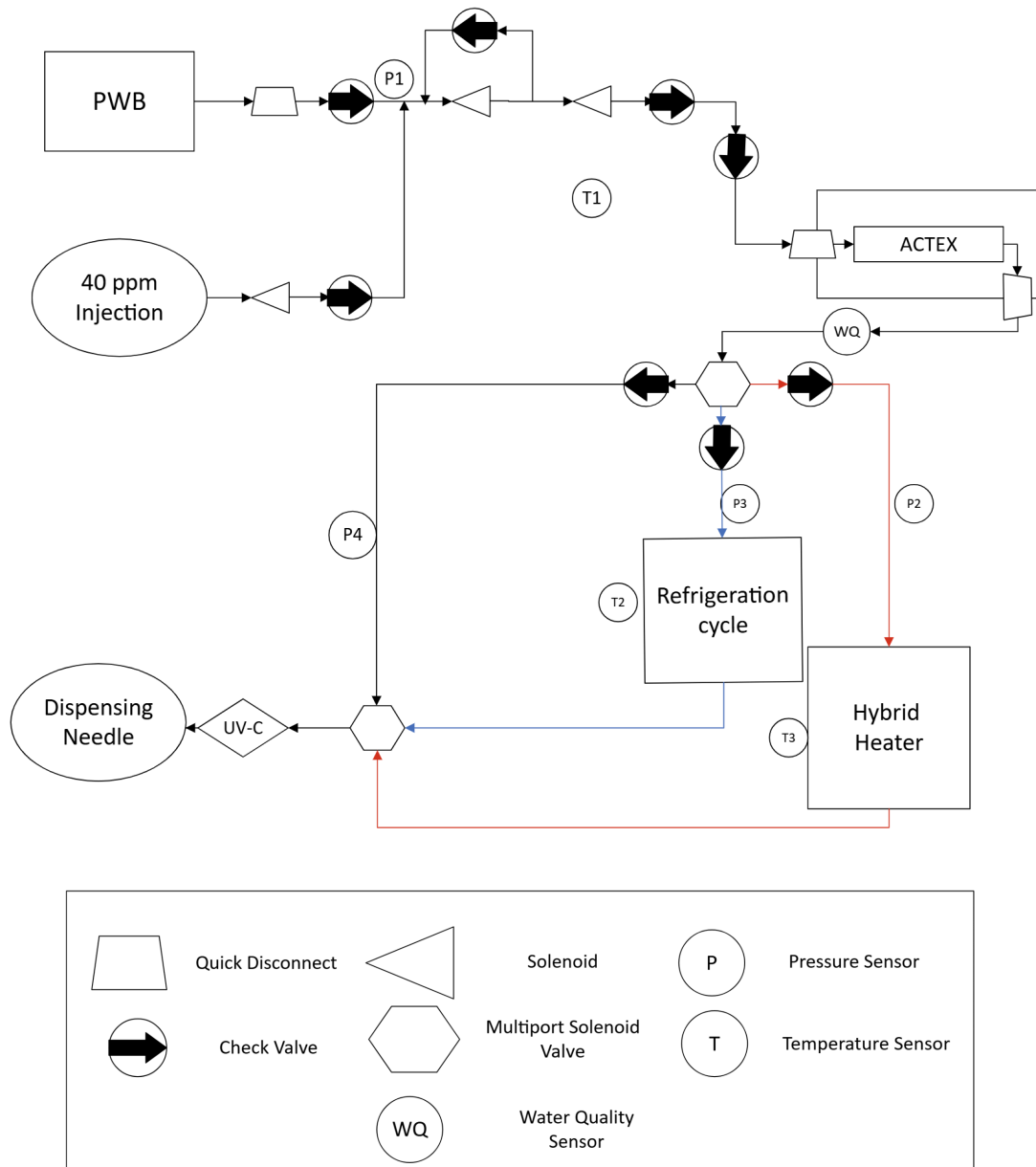


Figure 3. Fluid Flow Diagram

Additionally, a line volume and thermal mixing analysis was performed to measure temperature delivery accuracy across the dispensing range of 25-250 mL. The analysis utilized the aforementioned pipe geometry and conservation of energy equations to estimate the amount of stagnant water in the system (between the dispense needle and thermal elements). As shown in Figure 4, the results show that below 75 mL the dispense volume falls outside the acceptance band for hot water (66-93 °C) due to the stagnant water. This is mitigated using the CDHS pre-heating feature which ensures the full dispense volume is at the correct temperature before dispensing. Importantly, the analysis shows that the cold water dispensed at any volume is within the acceptance band.

