
STREAM: Space Temperature Regulated Efficient Aqua Module
University of Texas Rio Grande Valley Human Lander Challenge 2026 Team



Potable Water Dispenser

Student Members:

Iram Betancourt (Undergraduate, Mechanical Engineering)

Jaden Cardenas (Undergraduate, Mechanical Engineering)

Landen Garcia (Undergraduate, Mechanical Engineering)

William Jimenez (Undergraduate, Mechanical Engineering)

Cristobal Munoz (Undergraduate, Mechanical Engineering)

Emanuel Soto (Undergraduate, Mechanical Engineering)

Faculty Advisors:

José J Sanchez

Marcos Villareal

Noe Vargas

Gregory Pott



Theme Subtopic, Major Objectives & Technical Approach

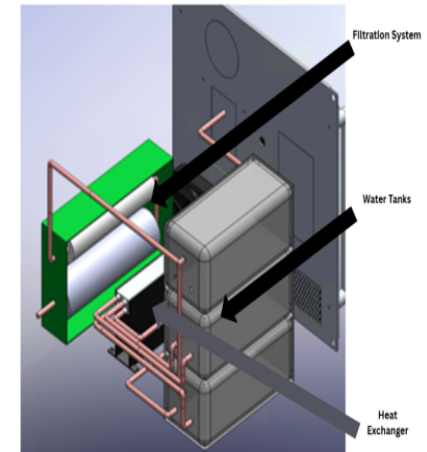
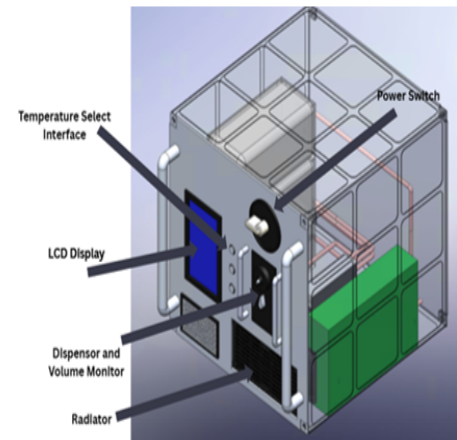
Major Objectives

- Deliver on-demand hot (~60° C) and cold (~10–15° C demonstrated) potable water in microgravity.
- Improve crew hydration and food preparation capability beyond current ISS systems.
- Minimize mechanical complexity using solid-state thermal control.
- Ensure compatibility with lunar surface ECLSS architectures.

Technical Approach

- Dual closed-loop architecture (Hot Loop + Cold Loop) with insulated 5–5.5 L storage tanks.
- Thermoelectric (TEC1-12709) modules for active heating/cooling.
- Peltier module sandwiched between two water boxes for direct thermal transfer.
- Radiator-assisted hot loop for improved heat rejection and thermal stability.
- Pump-driven recirculation for uniform tank temperature control.

Image/Graphic: STREAM CAD Design



Key Design Details & Innovations of the Concept

Design Details

- Dual-loop thermoelectric heating and cooling system
- Integrated hot and cold potable water reservoirs
- Peltier modules mounted between dual water blocks
- Radiator-assisted heat rejection loop
- Compact modular enclosure for space habitat integration
- Insulated thermal management system using aerogel materials
- Sensor-based monitoring and automated dispense interface

Innovations

- Simultaneous hot and cold-water generation within one system
- Compressor-free thermal regulation using thermoelectric technology
- Reduced moving parts for improved reliability and lower maintenance
- Compact and scalable architecture for lunar and Martian habitats
- Energy-efficient dual-loop heat transfer configuration
- Modular design adaptable for future NASA ECLSS integration

Summary of Schedule Cost for the proposed solutions path to adoption

Timeline

Timeline	Focus Area	Goal
Months 1–2	Peltier Testing	Thermal validation
Months 3–4	Filtration System	Water quality verification
Months 4–6	Dispensing System	Accurate dispensing
Months 6–7	System Assembly	Full integration
Months 7–9	System Testing	Risk analysis
Months 9–12	Stress Testing	Failure validation

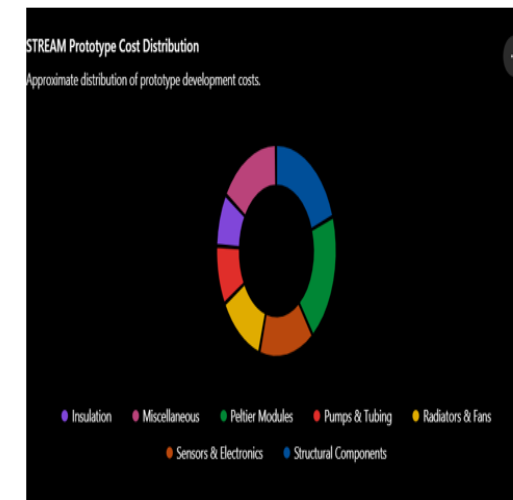


Table of Contents

1. Introduction.....	5
1.1 Executive Summary	
1.2 NASA Human Exploration and ECLSS Challenges	
1.3 Problem Statement	
1.5 System Overview	
1.6 NASA Design Constraints and Mission Requirements	
1.7 Innovation and Technology Readiness	
2. Heat Exchanger System.....	8
2.1 Heat Exchanger System Overview	
2.2 Thermoelectric Module Configuration	
2.3 Dual-Loop Thermal Architecture	
2.4 Cooling Block and Water Box Design	
2.5 Pump and Flow System Configuration	
2.6 Radiator Heat Rejection System	
2.7 Thermal Transfer Analysis	
2.8 Flow Rate Optimization and Testing	
2.9 Experimental Validation and Performance Results	
2.10 Thermal Risks and Mitigation Strategies	
3. Insulation System.....	12
3.1 Insulation System Overview	
3.2 Thermal Retention Requirements	
3.3 Aerogel Insulation Material Selection	
3.4 Multi-Layer Insulation Configuration	
3.5 Thermal Efficiency Testing and Results	
4. Interface and Dispense System.....	15
4.1 Control and Dispense System Overview	
4.2 Human-Machine Interface (HMI)	
4.3 ESP32 Control Architecture	
4.4 Sensor Integration and Monitoring	

4.5 Temperature and Volume Regulation	
4.6 Solenoid Valve Dispense System	
4.7 Automated Dispensing Logic	
4.8 Crew Interaction and Operational Safety	
4.9 Microgravity Operation Considerations	
5. Filtration System.....	18
5.1 Filtration System Overview	
5.2 Potable Water Requirements for Spaceflight	
5.3 Multi-Stage Filtration Architecture	
5.4 UV-C Sterilization System	
5.5 Water Quality Protection and Contamination Prevention	
5.6 ECLSS Water Sustainability Integration	
5.7 Reliability and Maintenance Considerations	
6. Schedule and Budgeting.....	20
6.1 Development and Implementation Strategy	
6.2 NASA Mission Integration Timeline	
6.3 Technology Maturation Roadmap	
6.4 Development, Test, and Evaluation (DT&E) Strategy	
6.5 Projected NASA Budget Assessment	
6.6 Path-to-Flight Feasibility	
7. Conclusion.....	22
7.1 Summary of Key Findings	
7.2 STREAM Value to NASA Human Exploration	
7.3 Future Development Recommendations	
7.4 Final Assessment	

1. Introduction

1.1 Executive Summary

Long-duration human spaceflight missions to the Moon and Mars require advanced Environmental Control and Life Support Systems (ECLSS) capable of supporting crew health, safety, and mission sustainability. Potable water delivery systems are essential components of these systems because they provide astronauts with water for hydration, food rehydration, hygiene, and medical operations. Current spacecraft potable water dispensers are primarily designed for microgravity environments and are limited in their ability to provide temperature-regulated water efficiently, particularly cold water for crew consumption and thermal comfort. To address this limitation, the proposed Space-Temperature Regulated Efficient Aqua Module (STREAM), a portable thermoelectric potable water dispenser capable of simultaneously producing hot and cold potable water for crew operations during space missions. The STREAM system integrates a dual-loop thermoelectric design utilizing Peltier modules to achieve simultaneous heating and cooling while maintaining continuous water circulation to minimize stagnation and microbial growth. The system incorporates multiple safety and purification mechanisms, including a multi-stage carbon filtration system, inline UV-C disinfection, stainless steel tubing, insulated storage tanks, and real-time sensor monitoring. Temperature sensors, water level sensors, and flow sensors are integrated with an Arduino-based control system to regulate thermal performance, monitor tank status, and dispensing operations. STREAM is designed to improve crew usability through on-demand temperature selection and precise dispensing control while minimizing waste and maintenance requirements. The proposed design emphasizes compactness, reliability, low complexity, and compatibility with NASA Human Landing System (HLS) and ECLSS. Preliminary subsystem testing demonstrated successful simultaneous heating and cooling operation using thermoelectric modules, validating the feasibility of the proposed thermal regulation concept. STREAM provides a scalable and modular solution that supports NASA's Artemis objectives and future human exploration missions beyond low Earth orbit.

