

Enhanced Potable Water Dispenser

Purdue University

Advised by Dr. Thomas Cunningham

6/24/26



School of Aeronautics
and Astronautics

The Team



Logan Hussein
Project Manager
Undergraduate
Aerospace Engineering



Sloan McDonald
Deputy Project Manager
Undergraduate
Aerospace Engineering



Riley Ficker
User Interface Lead
Undergraduate
Aerospace Engineering



Andrew Jensen
Lead Mechanical Engineer
Undergraduate
Mechanical Engineering



Christopher Butler
Lead Electrical Engineer
Undergraduate
Electrical Engineering



Harii Soni
Fluid Transporting Lead
Undergraduate
Aerospace Engineer

Agenda

Background and Context

- Challenges
- Driving Requirements

Solution

- System Overview
- Subsystem Details

Risk

- Identification
- Mitigation Techniques

Verification and Validation

- Revisit Requirements
- Potential Prototype

Project Management

- Cost
- Schedule
- Areas for Future Improvement

Background and Context



School of Aeronautics
and Astronautics

Background

- Potable Water Dispenser (PWD)'s primary objective:
 - Deliver drinkable water to astronauts for daily food and beverage needs
- 2008 USOS PWD:
 - Provided heated (65 – 93°C) and ambient water
 - Integrated capabilities with Water Recovery System (WRS)
 - Orbit Replacement Units (ORUs) for bacteria mitigation and removal of iodine
- Exploration PWD (xPWD – 2023)
 - UV-C light at point of dispensing replaces bacteria mitigation ORU
 - Enhanced system monitoring
 - Mitigate dead spots
- **No chilled water capabilities**



2008 USOS PWD
NASA

Major Objectives

**Add Cooling
Capabilities to PWD**

**Safely and
Efficiently Deliver
Water**

**Emphasize
Ergonomics and
User Compatibility**

**Minimize Mass,
Volume, Energy
Consumption**

**Emphasize
Throughput**

**Minimize Cleaning
and Waste**

System Driving Requirements

Req. ID	Requirement	Source / Reference
TMP1	The system shall be able to deliver between 25 and 250 mL of water between 4 °C and 93 °C within 10 minutes.	2008 USOS PWD Requirements; NASA Spaceflight Human-System Standard
SAF1	The system shall dispense water meeting NASA's potable water quality standards.	NASA Spaceflight Human-System Standard; Microbial Growth Control in the ISS PWD
SAF3	The system shall not cause any harm to the user or HLS during usage or maintenance.	2008 USOS PWD
INT1	The system shall be integrable with the HLS.	EXPRESS Rack Overview