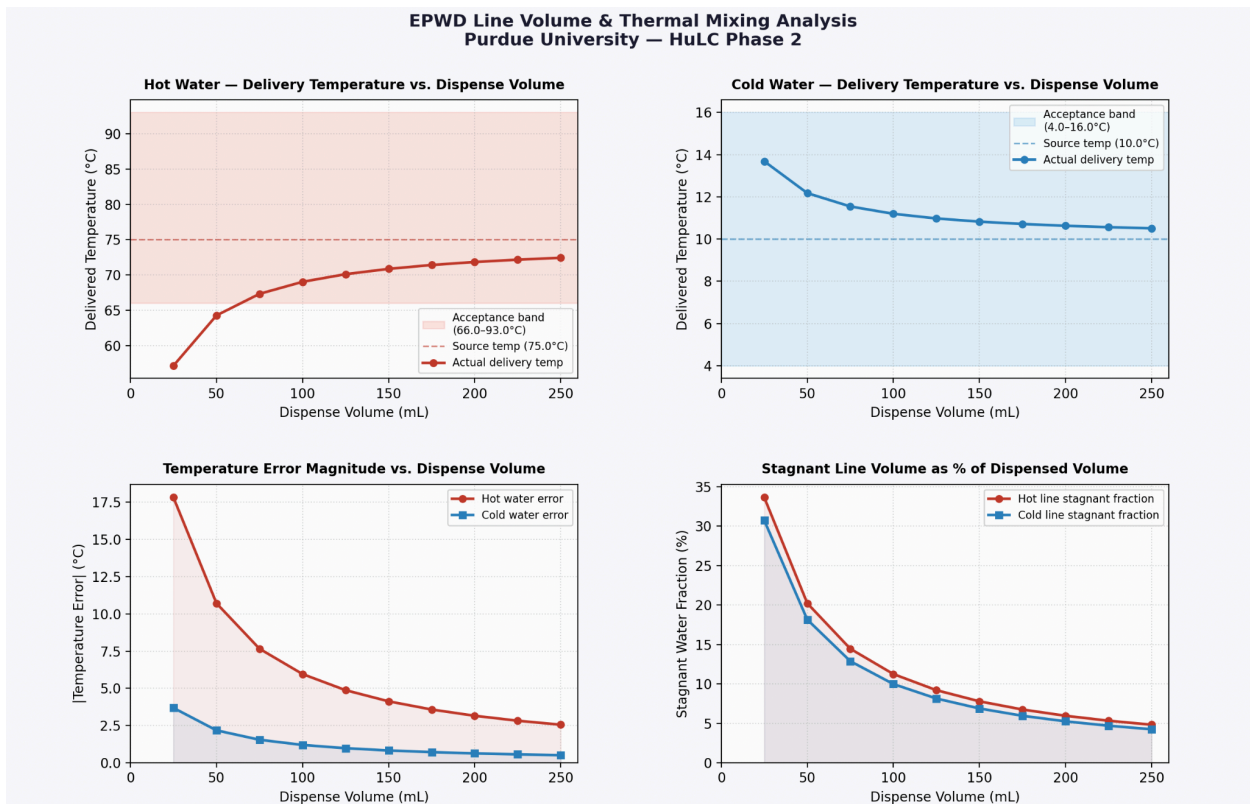


Figure 4 - Line Volume and Thermal Mixing Analysis Results

3.5. Command and Data Handling System

The Command and Data Handling System (CDHS) implements a flight-style software, integrating sensing, telemetry, fault management, and user interaction into a coordinated framework. A central microcontroller (MCU) acquires data from the sensor suite, monitors subsystem status, and executes mode-based control logic for heating, cooling, UV disinfection, dispensing, and fault safing (see Figure 5 for example decision flow). To mitigate the effects of radiation in space, all components chosen were manufactured using radiation-hardened (rad-hard) processes. Health is managed by watchdog supervision, continuous fault detection, isolation routines, and event logging so abnormal conditions generate alerts and place the unit into safe modes when required. Meal times will be logged into the MCU allowing heated/cooled water to be prepared 600 seconds in advance, minimizing wait time for astronauts.

Furthermore, the crew will have the ability to start pre-heating at any given moment through the enhanced user interface system.

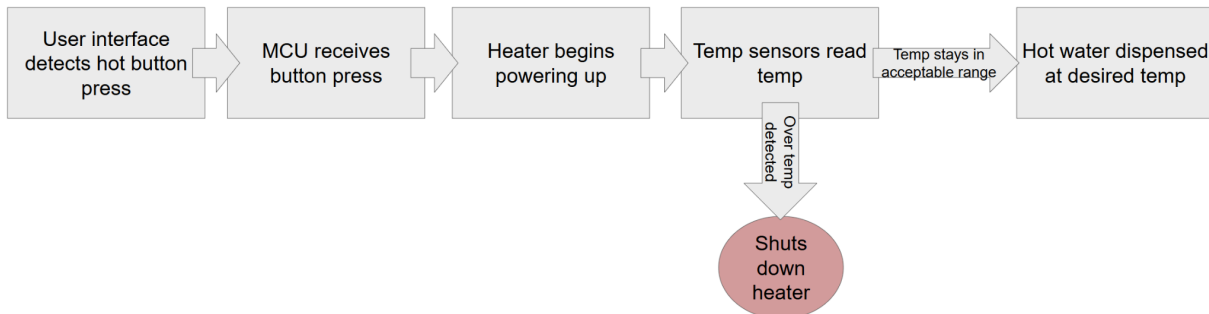


Figure 5. Hot Water Dispense Function

3.6. User Interface System

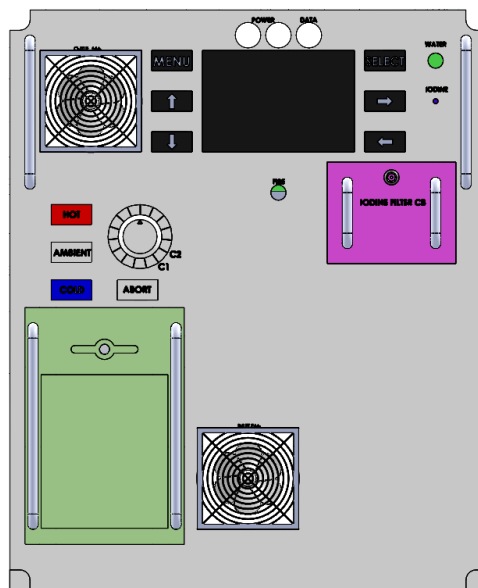


Figure 6. User Interface / Front Panel

The User Interface System accounts for the front panel of the EPWD consisting of a dial, an LCD screen, ten buttons, iodine filter access, and the rehydration station allowing users to control water output, obtain status information, and access other necessary features. The dial allows the user to input the desired water amount (25-250mL in 25 mL increments). After selecting one of the three dispense buttons (hot, ambient, cold), the set temperature and amount will be transmitted to the CDHS for dispensing. Dispensing can be aborted using the abort button in case of emergency or accidental dispensing. The LCD screen will have several pages controlled by six buttons (four arrows, select, and menu) surrounding the display. The pages will include status pages for all systems, maintenance instructions, annunciations, and current operational status. Additionally, there will be an access panel for the iodine filter to allow for easy filter access and maintenance. Finally, the current rehydration station will be implemented into the front panel to avoid a redesign of the entire food and water bag system.

3.7. Power Handling System

The power handling system connects with the EXPRESS rack system's 28 Vdc supply and safely distributes payload power to all the EPWD loads, while minimizing peak demand and increasing fault tolerance. High-powered loads (heater and cooler) are supplied through protected branches with inrush control, EMI filters and e-fuses while lower powered electronics are powered by DC/DC converters. Rad-hard components were chosen so space radiation will cause minimal faults. The direct-to-load architecture was chosen to reduce stress and efficiency for major thermal loads on the rack power interface. Included are voltage, current and temperature monitors to support the CDHS, enabling automatic safing actions such as disabling the heater or UV in the event of overcurrent, undervoltage, or over-temperature conditions. This design chooses a balanced approach that supports our on-demand heating/cooling without reservoirs while maintaining compatibility with current ISS systems. After taking into consideration judges' comments, the team saw a decrease in energy usage by about 3.75x shown in the summary table F3. Assuming a 30% margin, the EPWD will now draw ~ 488 W.

4. Verification and Validation

4.1 Verification Analyses

Requirements were derived directly from the HuLC project guidelines, as well as a variety of documents related to NASA's Moon to Mars architecture, the 2008 USOS PWD, and NASA's potable water quality standards. Four driving requirements were identified, relating to temperature control, water quality, safety, and integrability. For each of these requirements, pre-prototype and post-prototype verification plans were formed. The pre-prototype verification analyses refer to the analyses performed in this paper. The post-prototype verification analyses refer to tests and analysis that can be performed with a prototype or the full system in late-Phase B, as well as phases C and D. Table 1 shows a summarized version of these verification plans, and a full version of the post-prototype verification analyses can be found in Appendix A.