1.2 NASA Human Exploration and ECLSS Challenges

Environmental Control and Life Support Systems (ECLSS) are critical technologies required to sustain human life during long-duration space missions. These systems are responsible for maintaining breathable air, potable water, thermal regulation, waste management, and habitable environmental conditions for astronauts operating in extreme extraterrestrial environments. Future missions associated with NASA's Artemis program and eventual Mars transit missions will require highly reliable and autonomous ECLSS technologies capable of operating for extended durations under partial gravity, vacuum exposure, thermal cycling, and limited resource availability (NASA, 2023). Potable water systems play a significant role in crew performance and mission success. Astronauts rely on temperature-controlled water for hydration, meal preparation, medical activities, and psychological comfort during prolonged missions. Existing spacecraft water dispensers primarily utilize resistive heating systems capable of supplying limited quantities of heated water, while lacking integrated cooling capability and advanced thermal management functionality. Future exploration systems must also minimize mass, volume, power consumption, maintenance requirements, and contamination risk while remaining compatible with spacecraft and surface habitat architectures. In reduced gravity and vacuum environments, fluid behavior becomes increasingly difficult to manage because of altered convection, bubble formation, and fluid separation phenomena. Additionally, microbial growth and water stagnation present major concerns for long-duration missions because water systems may operate continuously for months or years with limited maintenance opportunities. NASA's Human Lander Challenge (HuLC) emphasizes the development of innovative technologies capable of supporting sustainable lunar and Martian exploration while satisfying strict engineering constraints related to reliability, survivability, and operational simplicity. STREAM directly addresses these challenges by integrating simultaneous thermal regulation, water purification,

smart monitoring, and compact system architecture into a single potable water delivery platform designed for future human exploration missions.

1.3 Problem Statement

Current spacecraft potable water dispensers are limited in their ability to provide both hot and cold potable water within a compact and efficient system architecture. Existing systems primarily rely on resistive heating technologies that can only deliver small amounts of heated water while lacking active cooling functionality. As NASA transitions toward sustained lunar habitation and future Mars missions, astronauts will require improved potable water systems capable of delivering temperature-controlled water for hydration, food rehydration, hygiene, and crew comfort. Long-duration missions introduce additional operational challenges related to water quality, microbial contamination, system maintenance, and thermal regulation. Furthermore, spacecraft systems must function reliably under reduced gravity conditions while satisfying strict constraints involving mass, power consumption, volume, and operational lifespan. The objective of the STREAM project is to develop a compact, reliable, and temperature-regulated potable water dispenser capable of simultaneously producing hot and cold water using dual-loop thermoelectric architecture. The system is designed to provide accurate thermal regulation, integrated purification, autonomous monitoring, and continuous fluid circulation while minimizing crew workload and maintenance requirements. STREAM seeks to provide an innovative solution that enhances habitability and operational sustainability for space missions using thermoelectric modules. The primary objective of the STREAM system is to develop a portable and reliable potable water dispenser capable of delivering both hot and cold water on demand for long-duration human space exploration missions. The system is intended to support crew hydration, food preparation, and operational efficiency while integrating with future NASA ECLSS architectures.

Specific objectives of the STREAM system include:

1. Develop a dual-loop thermoelectric thermal regulation system capable of simultaneously heating and cooling potable water using solid-state Peltier modules.
2. Provide temperature-controlled water delivery within operational target ranges suitable for crew hydration and food rehydration applications.
3. Integrate a multi-stage water purification system utilizing carbon filtration and inline UV-C disinfection to minimize microbial contamination and maintain potable water quality.
4. Implement continuous fluid circulation to reduce water stagnation and improve long-duration system reliability.
5. Incorporate smart monitoring and autonomous control systems capable of measuring temperature, water level, filter status, and dispensing volume in real time.
6. Minimize overall system mass, volume, maintenance requirements, and mechanical complexity to improve compatibility with NASA spacecraft and habitat constraints.
7. Design a modular and manufacturable architecture capable of surviving launch loads, thermal cycling, and reduced gravity operational environments.
8. Support NASA's long-term Artemis and Mars exploration objectives through a scalable and sustainable potable water management solution.

1.4 System Overview

The STREAM system is a compact dual-loop thermoelectric potable water dispenser designed to simultaneously provide hot and cold potable water for crew operations during long-duration space missions. The system architecture combines thermal regulation, water purification, fluid circulation, and smart monitoring into a unified modular platform. The thermal management subsystem utilizes thermoelectric Peltier modules capable of transferring heat between two independent fluid loops. One loop is dedicated to cooling potable water, while the second loop transfers rejected heat to a separate hot-

water reservoir. Continuous circulation allows both loops to operate simultaneously, enabling the system to maintain stable hot and cold-water supplies while minimizing thermal losses and water stagnation. Heat generated on the hot side of the thermoelectric modules is dissipated through a radiator-assisted heat rejection system to prevent overheating and maintain thermal stability. The fluid management subsystem includes insulated storage tanks, diaphragm pumps, solenoid valves, stainless steel tubing, and controlled dispensing pathways. Water first passes through a multi-stage filtration system designed to remove sediment, chemical contaminants, odors, and particulate matter. Following filtration, inline UV-C disinfection provides an additional microbial safety barrier before water enters the thermal regulation loops. The control subsystem utilizes an Arduino Mega microcontroller integrated with DS18B20 temperature sensors, flow sensors, water level sensors, and user interface controls. The monitoring system allows astronauts to select desired water temperatures and dispensing quantities while simultaneously tracking tank conditions and filter life status. Automated controls regulate pumps, valves, and thermal components to maintain stable operation and improve system autonomy. The current CAD design configuration occupies an approximate 20 in × 20 in × 20 in enclosure and incorporates modular subsystem integration for ease of maintenance and future scalability. Preliminary experimental testing demonstrated successful heating and cooling functionality, validating the feasibility of the thermoelectric dual-loop architecture for future spacecraft potable water applications.

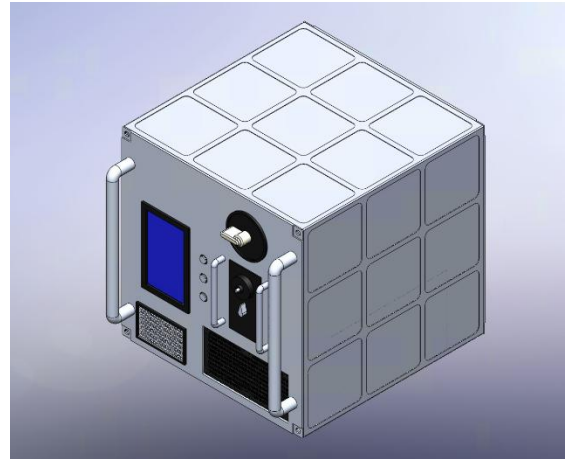


Figure 1: STREAM CAD Design

1.5 NASA Design Constraints and Mission Requirements

Spacecraft systems intended for lunar and Martian missions must satisfy numerous engineering and operational constraints associated with long-duration human exploration. NASA Human Landing Systems and ECLSS technologies must prioritize reliability, safety, efficiency, and survivability while minimizing logistical demands and crew maintenance requirements. One of the primary design constraints for the STREAM system involves minimizing mass and volume while maintaining operational capability. Spacecraft payload limitations require systems to remain compact and lightweight without sacrificing performance or reliability. The STREAM system addresses these requirements through the integration of heating, cooling, purification, and monitoring subsystems into a single modular architecture. Power consumption also represents a major challenge for long-duration missions because spacecraft power availability is limited and must be distributed among numerous life support and operational systems. STREAM utilizes solid-state thermoelectric modules that eliminate compressors and reduce moving mechanical components, improving system simplicity and reliability for extended mission durations. The system must additionally withstand launch loads, vibration, thermal cycling, vacuum exposure, and reduced gravity fluid behavior. Closed-loop circulation systems were incorporated to minimize fluid separation and bubble formation in reduced gravity environments while improving thermal consistency and operational reliability. Aerogel insulation was selected because of its low thermal conductivity, lightweight properties, and effectiveness under vacuum conditions, supporting both hot and cold operational modes. Crew safety and water quality are also essential mission requirements. The STREAM system integrates carbon filtration, UV-C disinfection, stainless steel tubing, and continuous circulation to reduce contamination risk and support long-term potable water safety. Automated monitoring systems further reduce crew workload by tracking temperature, dispensing volume, and filter status in real time.