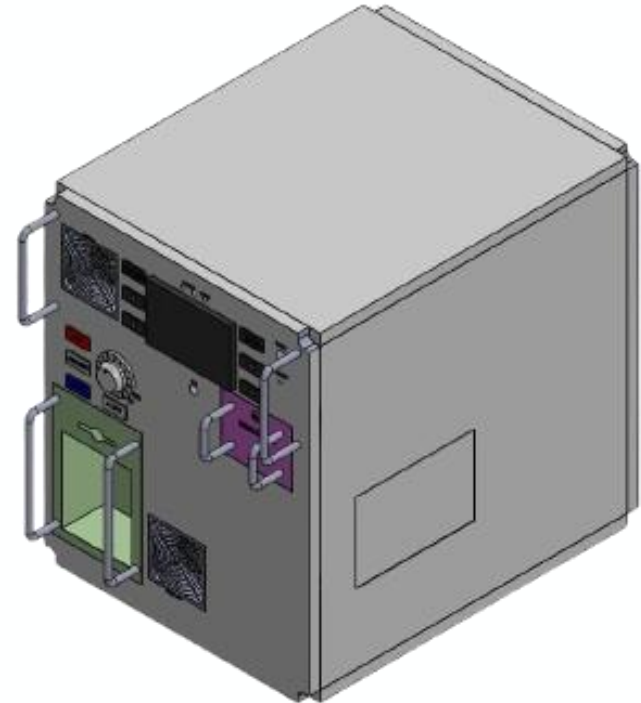
Solution



School of Aeronautics
and Astronautics

Solution Overview

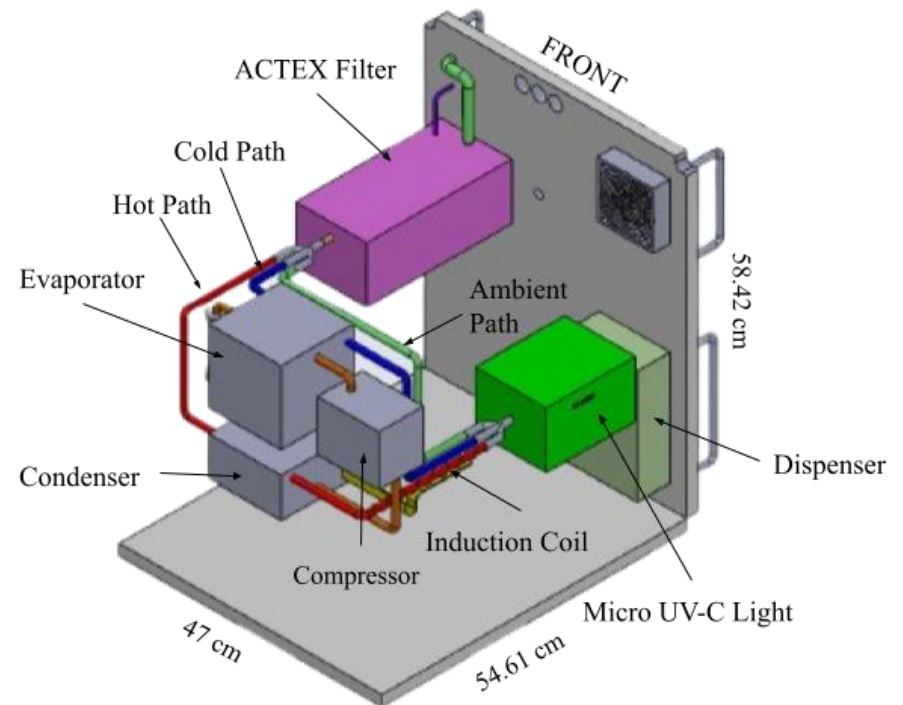
Key Features	
Thermal Control	<ul style="list-style-type: none">• Mini-Refrigeration Cycle• Hybrid heating system
Fluid Transporting	<ul style="list-style-type: none">• 316L Stainless Steel
Water Quality and Filtration	<ul style="list-style-type: none">• ACTEX ORU• Micro UV-C
User Interface	<ul style="list-style-type: none">• Enhanced UI



Solution Overview

Continued

Key Specifications	
Mass	30.623 kg
Cost (Flight Unit)	\$2.6 Million (USD)
Peak Power Draw	~488 W
Volume	47 cm x 58.42 cm x 54.61 cm



Thermal Control

Overview

TMP1

The system shall be able to deliver between 25 and 250 mL of water between 4°C and 93°C within 10 minutes.

Challenges:

- Cooling systems are generally inefficient.
- Nucleation can cause bubbles to remain stationary in the heater.

Goals:

- Satisfy TMP1
- Prevent nucleation while being time-conscious
- Limit power required
- Safety