Table 1. Summarized Verification Analyses

Requirement ID	Category	Requirement	Pre-Prototype Verification Method	Post-Prototype Verification Method
TMP1	Thermal Control	Deliver up to 250 mL of water between 4 °C and 93 °C within 10 minutes.	Line Volume and Thermal Mixing Analysis	Prototype Thermal Test / Full System Thermal Test
SAF1	Water Quality	Dispense water meeting NASA's potable water quality standards.	Water Quality System Trade Analysis	Full System Water Quality Test
SAF3	Safety	The system shall cause no harm to the user or HLS.	Risk Burndown Analysis	Fire Suppressant Test
INT1	Integrability	The system shall be integratable with the HLS.	TMP1 / SAF1 Verification	TMP1 / SAF1 Verification

TMP1 was verified through analyses presented in Section 3.4, SAF1 was verified in Appendix A, SAF3 was verified in Section 5, and INT1 was verified through the successful verification of TMP1 and SAF1, assuming the human lander will have the same interfaces and incoming fluid properties as the ISS.

4.2. Prototype to Full Scale Implementation

Implementing the EPWD on a HLS begins with the fabrication of a prototype. Although the team did not manufacture a prototype, a basic prototype was imagined to bridge the gap between analyses and testing, which would give EPWD a TRL of 5. Since many of the major components of the system have been flight-proven (ACTEX filter, UV-C, electrical components, etc.), the prototype's goal is to eliminate uncertainties about the hybrid heating and cooling approach, as well as the configuration of pipes' effect on volumetric flow. A bench-top prototype can be fabricated right away that replicates the end to end functional behavior of the system without requiring flight-certified materials or ISS integration hardware.

The prototype will be replicating the EPWD water path using standard transparent tubing, quick disconnect fittings and modular sections for flow metering and valves, heating, cooling, and UV-C treatment with ports for instrumentation at key points. The water path would be mainly straight runs and elbows matching the intended packaging envelope, including pressure taps at the entrance and exit of every major component. The instrumentation suite will include at least three pressure sensors (upstream, midstream, downstream), flow sensors for volumetric measurement, inlet/outlet temperature sensors, and electrical measurement points for heater/cooler power. The modular design will allow for quick reconfiguration of piping geometry to quantify how routing impacts flow rate, pressure drop and, ultimately, dispense accuracy.

Prototyping Timeline:

Phase 1 - Piping and Flow Characteristics (Week 1-2)

The initial prototype version will consist of the complete piping layout, the entire sensor suite will be installed without including the thermal modules to validate the hydraulic model. A fluid flow test with pressure sensors will allow better insight into the fluid properties within the system. Being able to accurately understand the pressure differentials throughout the EPWD using the prototype will lead to more accurate volume error analyses and will provide more accurate information for the thermal transfer. The deliverables from Phase 1 include a flow rate vs. position curve, pressure drop map, and a validated "line volume" model for time to dispense estimates.

Phase 2 - Thermal Subsystem Testing in Isolation (Weeks 3-5)

The second prototype version will have the heating and cooling elements installed onto a simplified version of our pipe run to keep piping constant while varying thermal conditions. Phase 2's primary test is a thermal performance analysis without confounding hydraulic uncertainty. The test of this version is a thermal analysis, where increasing volumes of water are passed through the prototype at different requested temperatures. The data is catalogued and compared to the acceptance band detailed in Section 3.4, where a more accurate preheating time is determined. Other necessary data will be collected to refine power and control before full integration. After completing this phase, the design team will have an experimentally grounded estimate of steady-state temperature error, preheating time, and energy per dispense for both heating and cooling.

Phase 3 - Controls, UX/UI, and Software State Logic (Week 6)

The goal of this phase is to mature the microcontroller/state software and prove that the system is operable, testable, and fault-tolerant before committing to a full hardware integration. The microcontroller implements the state machine (SAFE, STANDBY, HEAT, COOL, DISPENSE, UV-TREAT, FAULT), command/telemetry dictionary, watchdog supervision, and fault detection/isolation/recovery. UX/UI will include required controls: main status screen, navigation buttons, dials, along with dedicated flows for iodine filter access/flush controls, UV access, and rehydration station operations. The key metrics that will be gained from this test will be verification of state machine behavior, safing actions, UI navigation, and a finalized alert set.

Phase 4 - End to End Integration (Weeks 7-9)

The bench test prototype will combine phases one, two, and three along with a UV-C section, recreating the EPWD’s functional path. This final version of the prototype will allow for a full line volume and thermal mixing analysis of the system, providing robust experimental data for flow rate errors, heating errors, and time-to-dispense. Other tests not related to water flow and heating/cooling will also be supported such as sensor disconnects, brownout conditions and induced flow restrictions, to confirm safing logic and system health. Completion of the bench prototype will give the whole system a TRL of 5.

After the prototype and bench testing are completed, the system can progress to TRL 8 through design, tests, and fabrication detailed in Section 7. Key tests include a line volume and thermal mixing analysis of the entire system, vibration testing, and risk-simulation testing. The TRL can further increase to 9 if the system were to be tested on either the ISS or a HLS testing mission.

5. Risks

5.1. Technical Risks

A risk matrix (Figure 7) was developed to identify and mitigate risks. A total of 17 relevant design risks were identified by likelihood and consequence, and mitigation plans were formed (Appendix B). The analyses identified four critical risks, which encompass anything that could cause harm to the crew or HLS.

CONSEQUENCE	5	4, 6, 8, 12				
	4	1	7	5		
	3		16		2	
	2			3		
	1				15, 17	9, 10, 11, 13, 14
		1	2	3	4	5
		LIKELIHOOD				

Figure 7. Risk Identification Matrix

Fire (Risk 6) poses a significant threat to the crew and HLS, and was identified as having a likelihood of 1 and a consequence of 5. To mitigate the risk of fire, strong electrical connections, proper insulation, and multiple temperature sensors within the system will be implemented. To mitigate the consequence of fire, a fire port will be installed at the front of the system, allowing for a fire suppressant to be injected into the EPWD.

Leakage (Risk 3) represents a critical threat to nominal EPWD operation and adjacent Environmental Control and Life Support System (ECLSS) components, particularly avionics and electrical subsystems. Although catastrophic rupture is unlikely due to conservative material selection and pressure margins, minor seal degradation or fitting leakage remains a credible long-duration risk. Redundant solenoid isolation valves installed in series at key distribution nodes are configured to fail closed upon anomaly detection, enabling rapid isolation of affected segments and limiting fluid loss and electronic damage.

Backflow (Risk 4) presents contamination and performance risks by potentially introducing particulates, microbial contaminants, or thermally altered fluid into upstream systems. A controlled positive pressure gradient reduces this likelihood, while dual-check valves near the inlet prevent reverse migration into the Water Recovery System. An AquSense Technologies UV-C upstream of the dispenser provides an additional barrier to protect downstream hardware and maintain water quality standards.

Bubble Formation (Risk 2) poses a significant operational risk in microgravity due to capillary forces dominating buoyancy in the low Bond number regime. Entrained gas can obstruct flow paths and degrade system performance. Of the evaluated mitigation strategies, including induced electric fields, photosurfactants, and passive capillary structures, the passive approach was selected for reliability and flight heritage. Periodic wedge geometries and fine mesh screens disperse gas pockets and create localized capillary pressure gradients that wick liquid into narrow vertices while directing gas toward expansion regions, eliminating additional power demand and reducing failure modes.