NASA mission requirements additionally specify operational lifetimes of approximately 30 days for lunar surface missions and up to 1200 days for future Mars missions. Consequently, system durability, maintainability, and fault reduction were major considerations during the design process. STREAM's

simplified thermoelectric architecture and modular subsystem integration were selected to improve long-term operational sustainability for future exploration missions.

1.6 Innovation and Technology Readiness

The STREAM system introduces several innovative features that distinguish it from traditional spacecraft potable water dispensers. The most significant innovation is the implementation of a simultaneous dual-loop thermoelectric architecture capable of producing both hot and cold potable water within a single compact system. Unlike conventional resistive heating dispensers, STREAM integrates heating and cooling functionality while maintaining continuous circulation to improve thermal consistency and reduce microbial stagnation risks.

Another major innovation involves the integration of multiple water safety systems into a unified potable water management platform. The combination of carbon filtration,

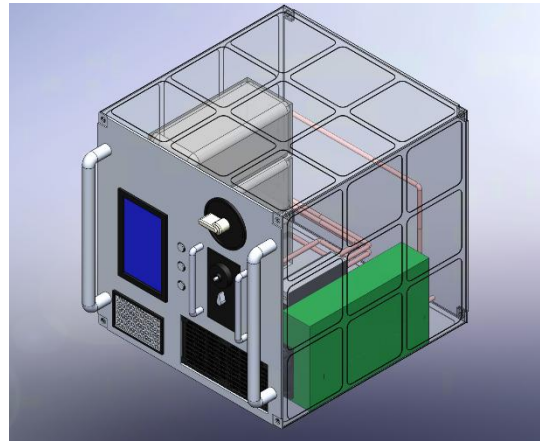


Figure 2: STREAM CAD Design

inline UV-C disinfection, stainless steel tubing, and automated monitoring creates a multilayered approach to water purification and crew safety. This design reduces contamination risks while minimizing maintenance complexity during long-duration missions. The system also incorporates smart autonomous monitoring features capable of tracking water temperature, water level, dispensing volume, and filter usage in real time. These features improve crew usability, reduce operational workload, and support long-term autonomous operation in deep space environments. The use of thermoelectric modules eliminates the need for compressors and refrigerants, reducing mechanical complexity, and improving reliability for extended-duration missions.

Based on the current development stage, STREAM is estimated to fall within Technology Readiness Level (TRL) 3 to 4. Analytical studies, subsystem modeling, CAD integration, and preliminary thermal testing have validated the feasibility of the proposed concept and demonstrated successful simultaneous heating and cooling operation. Additional future work involving integrated prototype testing, environmental validation, and reduced operational gravity would further mature the system toward higher TRL classifications suitable for mission implementation.

2. Heat Exchanger System

2.1 Heat Exchanger System Overview

The heat exchanger subsystem is the key feature of the STREAM potable water dispenser as the main thermal management system, allowing the concurrent heating and cooling of potable water in a compact closed-loop configuration. The system was developed to control water temperatures for extended stays of people in outer space with the least possible number of mechanical components, maintenance needs, and overall size of the system. In contrast to typical vapor compression systems, the STREAM system makes use of thermoelectric heat transfer in order to produce hot and cold potable water. The heat exchanger subsystem uses the thermoelectric Peltier modules placed between two water circulation loops. In operation, thermal energy from the cold-side loop is moved to the hot-side loop via the modules of thermoelectric heat exchange, thereby producing a temperature gradient across the heat exchanger system. In addition, the system employs a radiator-based heat rejection system to remove any excess thermal energy from the hot-side loop. Such an approach results in the creation of a compact and modular thermal system that could be used in the future in Environmental Control and Life Support System (ECLSS) applications on cis-lunar, lunar, and even Mars missions.

2.2 Thermoelectric Module Configuration

The STREAM thermal subsystem utilizes TEC1-12715 thermoelectric modules as the primary mechanism for thermal energy transfer between the hot and cold-water reservoirs. Thermoelectric modules were selected due to their compact size, solid-state operation, elimination of refrigerants, and ability to simultaneously generate heating and cooling through direct electrical energy conversion. Compared to traditional vapor-compression systems, thermoelectric cooling systems contain fewer moving components and provide improved modularity and reliability for spaceflight-oriented applications. The thermoelectric modules were arranged in a 2×2 configuration between the hot-side and cold-side cooling blocks in order to maximize thermal contact area and improve heat transfer

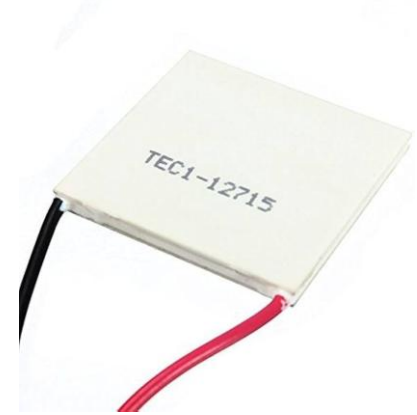


Figure 3: Peltier Module

capacity. Thermal interface paste was applied between all contact surfaces to reduce thermal resistance and improve conductive heat transfer between the modules and cooling blocks. Mechanical clamping pressure was then applied across the assembly to maintain uniform thermal contact during operation. The modules were electrically configured in parallel to allow consistent voltage distribution across each thermoelectric device while simplifying power delivery from the external DC power supply. As electrical current passed through the thermoelectric junctions, heat was absorbed from the cold-side cooling block and rejected to the hot-side cooling block, establishing the thermal gradient required for simultaneous water heating and cooling. The total thermal energy rejected on the hot side can be expressed as: $Q_h = Q_c + P_{elec}$, where Q_h represents the heat rejected by the hot side, Q_c represents the cooling load absorbed from the cold side, and P_{elec} represents the electrical input power supplied to the thermoelectric modules.

2.3 Dual-Loop Thermal Architecture

The proposed STREAM potable water dispenser employs a two-loop thermal design in which there are independent hot and cold-water circulation loops that utilize the same thermoelectric heat exchanger system. This allows both potable water sources to be regulated in terms of their temperatures simultaneously without interference between the heating and cooling subsystems. In the case of the cold loop, water from the cold-water reservoir will pass through a designated DC pump into the cooling block on the cold side of the thermoelectric system. The cooling of water will take place as the water passes through the cooling block and heat is extracted via the thermoelectric modules. The heated thermoelectric modules will result in the lowering of the water temperature. The hot loop operates similarly, except for the cooling process being reversed such that heat rejection from the thermoelectric module will result in water warming up before recirculating into the hot water reservoir. In order to avoid overheating of the hot water loop, a heat rejection subsystem featuring a radiator has been integrated into the system to continuously remove excess heat.

2.4 Cooling Block and Water Box Design

The cooling block and water box assemblies were designed to maximize conductive and convective heat transfer between the thermoelectric modules and the circulating potable water loops. The heat exchanger assembly consisted of thermally conductive cooling blocks mounted directly against the thermoelectric modules to facilitate efficient energy transfer between the hot and cold subsystems. The cooling block geometry was designed around the 2×2 thermoelectric module arrangement to provide uniform thermal distribution across the heat transfer surfaces. Internal flow passages within the water boxes were configured to promote continuous coolant circulation while minimizing stagnant flow regions that could negatively affect thermal performance. The compact structure of the cooling blocks also reduced unnecessary thermal mass, allowing faster thermal response during startup and transient operating

conditions. Thermal interface paste was applied between the thermoelectric modules and the cooling block surfaces to reduce interfacial thermal resistance and improve conductive heat transfer efficiency. Mechanical clamping pressure was then applied uniformly across the assembly to maintain consistent thermal contact during operation. The water box assemblies were designed as sealed closed-loop chambers capable of continuous potable water circulation while minimizing leakage risk and maintaining structural integrity. Material selection considered thermal conductivity, manufacturability, corrosion resistance, and compatibility with potable water systems. The resulting configuration provided a compact and modular thermal exchange system capable of supporting simultaneous heating and cooling operations within a confined spacecraft-compatible footprint.

2.5 Pump and Flow System Configuration

Fluid circulation throughout the STREAM thermal subsystem was achieved using independent DC water pumps integrated into each thermal loop. The pumps were responsible for maintaining continuous coolant flow through the heat exchanger assemblies, reservoirs, and radiator subsystem to ensure stable thermal transfer during operation. Each circulation loop utilized a closed-loop configuration consisting of a reservoir, circulation pump, tubing network, cooling block assembly, and heat rejection subsystem. Flexible tubing connections were used throughout the system to simplify routing within the enclosure while reducing mechanical stress and minimizing pressure losses across the circulation path. The thermal energy transferred by the circulating coolant can be expressed using the steady-flow heat transfer relationship: $Q = \dot{m}c_p\Delta T$ where Q represents the thermal energy transfer rate, \dot{m} represents the coolant mass flow rate, c_p represents the specific heat capacity of water, and ΔT represents the temperature change across the heat exchanger assembly. Flow rate optimization represented a critical aspect of the thermal system design because coolant velocity directly influenced convective heat transfer and fluid residence time within the cooling blocks. Excessively high flow rates reduced thermal contact duration between the coolant and heat exchanger surfaces, while insufficient flow rates limited the system's ability to transport thermal energy efficiently throughout the loops. Multiple pump operating conditions were therefore experimentally evaluated to identify the flow configuration that provided the best balance between thermal transfer efficiency, radiator heat rejection capability, and overall system stability.