Water Bubble in Space
NASA

Thermal Control

Trade Study

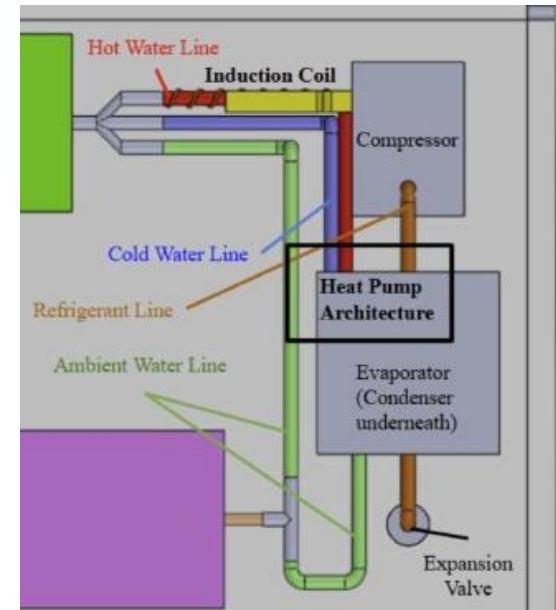
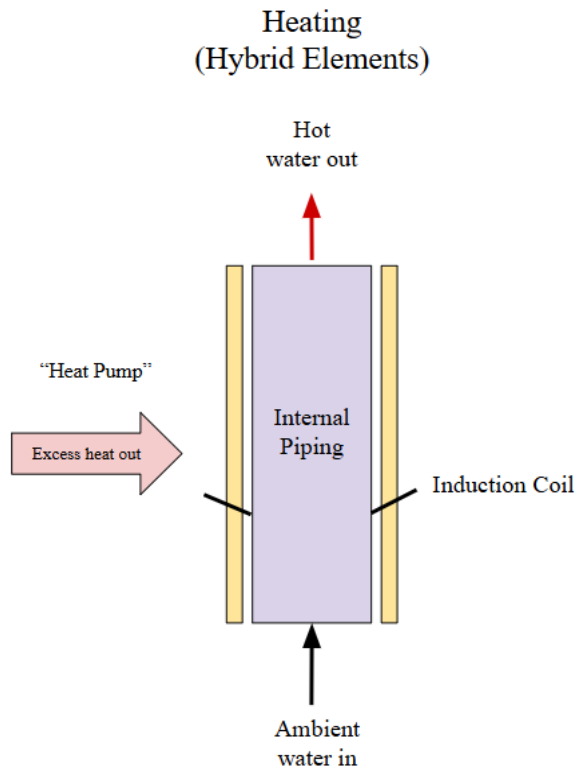
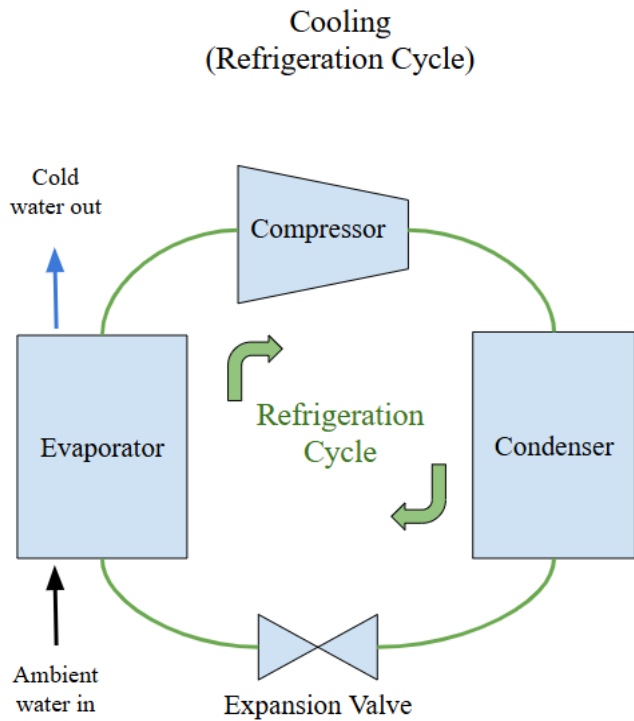
After conducting trade studies, it was found that best designs for thermal control were...

- Cooling subsystem: miniature refrigeration cycle
- Heating subsystem: hybrid heating with primarily induction
- Updated heat pump system to redirect waste heat from mini refrigeration cycle into heating subsystem

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

Thermal Control

Selected System



Thermal Control

Analysis Details

- Used standard thermodynamic equations and assumptions throughout analysis
 - Assumed steady-state boundary conditions, negligible fouling factors, and constant fluid properties
 - Modeled using 1D steady-state resistance networks and lumped capacitance transient equations

- The most relevant analyses include...
 - Time to reach target temperature
 - Energy usage / consumption
 - Waste heat into cabin environment

Equations:

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

Assumptions & Other Parameters:

$$\text{Area} = 0.05 \text{ m}^2$$

$$L = 0.0005 \text{ m}$$

Plate Material (Stainless Steel via ThyssenKrupp specifications):

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

Refrigerant Film Coefficient:

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

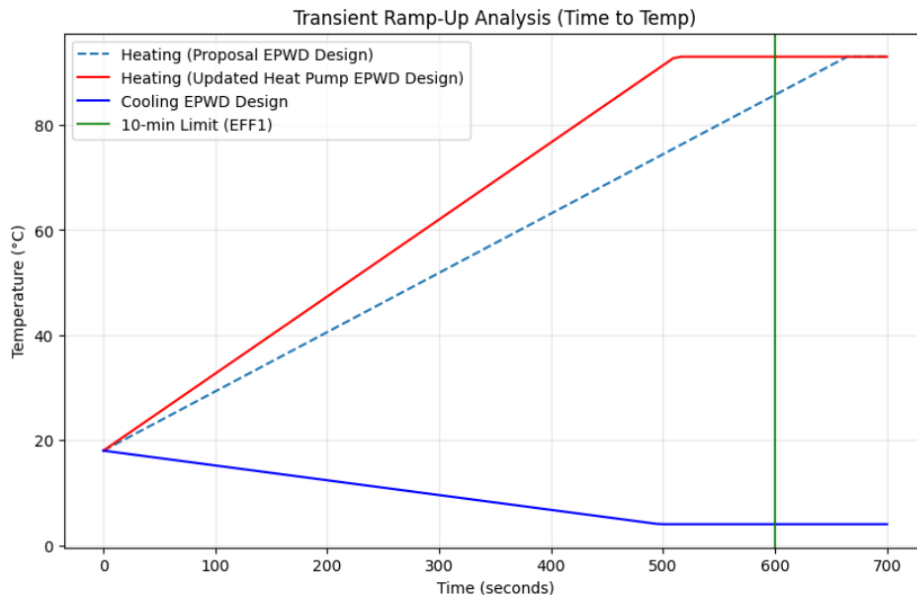
Water Film Coefficient:

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

Thermal Control

Analysis Results

Process	Proposal EPWD Energy Consumption [Wh]	Updated EPWD 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



- The time to appropriate temperatures for the Thermal Control system meets the 10-minute requirement.
- Energy consumption was reduced by 35% after adding the heat pump and now meets the energy consumption requirement.
- The waste heat (heat entering the cabin environment) was reduced by 81%, ensuring thermally neutral operation in sensitive cabin environments.

Fluid Transportation

Overview

TMP1

The system shall be able to deliver between 25 and 250 mL of water between 4°C and 93°C within 10 minutes.

Challenges:

- Bubble formation and cavitation
- Microbial growth in dead spots and during periods of dormancy

Goals:

- Satisfy TMP1
- Limit bubble formation and cavitation
- Limit microbial growth
- Minimize dead spots / pipe volume

Fluid Transportation

Trade Study

After conducting a trade study, it was found that the best tubing material is 316L stainless steel due to:

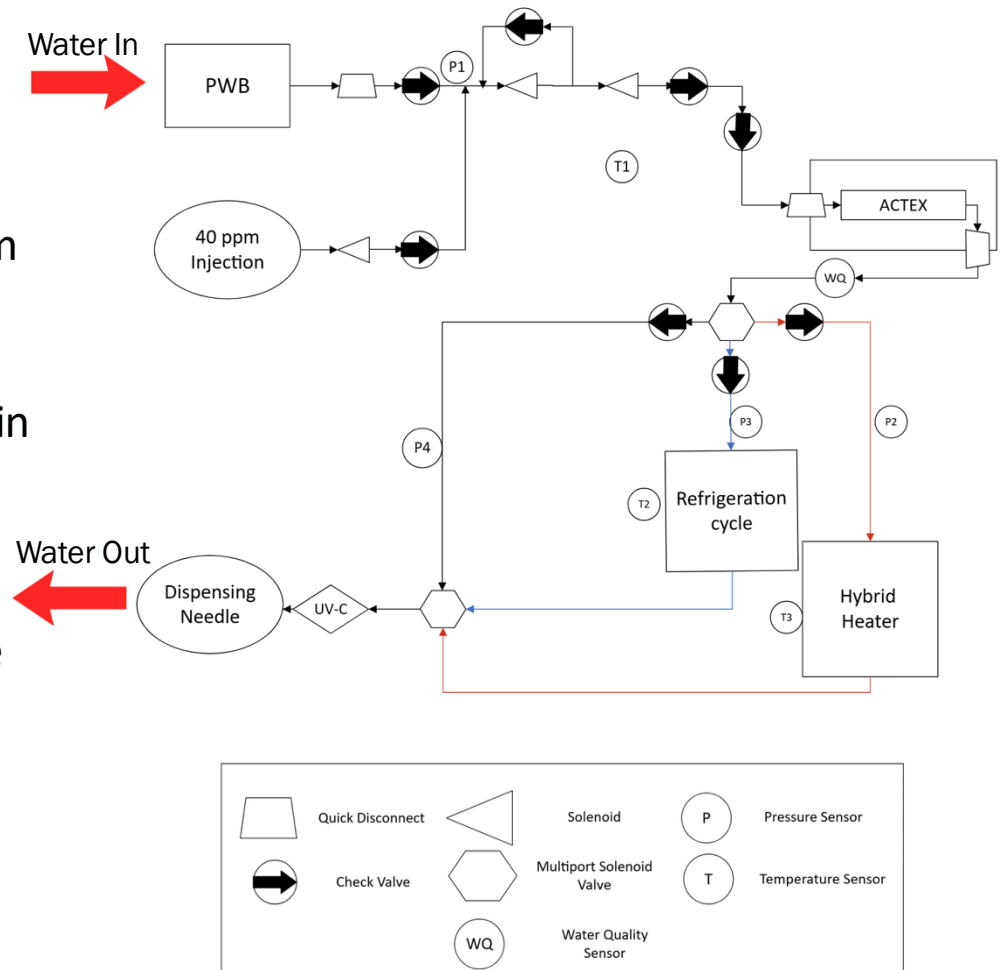
- High flight heritage and therefore high TRL
- Compatibility with Iodine – long-term durability with frequent Iodine flushes
- Low internal surface roughness ($Ra < 0.8 \mu m$) – smooth fluid flow and minimized microbial growth