5.2. V&V Risks

The primary risk associated with the verification and validation of the EPWD is the risk of assumption. The system assumes the HLS will have an ECLSS structure similar to the ISS, where water is supplied from the PWB. This inputted water is assumed to use iodine as a biocide. Furthermore, if the Water Processing Assembly (WPA) does not apply any biocide to the water, then the UV-C light within the system will not be effective in reducing the microbial count to meet NASA's potable water quality. A missing or incorrect assumption about the EPWD would result in a delay in schedule and an increase in cost.

6. Budget

Using NASA's Project Cost Estimating Capability (PCEC) tool, the total cost for the EPWD can be determined. Major components (detailed in Appendix E) were determined by finding similar commercial off-the-shelf items. These items allowed the team to input mass and heritage into the PCEC tool, which used First Pound Cost analyses and a 30% margin to determine the total cost of the EPWD (Table 2).

Table 2. PCEC Output in Millions of Dollars

Cost Type	FY2015 \$M	FY2026 \$M
Non-Recurring	9.1	12.5
Design and Development	6.6	9.1
System Test Hardware	2.5	3.4
Recurring	1.9	2.6
Total	11.0	15.1

The tool outputted a total system cost of \$15.1 million. Utilizing this output, along with the Path-to-Flight timeline (Section 7), a total project cost can be calculated (Table 3). Personnel costs were calculated using the NASA GS Pay Scale Guide for Huntsville, the Employee Related Expenses (ERE) were taken to be 30% of the personnel costs, a manufacturing margin of 50% was determined, and a total cost margin of 30% was applied in accordance with the NASA Cost Estimating Handbook Phase B margin. These factors result in a total project cost of \$35.26 million for the EPWD.

Table 3. Full Budget Breakdown in Millions of Dollars

Mission Phase	B		C			D	TOTAL
Year	2027	2028	2029	2030	2031	2032	
Personnel							
Engineering	0.19	0.19	0.46	0.46	0.46	0.38	2.14
Technicians	0	0	0.1	0.1	0.1	0.13	0.43
Administration	0.03	0.03	0.04	0.04	0.04	0.03	0.21
Project Management	0.07	0.07	0.13	0.13	0.13	0.13	0.66
Total Salaries	0.29	0.29	0.73	0.73	0.73	0.67	3.44
Total ERE	0.087	0.087	0.219	0.219	0.219	0.201	1.032
Total Personnel	0.377	0.377	0.949	0.949	0.949	0.871	4.472
Direct Costs							
System Cost	1.5	1.5	2.5	3	2.5	4.1	15.1
Manufacturing Margin (50%)	0.75	0.75	1.25	1.5	1.25	2.05	7.55
Total Direct Costs	2.25	2.25	3.75	4.5	3.75	6.15	22.65
Final Cost							
Total Projected Costs	2.627	2.627	4.699	5.449	4.699	7.021	27.122
Margin (30%)	0.7881	0.7881	1.4097	1.6347	1.4097	2.1063	8.1366
Project Costs	3.4151	3.4151	6.1087	7.0837	6.1087	9.1273	35.2586

7. Path-to-Flight Timeline

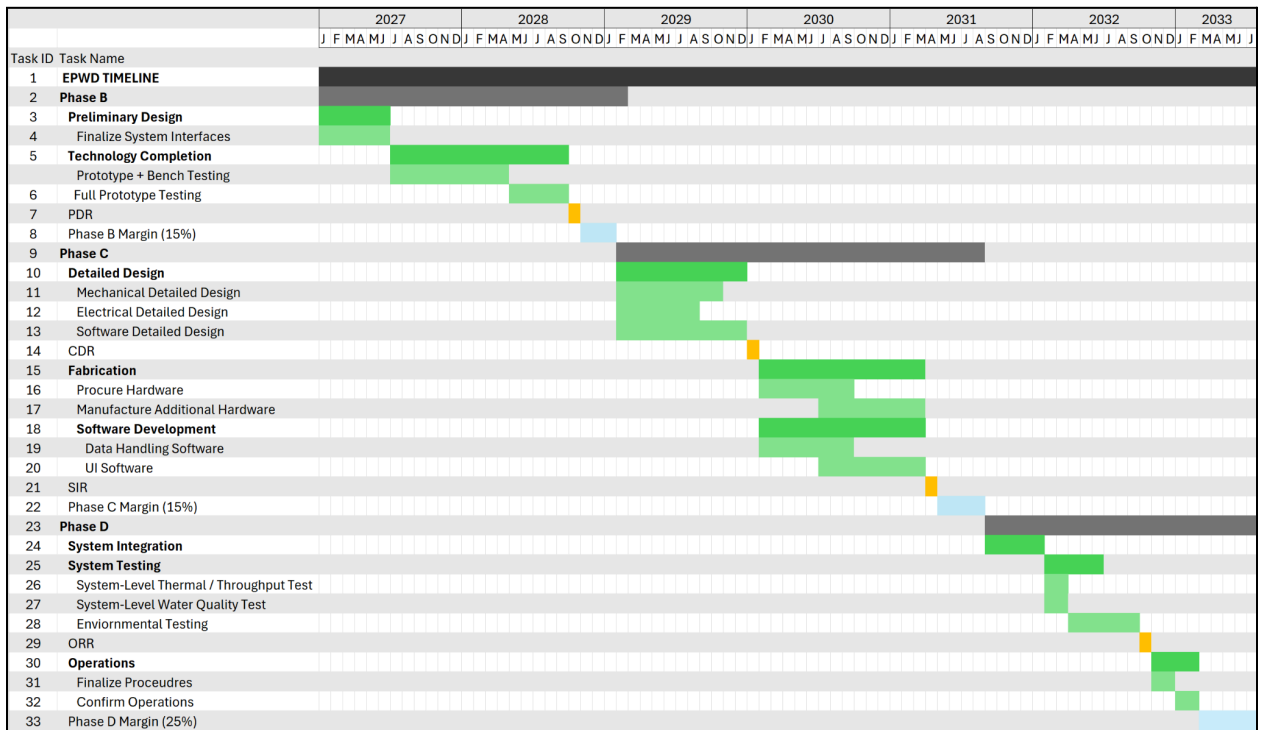


Figure 8. Path-to-Flight Project Timeline

The phases of the EPWD’s development have been put into a 79-month timeline (Figure 8). Major milestones are shown in orange, phase lengths are shown in grey, major tasks are represented by green, and phase margins are given by blue. The phases align with traditional project phases outlined in the NASA Systems Engineering Handbook.

Phase B aims to continue preliminary development of the EPWD. The interfaces with the rest of the human lander will be finalized, allowing for more accurate knowledge of nodes and constraints that the system must obey. After this, a prototype (discussed in Section 4.2) can be fabricated, and the basic thermal control test (see Appendix A) can be performed. Phase B concludes with PDR scheduled for 10/28 and contains 4 months of margin.

Phase C takes the knowledge of the bench testing and prototype and produces a final, robust design. The design is split into three distinct subsystems: mechanical, electrical, and software, with CDR estimated to take place in 2/30. After CDR, fabrication and software development can begin, with SIR scheduled for 3/31. This ends Phase C, which also has a margin of 4 months.