2.6 Radiator Heat Rejection System

The radiator heat rejection subsystem was incorporated into the hot-side circulation loop to remove excess thermal energy generated during thermoelectric operation. Because thermoelectric modules reject both absorbed cooling energy and electrical input energy to the hot side, effective heat dissipation was necessary to prevent thermal saturation and maintain continuous cooling performance. The system utilized a multi-fan radiator assembly integrated within the hot-water loop to dissipate thermal energy through forced convection. As heated water circulated through the radiator channels, thermal energy was transferred from the coolant into the radiator fins and subsequently removed through airflow generated by the cooling fans. This process reduced the temperature of the hot-side loop before recirculation into the heat exchanger assembly. Convective heat rejection within the radiator can be approximated using: $Q = hA\Delta T$, where Q represents convective heat transfer, h represents the convective heat transfer coefficient, A represents radiator surface area, and ΔT represents the temperature difference between the radiator surface and surrounding air. Experimental observations demonstrated that the radiator subsystem significantly improved thermal stability by reducing uncontrolled heat accumulation within the hot loop. Without sufficient heat rejection, both reservoirs experienced temperature increases due to excess thermal loading. The integration of the radiator therefore played a critical role in sustaining stable thermoelectric operation and improving overall system performance.

2.7 Thermal Transfer Analysis

Thermal performance within the STREAM potable water dispenser was governed by conductive, convective, and thermoelectric heat transfer mechanisms operating simultaneously throughout the system. Conductive heat transfer occurred between the thermoelectric modules and cooling blocks, convective heat transfer occurred within the circulating fluid loops and radiator subsystem, and thermoelectric transfer enabled direct movement of thermal energy between the hot and cold reservoirs. The overall thermal behavior of the system depended on several interacting parameters including thermoelectric efficiency, cooling block thermal conductivity, fluid flow rate, radiator dissipation capacity, and interfacial thermal resistance. Thermal interface resistance between the thermoelectric modules and cooling blocks was minimized using thermal interface paste and controlled mechanical compression to improve conductive heat transfer efficiency. The thermal energy transferred by the circulating fluid can be expressed using the steady-flow heat transfer relationship: $Q = \dot{m}c_p\Delta T$ where Q represents the thermal energy transfer rate, \dot{m} represents the fluid mass flow rate, c_p represents the specific heat capacity of water, and ΔT represents the temperature change across the heat exchanger assembly. During operation, the cold-side loop continuously absorbed thermal energy from the circulating water while the hot-side radiator dissipated excess heat into the surrounding environment. If heat rejection capacity became insufficient, thermal accumulation within the hot loop reduced the temperature differential across the thermoelectric modules and negatively affected cooling performance. Thermal analysis of the system assumed steady-state operation, incompressible fluid flow, and approximately constant ambient conditions during experimental testing.

2.8 Flow Rate Optimization and Testing

The test was done to assess the effects of changes in the coolant circulation rate on the thermal performance of the STREAM heat exchanger subsystem. This was done by changing the level of pump input voltages from 7V up to 12V with measurement of the corresponding temperature variation and coolant flow rate for a duration of 20 minutes. The recorded coolant flow rates were about 0.0389 kg/sec at 7 volts and 0.0667 kg/sec at 12 volts. The tests showed that as pump input voltage increased, the efficiency of coolant circulation increased. Thermal performance of the heat exchange was determined thro: $Q = \dot{m}c_p\Delta T$. Here, Q represents heat transfer rate, \dot{m} represents coolant mass flow rate, c_p represents the specific heat capacity of water, and ΔT represents temperature difference measurement for the entire system. The data analysis revealed an increment in the heat transfer rate value from 1534.59 W at 7 volts to 2878.70 W at 12 volts, indicating the effect of coolant flow rate on thermal energy transfer and overall

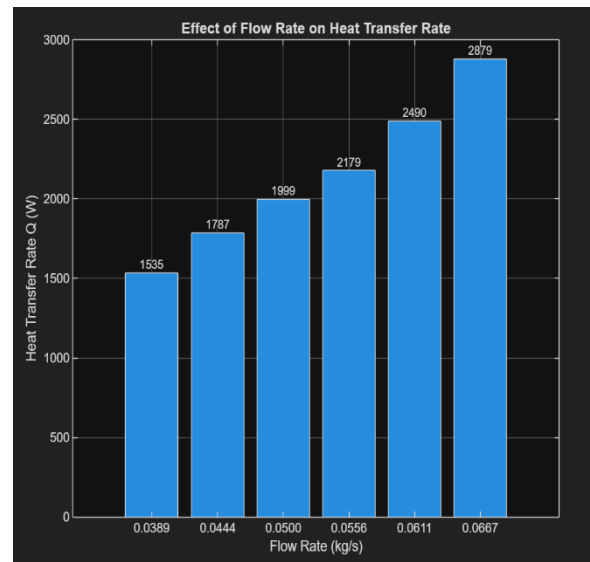


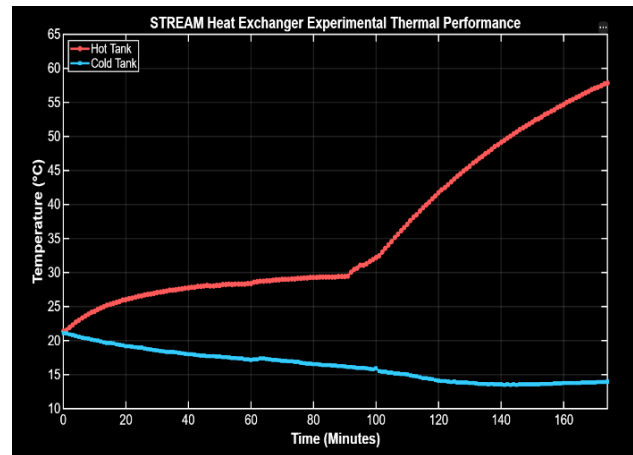
Figure 4: Water Pump Q Rate

system performance.

2.9 Experimental Validation and Performance Results

Experimental validation testing was conducted to evaluate the thermal performance and operational stability of the STREAM heat exchanger subsystem during simultaneous heating and cooling operation. Temperature measurements were recorded at one-minute intervals for both the hot and cold reservoirs in order to analyze transient thermal behavior, heat transfer effectiveness, and overall system stability throughout extended operation. The experimental results demonstrated successful simultaneous thermal

separation between the dual-loop reservoirs. During testing, the hot-side reservoir temperature increased from approximately 21.4°C to approximately 60.1°C, while the cold-side reservoir temperature decreased from approximately 21.1°C to a minimum operating range near 13.5–14.0°C. These results confirm that the TEC1-1215 thermoelectric modules were capable of continuously transferring thermal energy from the cold loop to the hot loop while maintaining stable fluid circulation through the closed-loop architecture. The cold-side reservoir exhibited a rapid initial temperature decrease during the early stages of operation before gradually approaching a lower



2.10 Thermal Risks and Mitigation Strategies

Figure 5: Temperature vs Time (Hot and Cold)

A number of thermal issues associated with the STREAM heat exchanger subsystem were recognized during its development such as thermal saturation, thermoelectric overheating, thermal imbalances, and decreased cooling capabilities due to inadequate thermal dissipation. Several mitigation approaches were employed to tackle these potential threats including a radiator-based thermal dissipation loop incorporated in the hot fluid circulation system in order to constantly reject the excess thermal energy. In addition to this, thermal paste along with clamping pressure was applied to minimize thermal resistivity at the contact interfaces between the TECs and their associated cooling blocks, thus facilitating effective thermal conduction. Finally, separate closed loop fluid circulation systems were employed to ensure stable circulation and minimize thermal imbalances.