Phase D focuses on assembling, testing, and documenting the system. It begins with system integration and moves to system testing, where thermal, throughput, water quality, and environmental tests are performed to verify the requirements. ORR is scheduled for 11/32, after which procedures can be finalized and operations can be confirmed.

8. Concept / Mission Architecture Timeline

Figure 9 displays the mission architecture timeline, displaying when certain key phases of the EPWD's lifetime occur.

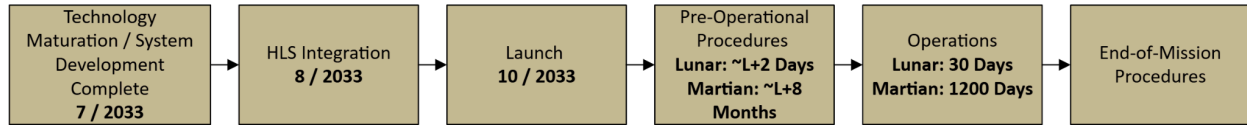


Figure 9. Mission Timeline

The technology maturation and system development of the EPWD occur during Phases B and C and are expected to be completed by 7/2033. The system will be integrated with the HLS by 8/2033, given an expected launch date around 10/2033. These phases are detailed in section 7.

Pre-operational procedures occur 2 days after launch for lunar missions and about 8 months after launch for Martian missions. These procedures are intended to prepare the system for operational use and include: powering on the system, ensuring the system survived the launch and transit, and injecting the 40 ppm iodine bag into the system for Martian missions.

The operational phase is defined as a combination of nominal use and routine maintenance, the latter of which consists of replacing the ACTEX filter and UV-C light. Since the ACTEX filter is certified for 7 months, it will not need to be replaced for lunar missions, but will need to be replaced about 5 times for Martian missions. For easy maintenance, the filter is placed within an Orbit Replacement Unit on the front panel. The UV-C light's lifetime of 10,000 hours ensures that it will not need to be replaced for a nominal mission, but easy access to the light through a side panel ensures that astronauts can maintain potable water quality standards. Other routine maintenance could include an injection of 40 ppm of I₂ into the system to combat any biofilm growth.

End-of-Mission procedures consist of powering down the system and ensuring any planetary protection protocols are met.

9. Conclusion

Long-duration human exploration missions demand life support systems that are efficient, reliable, and safe. Current potable water dispensers lack the ability to chill water and can only provide a limited amount of hot water. The EPWD aims to address these limitations through a hybrid thermal architecture, while seeking to mitigate biofilm growth within the system and enhancing user-interface capabilities. Over the past eight months, the team used trade analyses, thermal calculations, fluid mixing analyses, and line volume simulations to validate the system. The team also estimates the program is affordable, and can be implemented in a timely manner with little risk. As human exploration reaches beyond the Moon, the EPWD will take a vital role in providing astronauts comfort and ease, allowing them to place greater focus on their missions.

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Appendices

Appendix A: Driving Requirements Verification Plan

Requirement ID	Category	Requirement	Verification Method	Verification Description	Success Criteria
TMP1	Thermal Control	The system shall be able to deliver up to 250 mL of water between 4 °C and 93 °C within 10 minutes.	Test	Before full system integration, pump 3.6L of 22 °C, 255 kPa water containing 0.2 ppm I ₂ into the heating and cooling system. Repeat after full system integration.	Outputted water is within 4 °C and 16 °C for cold water and 66 °C and 93 °C for hot water. 630 mL of water can be dispensed within a minute.
SAF1	Water Quality	The system shall dispense water meeting NASA's potable water quality standards.	Test	After system integration, pump 3.6L of water containing 4 ppm I ₂ and 50 CFU into the system. Repeat for all three temperature settings. After 6 months, disable the ACTEX filter and flush the system with 1 L of 40 ppm I ₂ . Repeat the dispensing process and perform a coliform bacteria test.	Outputted water contains less than 50 CFU of bacteria and no detectable coliform.
SAF3	Safety	The system shall not cause any harm to the user or HLS during usage or maintenance.	Analysis	Risk identification, risk mitigation, risk burndown plans, FMEA plans. Risks are simulated to measure effect on	All risks achieve an overall score of 15 or less. After simulation, the system is operable / can

				the system.	be fixed easily.
INT1	Integrability	The system shall be integrable with the HLS.	Analysis / Test	Perform TMP1 and SAF1 tests with water properties of chosen HLS. Ensure interfaces with other systems on HLS are uniform.	Tests result in the successful verification of TMP1 and SAF1.

Appendix B: Risk Registrar

Risk Category	Risk Number	Risk Description	Likelihood	Consequence	Overall Level	Mitigation Technique
Water Quality and Filtration	1	The dispensed water does not meet NASA's potable water quality standards	1	4	7	Include shock bag, minimize dead spots, materials, add iodine flush mode. Conduct tests after landing and periodically.
Fluid Transporting	2	Bubble formation during fluid transportation	4	3	19	Include capillary fluidic structures (wedges and meshes)
Fluid Transporting	3	Leakage	3	2	11	Multiple solenoid valves, watchdog timers to close them. Replaceable seals to keep new and effective
Fluid Transporting	4	Backflow	1	5	10	Dual-check valve at inlet of PWD, 0.2-micron microbial filter upstream of heater to reduce back contamination

Thermal	5	Thermal insulation failure	3	4	18	Researching different insulation materials around pipes, using correct quantities of insulation
Thermal	6	Fire	1	5	10	Ensuring strong electrical connections, multiple temp sensors
Thermal	7	Freezing occurs in cooling thermal subsystem	2	4	13	Ensuring refrigeration cycle does not cool water below 4°C, multiple failsafes to ensure water does not freeze
Power Handling	8	Heater power stuck on (runaway)	2	5	10	Thermal fuse, dual-channel enable(HW lock + SW command)
Power Handling	9	Undervoltage/Brownout	3	4	12	Undervoltage lockout and reset strategy
Power Handling	10	Inrush causes trips or resets	4	3	12	Set protection thresholds appropriately, stage enabling
Power Handling	11	EMI from converters	3	4	12	LC filters, grounding, EMI filters
Power Handling	12	Harness overheating	2	5	10	Periodic continuity/resistance checks
Data Handling	13	Sensor Fault or drift causing incorrect dosing	4	3	12	Plausibility checks, redundancy for critical sensors
Data Handling	14	Controller crash during operation	3	4	12	Boot-to-safe defaults, health

						monitors
Data Handling	15	False alarms	4	2	8	Debouncing, confirmation logic, clear alert hierarchy
Data Handling	16	UI input Error (dispenses wrong vol/temp)	3	3	9	Undo/cancel button, two-step confirmation for large changes
Data Handling	17	Firmware Update Failure	2	4	8	Recovery procedure documentation, A/B firmware with rollback