3. Insulation System

3.1 Insulation System Overview

The insulation system was designed to support thermal stability within the dual-temperature potable water dispensing system by minimizing heat transfer between the reservoirs and the surrounding environment. Because the system simultaneously provides both heated and cooled water, effective thermal insulation is required to maintain temperature retention and reduce thermal losses. Insulation was incorporated around the hot and cold reservoirs to reduce conductive heat transfer, improve thermoelectric efficiency, and support stable system operation. By limiting heat loss from the heated subsystem and reducing heat gain into the chilled subsystem, the insulation system contributes directly to maintaining desired operating temperatures. Because the system is intended for microgravity operation, thermal analysis was performed using conduction-based heat transfer assumptions. Under microgravity conditions, natural convection is significantly diminished due to the absence of buoyancy-driven fluid motion, making conductive heat transfer the governing mechanism for evaluating insulation effectiveness.

3.2 Thermal Retention Requirements

The insulation subsystem was designed to satisfy thermal retention requirements necessary for reliable dual-temperature potable water dispensing under microgravity operating conditions. Because the system simultaneously supports both heated and chilled water reservoirs, insulation performance directly influences temperature stability, thermal efficiency, and overall system reliability. The primary thermal retention requirement for the heated subsystem involves maintaining the hot water reservoir at a minimum operating temperature of 60°C while minimizing thermal energy losses to the surrounding environment.

Maintaining this temperature threshold is necessary to ensure reliable hot-water availability and reduce the thermal workload imposed on the thermoelectric heating components. Effective insulation therefore serves to preserve thermal energy within the reservoir and limit conductive heat dissipation through the system walls. The chilled subsystem was designed to maintain water temperatures at or below 15.6°C by limiting environmental heat gain and minimizing conductive heat transfer into the cold reservoir. Preserving this thermal condition is essential for maintaining chilled potable water availability while reducing the cooling demand placed on the thermoelectric modules. By reducing thermal leakage into the cold subsystem, insulation supports stable temperature retention and improved cooling efficiency. A secondary thermal requirement involves minimizing heat transfer between thermally distinct system regions. Since the hot and cold reservoirs operate simultaneously within a compact assembly, uncontrolled thermal crossover may degrade system performance and increase electrical power demand. The insulation subsystem therefore functions not only as a thermal barrier but also as a thermal isolation mechanism intended to preserve temperature separation between heated and cooled reservoirs. Energy efficiency represents an additional design requirement for the insulation of the subsystem. Excessive heat leakage increases the operating workload imposed on thermoelectric heating and cooling modules, resulting in greater electrical power consumption and reduced overall system efficiency. By minimizing conductive thermal losses through reservoir walls and surrounding materials, the insulation subsystem contributes to lower power demand and improved thermal stability throughout system operation. Thermal retention requirements were evaluated using conduction-based heat transfer analysis consistent with expected microgravity operating conditions. Under terrestrial conditions, natural convection contributes significantly to heat transfer through buoyancy-driven fluid motion. However, because buoyancy effects are substantially diminished in microgravity environments, natural convection was neglected in the insulation analysis, and conductive heat transfer was treated as the governing mechanism for thermal loss estimation. This approach provides a microgravity-relevant assessment of insulation effectiveness and supports thermal management strategies intended to maintain reservoir temperatures above 60°C for the heated subsystem and at or below 15.6°C for the chilled subsystem.

Table 1. Insulation Thermal Retention Design Requirements

Thermal Requirement	Design Criterion	Subsystem Purpose
Hot Water Thermal Retention	Maintain reservoir temperature \geq 60°C	Preserve heated potable water and reduce thermal losses
Cold Water Thermal Retention	Maintain reservoir temperature \leq 15.6°C	Preserve chilled potable water and limit environmental heat gain
Thermal Isolation	Minimize conductive thermal crossover	Maintain separation between hot and cold reservoirs
Energy Efficiency	Reduce thermoelectric thermal workload	Lower electrical power demand and improve system efficiency

3.3 Aerogel Insulation Material Selection

The insulation material selection process was guided by the thermal retention requirements established for the dual-temperature potable water dispensing system. Because the system must maintain hot water above 60°C and chilled water at or below 15.6°C, the insulation material required high thermal resistance while remaining lightweight and compact. Aerogel was selected as the primary insulation material due to its exceptionally low thermal conductivity, approximately 0.015 W/m·K, which provides superior thermal resistance compared to many conventional insulation materials. Its low conductivity reduces conductive heat transfer, supporting thermal retention within both heated and chilled reservoirs. Material selection also considered aerospace design constraints, including mass, volume, and thermal efficiency. Compared to traditional insulation materials such as polymer foams, aerogel provides improved thermal performance while requiring less thickness to achieve comparable insulation effectiveness. By minimizing conductive heat loss and limiting environmental heat gain, aerogel supports the thermal retention requirements identified in **Table 1** and contributes to improved thermoelectric efficiency and temperature stability throughout system operation.

Table 2. Insulation Material Comparison

Material	Thermal Conductivity (W/m·K)	Thermal Performance	Selection Outcome
Polyethylene	~0.42	Low	Not Selected
Polymer Foam	~0.03–0.04	Moderate	Considered
Aerogel	~0.015	High	Selected

3.4 Multi-Layer Insulation Configuration

The insulation system utilizes a multi-layer configuration designed to improve thermal retention and reduce conductive heat transfer within the dual-temperature potable water dispensing system. Insulation is applied around both the heated and chilled reservoirs to maintain temperature stability during operation. The configuration consists of the reservoir wall, an aerogel insulation layer, and an external protective boundary to preserve insulation integrity and mechanical stability. This layered design increases thermal resistance while maintaining compact geometry suitable for aerospace applications. By surrounding both reservoirs with aerogel insulation, the system minimizes heat loss from the heated subsystem and limits environmental heat gain into the chilled subsystem. The multi-layer configuration also provides thermal isolation between hot and cold regions, reducing thermal crossover and supporting improved thermoelectric efficiency.

3.5 Thermal Efficiency Testing and Results

Thermal efficiency testing was conducted to evaluate the effectiveness of the insulation system in maintaining temperature retention within the dual-temperature potable water dispensing system. Initial testing conditions began with both reservoirs at approximately 25°C prior to thermoelectric operation. Following approximately 1 hour and 45 minutes of operation, the heated reservoir reached approximately 60°C, while the chilled reservoir achieved temperatures near 14°C. These results demonstrate the

capability of the insulation system to satisfy the thermal retention requirements established in Table 1. To analytically evaluate insulation performance, conductive heat transfer through the insulation layer was estimated using Fourier's Law of Heat Conduction:

$$q = \frac{kA\Delta T}{L}$$

where q represents heat transfer rate (W), k is thermal conductivity (W/m·K), A is surface area (m²), ΔT is temperature difference (°C or K), and L is insulation thickness (m). Thermal analysis was performed using conduction-based modeling consistent with microgravity conditions, where natural convection is significantly reduced due to the absence of buoyancy-driven fluid motion. For the heated reservoir, thermal losses were evaluated using an aerogel thermal conductivity of approximately 0.015 W/m·K, an estimated insulated surface area of 0.198 m², an insulation thickness of 0.01 m, and a temperature difference of 35°C between the 60°C reservoir and the surrounding 25°C environment. The resulting conductive heat transfer rate was estimated as:

$$q_{hot} \approx 10.4 \text{ W}$$

indicating conductive heat loss from the heated subsystem to the surrounding environment. For the chilled reservoir, the direction of heat transfer is reversed, as thermal energy is transferred from the warmer environment into the cooled reservoir. Using a cold reservoir design temperature of 15.6°C and the same environmental temperature of 25°C, the temperature difference becomes 9.4°C, resulting in:

$$q_{cold} \approx 2.8 \text{ W}$$

representing conductive heat gain into the chilled subsystem. These results indicate that the insulation system effectively limited both conductive heat loss from the heated reservoir and conductive heat gain into the chilled reservoir. The comparatively low heat transfer rates demonstrate the effectiveness of the aerogel insulation in reducing thermoelectric workload and supporting stable temperature regulation. Experimental and analytical results together confirm that the insulation configuration successfully contributed to maintaining reservoir temperatures above 60°C for the heated subsystem and below 15.6°C for the chilled subsystem.

4. Interface and Dispense System

The interface and dispense system serve as the crew operated control and monitoring layer for STREAM. This subsystem allows the user to select the desired water source, volume, monitor system status, and initiate or cancel dispensing operations. The interface connects hot, cold, and ambient tanks to embedded control systems displaying temperature, tracking selected tank and volume values, and manages dispense state logic.

4.1 Control and Dispense System Overview

The control and dispense system coordinates crew input, sensor feedback, tank selection, target volume selection, and dispense state control. STREAM is designed around three selectable water sources; hot, cold, and ambient. Each source corresponds to their respective storage tank and dispensing path. During operation the user selects the desired tank and target volume through the interface. The embedded controller then manages the dispense sequence, monitors progress, and transitions the system to complete, canceled, or fault states depending on system condition. In the current prototype, the dispense is implemented in software to validate the interface and system logic prior to physical fluid actuation. This allows the system to verify tank selection, volume selection, progress tracking, cancel behavior, and fault response without the risk of uncontrolled water release. In the next development phase, this validated logic will be connected to flow sensors, solenoid valves, and pump drivers to achieve closed-loop volume-based dispensing.