Appendix C: Heating Thermal Subsystem Trade Analysis

Factor	Weight	Design 1: Induction	Design 2: Silicone	Design 3: MI Cable
Reliability	0.2	9 (Solid state, no contact)	7 (Wear/tear on mats)	9 (Extremely durable)
Time (Speed)	0.2	10 (Instant heat)	4 (Low watt density)	8 (High power output)
Mass	0.1	7 (Needs power unit)	9 (Very lightweight)	8 (Compact)
Cost	0.1	3 (Expensive equipment)	9 (Inexpensive)	6 (Moderate)
Maintenance	0.1	8 (Non-contact)	6 (Adhesive issues)	7 (Hard to replace)
Temp Stability	0.15	9 (Precise control)	6 (Lags/limitations)	8 (High temp capable)
Power Consumption	0.1	8 (High efficiency)	7 (Heat loss issues)	7 (Standard resistive)
COP	0.05	9 (Direct coupling)	5 (Surface loss)	6 (Standard resistive)
Weighted Score	1	8.15	6.35	7.75

Appendix D: Cooling Thermal Subsystem Trade Analysis

Factor	Weight	Design 1: Immersion	Design 2: Contact Plates	Design 3: Mini Refrigeration Cycle
Reliability	0.2	7 (Simple, low fail points)	7 (TIM can degrade/leak)	7 (Vibration risks/leaks)
Time (Speed)	0.2	8 (Excellent with	7 (Contact limited)	10 (Maximum ΔT)

		pump)		
Mass	0.1	2 (Heavy due to fluid)	4 (Heavy metal saddles)	8 (Lightweight copper)
Cost	0.1	7 (Standard tankage)	3 (Expensive machining)	6 (High labor/solder)
Maintenance	0.1	9 (Easy tank cleaning)	5 (Cleaning paste/gaps)	4 (Permanent/Hard to fix)
Temp Stability	0.15	8 (Fluid buffer)	6 (Spotty contact)	7 (Fast but can spike)
Power Cons.	0.1	8 (Steady state)	7 (Less efficient)	5 (High cycle frequency)
COP	0.05	8 (High thermal mass)	6 (Moderate)	8 (Efficient transfer)
Weighted Score	1	7.4	6.15	7.4

Appendix E: Master Equipment List

Subsystem	Item	Qty	Total Mass (kg)	Energy Use W (V DC)	TRL	Based On
WQ&F	UV-C Micro Light (9C)	1	0.162	7-11 (12)	9	AquiSense Micro UV-C
WQ&F	ACTEX Filter	1	1.5	0	9	LifeSaver Jerrycan Activated Carbon Filters
WQ&F	ORU	1	1.4	0	9	2008 USOS ORU dimensions / Aluminum-Lithium alloy density
WQ&F	Insert Port	1	0.1	0	9	Luer lock
WQ&F	40 ppm iodine bag	1	2	0	9	40 ppm I2 in 1L teflon bag
Thermal	Induction Heater	1	0.85	1000 (220)	8	Standard 1kW PCB/IGBT Driver
Thermal	Induction Coil	1	0.2	0	9	4 mm OD Copper Tubing
Thermal	Secondary MI Cable	5	0.35	150 (120/240)	9	MI Cable
Thermal	FPF-44 Wrap	1	0.05	0	8	NASA Insulation
Thermal	Compressor	1	0.65	150 (24)	9	Aspen Miniature BLDC
Thermal	Evaporator	1	0.4	0	9	Copper Coaxial Coil
Thermal	Condenser	1	0.3	0	9	10-Plate 316L BPHE
Water Handling	1/4" (6.35 mm) 316L Stainless Steel Pipes	265.03 cm	1.1	0	7	1/4" 316L Stainless Steel Seamless Tubing
Water Handling	Solenoid Valves	3	0.849	15 (12)	9	Electromic Solenoid Valves 1/4" Brass Solenoid Valve
Water Handling	Multi-Port Solenoid Valves	2	0.724	15 (12)	7	3-way Split Aluminum Manifold with Compact Solenoid
Water Handling	Check Valves	8	0.64	0		Ham-Let 1/4" Compression Check Valve
User Interface	LCD Screen	1	0.14	2.17 (12)	7	Tianma 7" Rugged Display Panel
User Interface	Rehydration Station	1	~3	~	9	2008 USOS PWD Document
System Monitoring	Micro controller	1	0.1043280028	2W	9	VORAGO Microcontroller for Space Applications
System Monitoring	Temp Sensor	3	~	~	9	iST RTD Platinum Temperature Sensor
System Monitoring	Temp/Quality Sensor	3	~	~	9	iST Conductivity Sensor LSF1107
System Monitoring	Pressure Sensor	4	4.53592	~	9	STI ST1300 Space Rated Pressure Transducer
Power Handling	Inrush Limiter	1	0.016	8.5	9	VPT Space Qualified Hybrid Inrush Current Limiter
Power Handling	E-fuse	1	0.0065	1.6	8	Schurter FRM-A Schock-Safe Fuseholder
Power Handling	EMI filter	1	0.083	15.75	9	VPT DVME28 EMI Filter
Power Handling	DC/DC converter (3.3/5)	2	0.172	3	9	VPT SVFL2800S Space Qualified Hybrid DC-DC Converters
Structure	Outer Casing	47 cm x 58.42 cm x 54.61 cm x 0.3 cm	14.3	0	9	Aluminum 7075-T6 Density
TOTAL		49	30.632748			

Appendix F: Thermal Analysis

F1: Initial Baseline Heating and Cooling System Calculations

Heating Calculations

Variables:

m : mass [kg]

c_p : specific heat capacity [J/kg*K]

T : temperature [K]

Q : heat energy [kJ]

t : time [s]

P : power [kW]

Solution:

m = 2 L water = 2 kg

$c_p = 4.200 \frac{kJ}{kg \cdot K}$

$\Delta T_{max} = T_{max} - T_{min} = 93^\circ C - 18^\circ C = 75^\circ C = 75K$

$t_{expected} = 600 s$

Equations:

$$Q = m * c_p * \Delta T$$

(1)

$$P = \frac{Q}{\Delta t}$$

(2)

$$Q_{max} = 2 * 4.200 * 75 = 630 kJ$$

$$P_{max} = \frac{630 kJ}{600 s} = 1.05 kW$$

Cooling Calculations

Variables:

m : mass [kg]

c_p : specific heat capacity [J/kg*K]

T : temperature [K]

Q : heat energy [kJ]

t : time [s]

P : power [kW]

Solution:

m = 2 L water = 2 kg

$c_p = 4.184 \frac{kJ}{kg \cdot K}$

$\Delta T_{max} = T_{max} - T_{min} = 18^\circ C - 4^\circ C = 14^\circ C = 14K$

$t_{expected} = 600 s$

$$Q_{max} = 2 * 4.184 * 14 = 118 kJ$$

$$P_{max} = \frac{118 kJ}{600 s} = 0.1967 kW = 196.7 W$$

Equations:

$$Q = m * c_p * \Delta T$$

(1)

$$P = \frac{Q}{\Delta t}$$

(2)

With estimated 20% Losses for Mini Refrigeration Cycle:

$$P_{max} = 236 W$$

F2: Lumped Capacitance & Thermal Resistance Calculations

Lumped Capacitance Calculations

Variables:

m : mass [kg]

c_p : specific heat capacity [kJ / kg * K]

$\frac{dT}{dt}$: temperature gradient over time [J / kg * K]

\dot{Q}_{in} : heat rate input [kW]

\dot{Q}_{out} : heat rate output [kW]

$\dot{Q}_{req,max}$: max required power capacity [kW]

η : system efficiency [%]

Equations:

$$m * c_p * \frac{dT}{dt} = \dot{Q}_{in} - \dot{Q}_{out}$$

Solution:

Heating Cycle:

$$\dot{Q}_{req,max} = 1.05 \text{ kW}$$

Cooling Cycle:

$$\dot{Q}_{req,max} = 0.197 \text{ kW}$$

$$\dot{Q}_{req,max,design} = 0.236 \text{ kW}$$

Thermal Resistance Calculations

Variables:

R_{total} : total thermal resistance [K / W]

$R_{\text{conv,ref}}$: convection resistance of the refrigerant [K / W]

$R_{\text{cond,plate}}$: conduction resistance of the exchanger plate [K / W]

$R_{\text{conv,water}}$: convection resistance of the water [K / W]

h_{refrig} : convection heat transfer coefficient, refrigerant [$\text{W} / \text{m}^2 \cdot \text{K}$]

h_{water} : convection heat transfer coefficient, water [$\text{W} / \text{m}^2 \cdot \text{K}$]

k_{plate} : thermal conductivity of the stainless-steel plate [$\text{W} / \text{m} \cdot \text{K}$]

A : heat transfer surface area [m^2]

L : thickness of the exchanger plate [m]

Equations:

$$\dot{Q} = \frac{\Delta T_{\text{trans}}}{R_{\text{total}}}$$
$$R_{\text{total}} = \frac{1}{h_{\text{refrig}} \cdot A} + \frac{L}{k_{\text{plate}} \cdot A} + \frac{1}{h_{\text{water}} \cdot A}$$

Assumptions & Other Parameters:

Area = 0.05 m^2

L = 0.0005 m

Plate Material (Stainless Steel via ThyssenKrupp specifications):

$k_{\text{plate}} = 15 \text{ W} / \text{m} \cdot \text{K}$

Refrigerant Film Coefficient:

$h_{\text{refrig}} = 2000 \text{ W} / \text{m}^2 \cdot \text{K}$

Water Film Coefficient:

$h_{\text{water}} = 2500 \text{ W} / \text{m}^2 \cdot \text{K}$

Solution:

$$R_{\text{total}} = 0.018667 \text{ K} / \text{W}$$

$$\Delta T_{\text{transient}} = \dot{Q}_{\text{total}} \cdot R_{\text{total}} = 5.88 \text{ K} = 5.88 \text{ }^\circ\text{C}$$

F3: Thermal Efficiency Calculations

Thermal Efficiency & COP Calculations

Variables:

t_h : heating time [s]
 t_c : cooling time [s]
 m : mass [kg]
 c_p : specific heat capacity [kJ / kg * K]
 \dot{Q}_{in} : heating power input [kW]
 \dot{Q}_{cool} : cooling power capacity [kW]
 η : system efficiency [%]
COP: coefficient of performance [...]

Equations:

$$t_h = \frac{m \cdot c_p \cdot (T_{final} - T_{initial})}{\dot{Q}_{in} \cdot \eta}$$

$$t_c = \frac{m \cdot c_p \cdot (T_{initial} - T_{final})}{\dot{Q}_{cool}}$$

Equations:

$$W = \frac{Q}{COP}$$

$$Q_{rejected} = Q_{cool} + W_{comp}$$

$$Q_{net,lost} = Q_{heat} - Q_{rejected}$$

$$W_{heat,net} = \frac{Q_{net,lost}}{\eta}$$

Solution:

$$W_{cool} = 168.57 \text{ kJ}$$

$$W_{heat} = 700 \text{ kJ}$$

$$W_{comp} = 37.67 \text{ kJ}$$

$$Q_{rejected} = 157.33 \text{ kJ}$$

$$Q_{lost,net} = 472.67 \text{ kJ}$$

$$W_{heat,net} = 525.19 \text{ kJ}$$

Variables:

t_h : heating time [s]
 t_c : cooling time [s]
 m : mass [kg]
 c_p : specific heat capacity [kJ / kg * K]
 \dot{Q}_{in} : heating power input [kW]
 \dot{Q}_{cool} : cooling power capacity [kW]
 η : system efficiency [%]
COP: coefficient of performance [...]

Equations:

$$t_h = \frac{m \cdot c_p \cdot (T_{final} - T_{initial})}{\dot{Q}_{in} \cdot \eta}$$

$$t_c = \frac{m \cdot c_p \cdot (T_{initial} - T_{final})}{\dot{Q}_{cool}}$$

Solution:

$$t_h = 664.4 \text{ s} = 11.07 \text{ min}$$

$$t'_h = 9.63 \text{ min}$$

$$t_c = 992.8 \text{ s} = 16.5 \text{ min}$$

$$t'_c = 7.10 \text{ min}$$

Combined... $t = 8.27 \text{ min}$

Solution:

Cooling COP Improvement

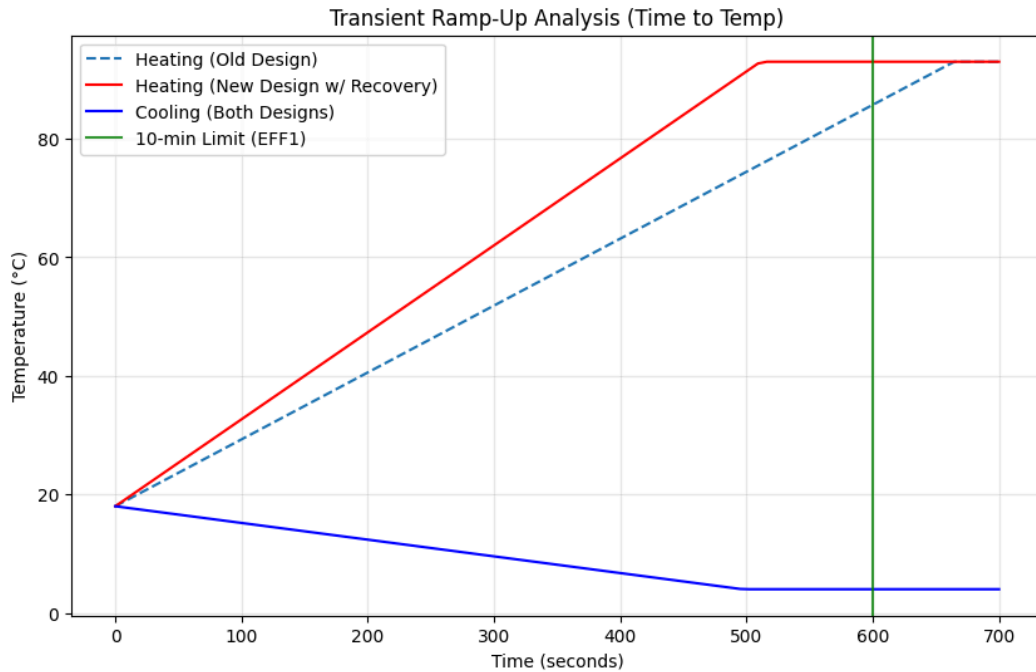
- Baseline COP: $COP_c = 0.7$
- New System COP: $COP_c = 3.0$