4.2 Human-Machine Interface (HMI)

The Human-Machine Interface is designed to provide clear and low distraction control screen for crew use. The display presents the available water sources, selected tank, target volume, dispense progress, and system status in a simplified layout. Tank selection is separated from the volume and progress display so the user can quickly confirm the active water source before dispensing. The interface avoids unnecessary visual clutter and prioritizes readability, fast interpretation, and stable display behavior. The current HMI design uses a dark industrial style display with minimal telemetry and clear control prompts. A rotary encoder and mode button are the primary input method, allowing users to navigate tank and volume options without relying on touchscreen input. This provides a tactile control method that may be more reliable in operational environments where gloves, vibration, or limited attention could affect touch accuracy. The display software also uses partial redraw techniques to reduce flickering, selection jitter, and visual artifacts during operation.

4.3 ESP32 Control Architecture

The prototype control architecture uses an ESP32-based display controller to manage HMI, dispense interface, and system status display. Temperature data is received from sensing subsystem through UART communication, allowing the display controller to update tank conditions while maintaining independent user-interface operation. This separation between sensing and display/control improves modularity and allows each subsystem to be tested independently before full system integration. The ESP32 control software is structured around phased development. The verified temperature-monitoring functions are preserved as the baseline, while tank selection and volume selection, dispense progress, cancel behavior, and fault logic are added incrementally. This approach reduces the risk of disrupting previously verified functions while allowing new control features to be tested one at a time. The architecture is also expandable, allowing for future integration with solenoid valve drivers, pump control circuits, flow sensors, and water level sensors without requiring complete redesign.

4.4 Sensor Integration and Monitoring

The current prototype uses DS18B20 temperature sensors to monitor the hot, cold, and ambient water tanks. These sensors provide real-time temperature feedback to the display and allow the crew to observe the operation condition of each tank. This temperature monitoring forms the baseline sensing layer for STREAM and supports future control logic that can determine whether a selected tank is within target temperature range before dispensing. The monitoring logic is designed to reject invalid temperature readings before they affect displayed values or future control decisions. For example, disconnected or improperly initialized DS18B20 sensor may report invalid values such as -127.000 °C. Filtering these values improves system reliability and prevents false tank status information from being presented to the crew. The controller also monitors communication status between the sensing subsystem and display controller. If valid telemetry is not received within a defined time window, the system can indicate a lost

sensor link and prevent unsafe dispense behavior. Future sensor integration will include flow sensors for dispensed volume tracking and water level sensors for verified tank availability monitoring. These additions will allow the systems transition from software-validated dispense logic to closed-loop physical dispensing.

4.5 Temperature and Volume Regulation

Temperature regulation is primarily handled by the STREAM thermal subsystem, while the interface and control subsystem monitors tank conditions and communicates system readiness to the crew. Real-time temperature feedback allows the user to verify whether the selected water source is suitable for use. In future revisions, acceptable temperature bands can be added to the control logic so the system can prevent dispensing from a tank that has not reached the required operation range. Volume regulation is currently validated through a software-based dispense sequence. The crew selects a target volume, and the controller tracks progress toward that selected value during the dispense state. This allows the interface, progress display, and completion logic to be tested before physical flow hardware is activated. In the final hardware configuration, this same control logic will use flow sensor feedback to calculate dispensed volume in real time. Once the measured volume reaches the target volume the controller will command the selected valve closed and stop the active pump or dispense mechanism.

4.6 Solenoid Valve Dispense System

The planned physical dispense system will use solenoid valves to control flow from the hot, cold, and ambient tanks. Each tank will have an independent dispensing path controlled by its own valve. During operation only the valve corresponding to the selected tank will open, preventing unintended mixing between temperature zones and ensuring the water dispensed is from the correct source. The ESP32 controller will not directly power the solenoid valves or pumps. The controller will send low-voltage command signals to external driver circuits, such as MOSFET-based valve and pump drivers. The valves and pumps will receive power from a dedicated power source. This separation protects the low-voltage control electronics and improves system reliability during actuation. In future testing, the valve system will be integrated with the automated dispense logic. When the user starts dispensing, the controller will open the selected valve and activate the appropriate flow mechanism. When the target volume is reached, or if a cancellation or fault occurs, the controller will close all the valves and stop active flow components.

4.7 Automated Dispensing Logic

The automated dispensing logic is organized as a state-based control sequence. In the idle and selection states, the user can choose the desired tank and target volume. Once dispensing begins, the system enters the dispensing state and tracks progress toward the selected volume. When the target volume is reached, the controller transitions to the completed state and terminates the dispense state. Additional cancelled and fault states are included to improve operational safety. The cancelled state allows the user to stop dispensing before the selected volume is reached. The fault state is used when controller detects abnormal conditions such as lost sensor communication, invalid sensor data, unexpected flow behavior, or future low-water conditions. In the final physical implementation, any fault condition would command all valves closed and stop the active pump operation.

4.8 Crew Interaction and Operational Safety

Crew interaction is intentionally simplified to reduce workload and minimize user error. The user selects the desired water source, chooses a target volume, confirms dispensing, and monitors progress through the display. Clear visual feedback identifies the active tank, selected volume, dispense progress, and current system state. This approach allows the crew to understand system quickly without navigating a complex interface. Operational safety is supported through cancel behavior, fault handling, and sensor-

link monitoring. If communication with the sensing subsystem is lost or invalid data is detected, the controller can notify the crew and prevent unsafe dispensing. During future physical dispensing, these safety states will be tied directly to valve and pump shutdown commands. This is especially important for spacecraft and surface habitat environments, where uncontrolled water release could damage equipment, contaminate surfaces, or create additional crew workload. The interface is designed to support reliable crew operation rather than visual complexity. A stable, readable display with clear control prompts improves usability and reduces the likelihood of incorrect tank or volume selection.

4.9 Microgravity Operation Considerations

Reduced-gravity operation creates additional challenges for water dispensing because liquid does not settle predictably at the bottom of a tank, and gas bubbles may not naturally separate from the flow path. These conditions can affect pump priming, flow sensor accuracy, tank level measurement, and dispensing reliability. As a result, the final STREAM dispense architecture must maintain wetted lines, reduce air ingestion risk, and verify water availability before opening a dispense path. Future development should evaluate positive-feed storage methods, such as bladder-based tanks or other controlled fluid management approaches, to maintain consistent water delivery independent of gravity. Additionally, interlocks may include tank-level confirmation, flow confirmation, pressure feedback, or a combination of these methods before and during dispensing. These features would help ensure that the system only dispenses when water is available and the selected flow path is properly primed. For the current prototype, these microgravity concerns are addressed at the control-logic level through planned fault states, sensor validation, and dispense interlocks. Hardware validation will be required in later development phases to confirm reliable water handling under reducing gravity conditions.

5. Filtration System

5.1 Filtration System Overview

A filtration system was developed to provide safe potable water for astronauts to use by combining a physical filtration system and a UV-C disinfection system. This system creates a compact and energy-efficient system. The design uses a multi-stage approach to remove sediments, reduce chemical contaminants, improve the taste and odor of the fluid, and disinfect microorganisms before the water reaches the outlet. Water will flow through the inline filtration; this is where sediments are removed, the taste and odor are improved and help reduce chemical contaminants. The water will then flow to the UV-C sterilization unit, where microorganisms are exposed to ultraviolet light for a final disinfection. This system was developed with consideration for low power consumption, compact size, ease of maintenance, and being compatible with a closed loop spacecraft water system.

5.2 Potable Water Requirements for Spaceflight

The requirements for potable water in space follow strict safety requirements and quality standards to ensure crew health during long-duration missions. The water must be free of harmful microorganisms, and chemical contaminants while maintaining acceptable levels of pH, taste, and odor characteristics. During spaceflight, the system must also minimize water waste and operate in confined environments. Most importantly, it must prevent biological growth within tubing and storage tanks. The systems must be lightweight, energy efficient, and capable of functioning continuously with minimal crew maintenance.

5.3 Multi-Stage Filtration Architecture

The proposed system uses a multi-stage filtration architecture to improve overall water quality before disinfection. The first stage removes larger particles such as dirt, rust, and other sediments that may enter the system from the water source. There are additional filtration stages that use activated carbon to reduce chlorine, organic compounds, odors, and other dissolved contaminants. Using multiple filtration stages improve contaminants removal efficiency while protecting the rest of the components like the UV-C sterilization. The staged design allows individual filter cartridges to be replaced independently during maintenance.