Heating COP Improvement

- Baseline COP: $COP_h = 1.0$
- New System COP: $COP_h = 1.33$

Summary Table

Process	Old Energy Consumption [Wh]	Updated Energy Consumption [Wh]	Energy Saved per Cycle [Wh]	Net Reduction per Cycle [%]
Cooling	46.8	10.9	35.9	76.7
Heating	194.4	145.9	48.5	25.0
Combined	241.2	156.8	84.4	35.0



F4: Miscellaneous Thermal System Calculations

Thermal Load on Environment Calculations

Variables:

$\dot{Q}_{\text{rejected}}$: total heat rejected from the cooling sub-system [kW]

$\dot{Q}_{\text{thermal,lost}}$: inefficient heat lost directly to the ambient surroundings [kW]

$\dot{Q}_{\text{in,elec}}$: electrical heater power input [kW]

$\dot{Q}_{\text{waste,total}}$: cumulative thermal energy dumped into the environment per cycle [kJ]

η : system efficiency [%]

Equations:

$$\dot{Q}_{\text{thermal,lost}} = (1 - \eta) \cdot \dot{Q}_{\text{in,elec}}$$

$$Q_{\text{waste,total}} = Q_{\text{rejected}} + Q_{\text{thermal,lost}}$$

Solution and Takeaways:

Baseline -- Over 600s cycle:

$$Q_{\text{rejected}} = 189 \text{ kJ}$$

$$Q_{\text{thermal,lost}} = 63 \text{ kJ}$$

$$Q_{\text{waste,total}} = 252 \text{ kJ}$$

Saving 204.7 kJ, net thermal load to environment decreased by 81%

Updated -- Over 600s cycle:

$$Q_{\text{waste,total}} = 47.3 \text{ kJ}$$

Appendix G: Fluid Transporting System Trade Analysis

Factor	Weight	Design 1: PTFE (Teflon)	Design 2: Stainless Steel	Design 3: Copper
Durability	0.45	1	5	3
Smoothness	0.1	5	3	2
Iodine Compatibility	0.18	5	3	1
Biofilm Resistance	0.27	4	2	5
Weighted Score	1	2.93	3.63	3.08

Appendix H: Fluid Transporting Equations

$$Q_p = \frac{\pi r^4 \Delta P}{8\mu L} \quad (1)$$

$$Q_o = C_d A \sqrt{\frac{2\Delta P}{\rho}} \quad (2)$$

Variables:

Q_p : Piping Volumetric flow rate (m^3/s)

Q_o : Orifice Volumetric flow rate (m^3/s)

r : Pipe radius (m)

ΔP : Pressure drop (Pa)

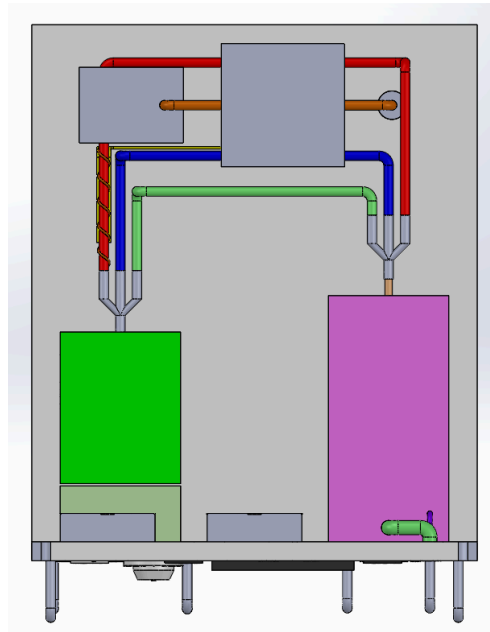
μ : Dynamic viscosity ($Pa \cdot s$)

L : Pipe length (m)

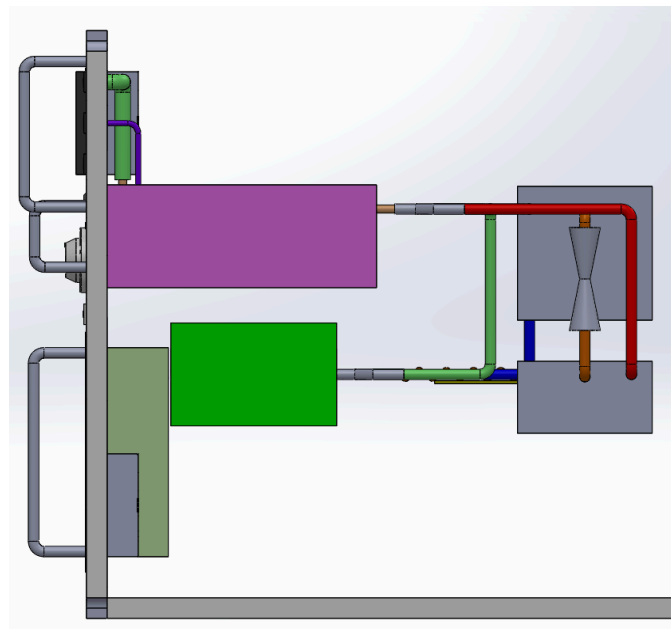
C_d : Discharge coefficient (~ 0.6 for sharp edge orifice)

A : Orifice area (m^2)

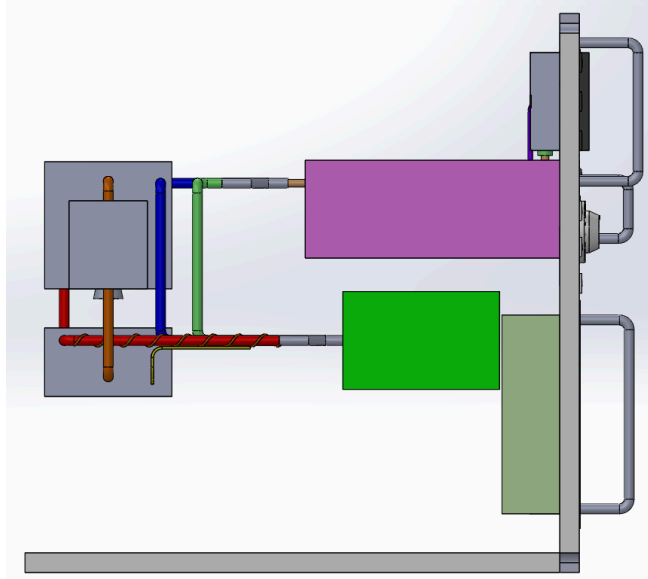
Appendix I: Additional EPWD Modeling



Top-Down View



Side View 1



Side View 2