5.4 UV-C Sterilization System

Once the water has passed the first filtration stage, the water then enters the UV-C sterilization unit for microbial disinfection. The UV-C is an ultraviolet light within the germicidal wavelength range to disinfect bacteria, viruses, and other microorganisms. This system solely focuses on disinfection, so it does not alter the water chemistry or pH levels. The sterilization is only activated through the flow of the water pressure, allowing the system to reduce unnecessary power usage during inactive periods. This stage acts as a final barrier against microbial contamination before potable water is dispensed or enters the water tanks.

5.5 Water Quality Protection and Contamination Prevention

Several considerations from different designs were incorporated into the main design to help reduce contamination risk and maintain water quality throughout the system. Stainless steel tubing was one that was selected because of its durability, corrosion resistance, and reduce the amount of bacteria buildup compared to other materials. Another was the closed-loop flow path because it helps minimize the external contamination exposure, while the inline filtration reduces the transport of particles into sensitive components. Proper fittings on the tubing and leak preventions are also important to maintain the system's performance and prevent contamination from entering the potable water pathway.

5.6 ECLSS Water Sustainability Integration

The filtration system was designed to be similar to the one already being used in the ISS which follows the Environmental Control Life Support System (ECLSS), where water is being recovered and reused for NASA's long-term missions. Integrating compact filtration and UV disinfection technologies support the water's sustainability by reducing the dependence on stored water and minimizing the waste. The system allows it to potentially integrate with future water recovery subsystems used for recycling and purification in closed-loop habitats. The design also supports reduced maintenance demands and efficient resource utilization in spaceflight environments.

5.7 Reliability and Maintenance Considerations

A key part of this system is its reliability and ease of maintenance. This is critical for spacecraft water systems because replacement opportunities are limited during missions. The system's inline filter configuration allows cartridges to be replaced individually without redesigning the entire system. Some maintenance considerations can include monitoring the filter's condition, checking the tubes for water leaks, and verifying that the UV-C lamp is functioning properly. The use of commercially available components also improves accessibility and reduces the overall cost of the components and system.

6. Schedule and Budgeting

6.1 Development and Implementation Strategy

The development and implementation of the new water dispenser system in the space station is important. For starters, a single system is used to cool and heat the water, which helps reduce space and components required to achieve the same results. Furthermore, the casing for the water dispenser is base off the current measurements use at the space station, which means that once the system is finish and sent to space for installation, the transition should be smooth like just changing one box for another. Also, the new dispenser will be sitting at a table like a platform inside of the casing, which will allow easy access to the interior of the system by just rolling out the platform.

6.2 NASA Mission Integration Timeline

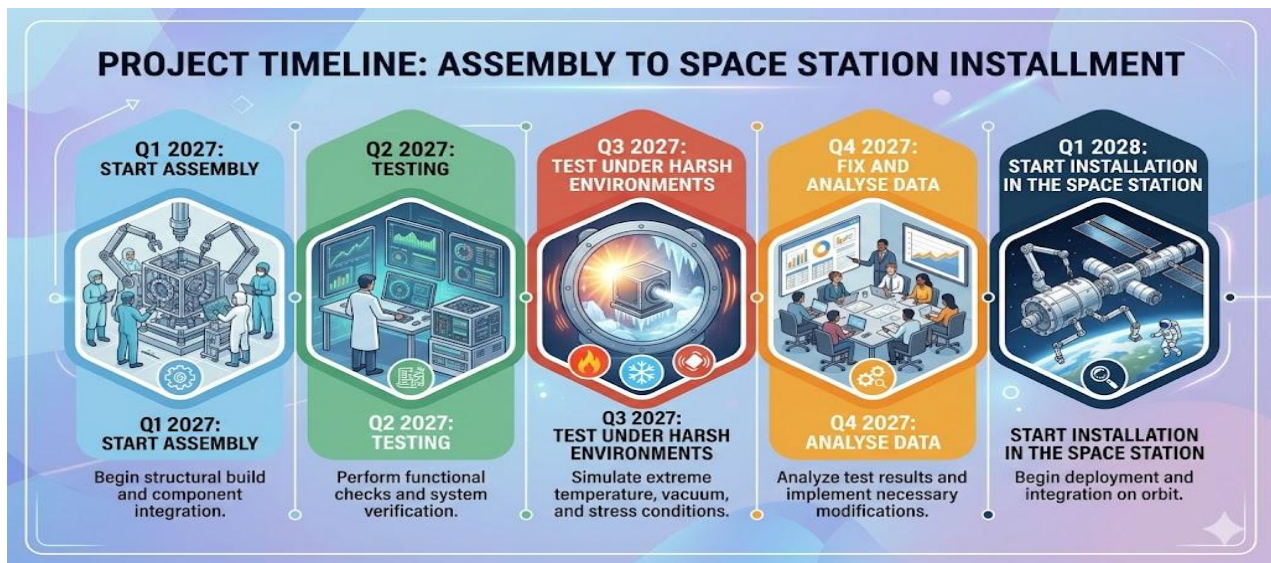


Figure 6: Project Timeline

6.3 Technology Maturation Roadmap

The following will explain the maturation roadmap: First 2 months: Test the Peltier - this will ensure that the Peltiers do heat up and cool down to the require temperatures; Month 3-4: Filtration System - ensure that the water reaches the require quality for drinking; Months 4-6: Dispensing System - ensure that the water is able to dispense in accurate amounts even when a pump or water supply is reduce; Months 6-7: Assemble the Water Dispenser - ensure that all the components work together; Months 7-9: Test the System - analyze any potential risks in the system; Months 9-12: Test the System in Harsh Conditions - ensure that the system will work even when certain components may fail; Months 13-15: Complete the installation in the space station.

Timeline	Phase / Focus Area	Primary Goal
Months 1–2	Peltier Testing	Thermal heating/cooling verification
Months 3–4	Filtration System	Certify drinking water quality
Months 4–6	Dispensing System	Ensure accurate dispensing during low supply/pressure

Months 6–7	System Assembly	Integrate all components together
Months 7–9	System Testing	Analyze and map potential system risks
Months 9–12	Stress Testing	Component failure and harsh condition validation
Months 13–15	Space Station Installation	Final deployment and setup

6.4 Development, Test, and Evaluation (DT&E) Strategy

It is calculated that STREAM should be ready and installed in a span of 15 months. By the end of the first quarter of 2028, STREAM should already have reached TRL 8, meaning that testing and analysis are done and the system is ready to fly. The goals to achieve this date line is as follows:

Goal	Description	Elapsed Time (Months)
Gather Necessary Equipment	Ensure that all components for heat transfer, dispensing, and filtration are purchased.	T+2.0
Test all components individually	Ensure that all components are working properly and sensors are being calibrated	T+4.0
Built and Test System	Test the system to see how efficient it is running and what might be at risk	T+6.0
Analyze the Data	Gather and analyze the data and see what some possible modifications are to increase efficiency	T+7.0
Test in Required Environment	Test the system in the environment where the system will be installed at	T+9.0
Validate the Data	Ensure that the data gather is valid, and it clears any worse case scenarios the system might face.	T+12.0
Installed the System	Once the system is at TRL 8, it will be installed at the space station	T+15.0

6.5 Projected NASA Budget Assessment

STREAM is a budget friendly system that will accomplish the requirements for a better and improve water dispenser system that both cools and heats water. After all, this system only uses one component that will do both the heating and the cooling, which will normally take two systems to achieve the same results. Furthermore, the system is lightweight and small, which will make it easy to transport and install. The table below shows an estimate of the cost for the components in the system, but realistically it will be thirty percent more, since some components can be improved which will increase the final cost, but maintained will lower at the end.

Parts Name	Quantity	Cost Per Part	Total Cost (\$)
Peltier Module HP-199-1.4-0.8	4	60	240
Radiator Fans	1	40	40
Cold Loop Pump	1	20	20
Hot Loop Pump	1	20	20
Microcontroller ESP32-S3	1	15	15
MOSFET Driver Board	1	60	60
LCD Display	1	4	4
Dispense Push Buttons	1	5	5
Temperature Sensors	1	1	1
Volume Sensors	1	1	1
Filter Status Sensor (TDS)	1	10	10
DC-DC buck converter	1	10	10
Diaphragm Pump	1	60	60
Solenoid Valve	1	40	40
Alert	1	3	3
Water Tanks	3	20	60
304 Stainless Steel Tubing	na	0.56 per in	120
Aerogel Insulations Sheets	5	25	125
6061 Aluminum	na	6 per lbm	120
Total Cost:			954

6.6 Path-to-Flight Feasibility

By late Q1 of 2028 or early Q2 of 2028, the project should already be at TRL 8 and ready for integration at the space station. After all, during 2027, the prototype will be finished and tested under harsh environmental conditions to see how it could fail and what risk might happen. For starters, in case of contamination in the water supply, the system will be tested to ensure that it is able to detect the water quality and filter enough times until the water is at a required quality level for drinking.

7. Conclusion

7.1 Summary of Key Findings

The STREAM (Space Temperature Regulated Efficient Aqua Module) system successfully demonstrated the feasibility of a compact thermoelectric potable water dispenser capable of simultaneously producing heated and cooled water through a dual-loop configuration. Experimental testing showed that the cold loop achieved temperatures near 14–15°C while the hot loop exceeded 40°C during extended operation. The integration of a radiator-based heat rejection system prevented thermal saturation and improved overall thermal stability. Testing also demonstrated that flow rate, insulation, and thermal contact quality significantly influenced system performance. Aerogel insulation reduced thermal losses, while improved contact between the Peltier modules and cooling blocks enhanced heat transfer efficiency. Overall, the prototype validated that thermoelectric technology can effectively regulate potable water temperatures within a compact and modular system architecture.

7.2 STREAM Value to NASA Human Exploration

The STREAM system supports NASA’s long-duration human exploration goals by providing a compact, reliable, and energy-efficient method for temperature-controlled potable water delivery. Unlike traditional refrigeration systems, thermoelectric cooling eliminates the need for compressors and refrigerants, reducing mechanical complexity and maintenance requirements.

The system's dual-loop design allows simultaneous heating and cooling within a single integrated platform, improving efficiency while minimizing mass and volume. These characteristics align with NASA's objectives for future lunar, Martian, and deep-space habitats where reliability, modularity, and efficient resource utilization are critical.

7.3 Future Development Recommendations

Future development should focus on improving thermal efficiency through higher-performance thermoelectric modules, optimized heat exchanger geometries, and enhanced insulation materials. Additional radiator optimization and airflow improvements could further increase heat rejection performance and temperature separation. Future iterations should also integrate automated temperature regulation using sensors, microcontrollers, and adaptive power management systems. Additional long-duration testing, microgravity validation, and lightweight material integration would further improve the system's readiness for aerospace applications.

7.4 Final Assessment

The STREAM project successfully demonstrated the technical feasibility of a thermoelectric-based potable water dispenser for human space exploration applications. Through iterative prototyping and experimental validation, the system achieved simultaneous heating and cooling within a compact integrated platform while maintaining stable operation. Although additional optimization and environmental testing are still required, the current prototype establishes a strong foundation for future development. The project demonstrates the potential for thermoelectric potable water systems to contribute to future NASA Environmental Control and Life Support Systems by improving reliability, reducing mechanical complexity, and supporting sustainable long-duration missions.

References

- 1) ASHRAE. (2021). *ASHRAE handbook—Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.
<https://www.ashrae.org/technical-resources/ashrae-handbook>
- 2) Bergman, T. L., Lavine, A. S., Incropera, F. P., & DeWitt, D. P. (2011). *Introduction to heat transfer* (6th ed.). Wiley.
<https://www.wiley.com/en-us/Introduction+to+Heat+Transfer,+6th+Edition-p-9780470501979>
- 3) Çengel, Y. A., & Cimbala, J. M. (2018). *Fluid mechanics: Fundamentals and applications* (4th ed.). McGraw-Hill Education.
<https://www.mheducation.com/highered/product/fluid-mechanics-fundamentals-applications-cengel/M9781259696539.html>
- 4) Çengel, Y. A., & Ghajar, A. J. (2020). *Heat and mass transfer: Fundamentals and applications* (6th ed.). McGraw-Hill Education.
<https://www.mheducation.com/highered/product/heat-mass-transfer-fundamentals-applications-cengel/M9781259822679.html>
- 5) Ferrotec Corporation. (2023). *Thermoelectric technical reference guide*. Ferrotec Holdings Corporation.
<https://thermal.ferrotec.com/technology/thermoelectric-reference-guide/>
- 6) Gilmore, D. G. (Ed.). (2002). *Spacecraft thermal control handbook: Fundamental technologies* (2nd ed.). The Aerospace Press.
<https://arc.aiaa.org/doi/book/10.2514/4.867224>
- 7) Hebei I.T. (Shanghai) Co., Ltd. (n.d.). *TEC1-12709 thermoelectric module datasheet*.
<https://www.alldatasheet.com/datasheet-pdf/pdf/313841/HB/TEC1-12709.html>
- 8) Holman, J. P. (2010). *Heat transfer* (10th ed.). McGraw-Hill Education.
<https://www.mheducation.com/highered/product/heat-transfer-holman/M9780073529368.html>
- 9) Howell, J. R., Siegel, R., & Mengüç, M. P. (2020). *Thermal radiation heat transfer* (7th ed.). CRC Press.
- 10) Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2017). *Fundamentals of heat and mass transfer* (8th ed.). Wiley.
<https://www.wiley.com/en-us/Fundamentals+of+Heat+and+Mass+Transfer,+8th+Edition-p-9781119320425>
- 11) Ioffe, A. F. (1957). *Semiconductor thermoelements and thermoelectric cooling*. Infosearch.
<https://archive.org/details/semiconductorthe00ioff>
- 12) Kays, W. M., London, A. L., & Shah, R. K. (2004). *Compact heat exchangers* (3rd ed.). McGraw-Hill Education.
<https://www.mheducation.com/highered/product/compact-heat-exchangers-kays/M9780070334248.html>
- 13) Kreith, F., Manglik, R. M., & Bohn, M. S. (2011). *Principles of heat transfer* (7th ed.). Cengage Learning.
<https://www.cengage.com/c/principles-of-heat-transfer-7e-kreith/>

-
- 14) MathWorks. (2024). *MATLAB plotting and data visualization documentation*. MathWorks Inc.
<https://www.mathworks.com/help/matlab/graphics.html>
 - 15) NASA. (2015). *NASA systems engineering handbook* (NASA/SP-2016-6105 Rev 2). NASA.
<https://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook/>
 - 16) NASA. (2023). *Environmental Control and Life Support Systems (ECLSS)*. National Aeronautics and Space Administration.
<https://www.nasa.gov/humans-in-space/living-in-space/environmental-control-and-life-support-systems/>
 - 17) NASA. (2023). *Human landing system (HLS) overview*. NASA.
<https://www.nasa.gov/humans-in-space/human-landing-system/>
 - 18) NASA. (2023). *Technology Readiness Level (TRL) definitions*. NASA Office of the Chief Technologist.
<https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/>
 - 19) NASA. (2024). *Human Lander Challenge (HuLC)*. National Aeronautics and Space Administration.
<https://www.nasa.gov/learning-resources/stem-engagement-at-nasa/human-lander-challenge/>
 - 20) NASA Human Lander Challenge (HuLC). (2026). *Final deliverables scoring matrix*. National Aeronautics and Space Administration.
 - 21) NASA. (n.d.). *APPEL Knowledge Services*.
<https://www.nasa.gov/learning-resources/for-professionals/appel/>
 - 22) NASA. (n.d.). *JSC thermal management subsystems*.
<https://www.nasa.gov/reference/jsc-thermal-management-subsystems/>
 - 23) NASA. (n.d.). *Moon to Mars architecture components*.
<https://www.nasa.gov/moontomarsarchitecture-components/>
 - 24) Performance PCs. (n.d.). *Loop design blog*.
<https://www.performance-pcs.com/a/blog/blog/post/loop-design-blog?srsltid=AfmBOoq1hCOVhuBCjH7KFJMweKEAi0KuTdgZyg9HE40Amz8MD3lrqZ>
 - 25) Rowe, D. M. (Ed.). (2006). *Thermoelectrics handbook: Macro to nano*. CRC Press.
 - 26) Rowe, D. M. (Ed.). (2018). *Thermoelectrics and its energy harvesting, volume 1: Materials, preparation, and characterization in thermoelectrics*. CRC Press.
<https://www.routledge.com/Thermoelectrics-and-Its-Energy-Harvesting-Volume-1-Materials-Preparation-and-Characterization-in-Thermoelectrics/Rowe/p/book/9781498768134>
 - 27) TE Technology, Inc. (2024). *Introduction to thermoelectric cooling*. TE Technology, Inc.
<https://tetch.com/thermoelectric-cooling/>
 - 28) TEC1-1215 thermoelectric module datasheet. (2024). *Thermoelectric cooling module specifications*.
 - 29) Thermal Fluids Project Data. (2026). *STREAM experimental flow rate and heat transfer testing results*. University of Texas Rio Grande Valley.

- 30) White, F. M. (2016). *Fluid mechanics* (8th ed.). McGraw-Hill Education.
<https://www.mheducation.com/highered/product/fluid-mechanics-white/M9780073398278.html>