Factor	Weight	Design 1: PTFE (Teflon)	Design 2: Stainless Steel (316L)	Design 3: Copper
Durability	0.45	1	5	3
Smoothness	0.09	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

Fluid Transportation

Selected System

- Pump-Free Operation: Water flow driven by a 230–280 kPa positive pressure gradient from the upstream Water Recovery System
- High Flow Performance: Predicted ambient dispense rate of 756 mL/min after accounting for pressure losses and capillary effects
- Improved Capability: Delivers approximately 9.2% higher flow rate than the current potable water dispenser



Fluid Transportation

Analysis

	Thermal Mixing Analysis	Throughput Analysis
Description	How much the delivered water temperature is affected by the stagnant water sitting between heater/cooler and exit	Predicts the volumetric flow rate for hot, ambient, and cold water
Assumptions	<ul style="list-style-type: none"> • Pipe geometry taken from design • Stagnant water at 22° C • Instantaneous mixing • No heat loss during dispensing 	<ul style="list-style-type: none"> • Steady-state, fully developed, laminar flow • No transient startup effects • Circular pipe geometry • Constant discharge coefficient
Main Equations	$T_{final} = \frac{m_{line}T_{line} + m_{request}T_{source}}{m_{line} + m_{request}}$	$\Delta P_{pipe} = \frac{8\mu LQ}{\pi r^4},$ $\Delta P_{orifice} = \frac{\rho Q^2}{2C_d^2 A^2}$

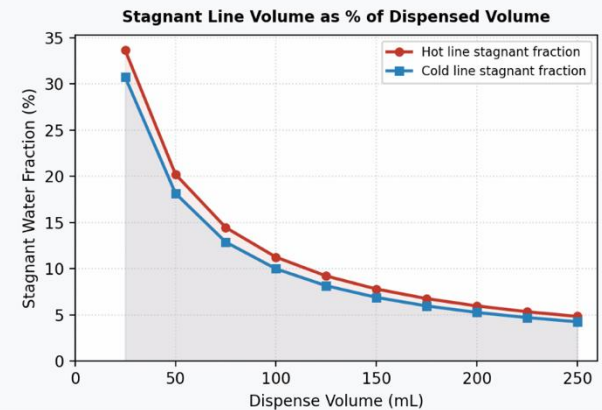
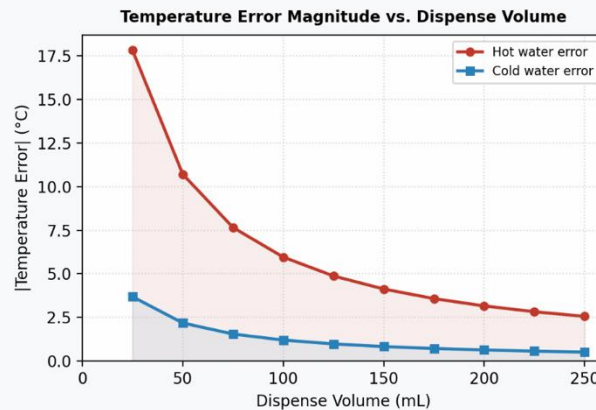
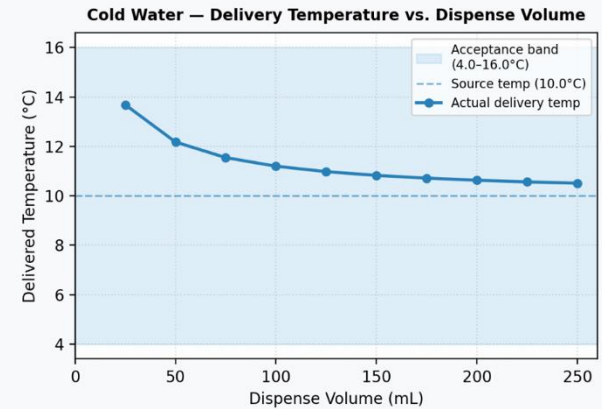
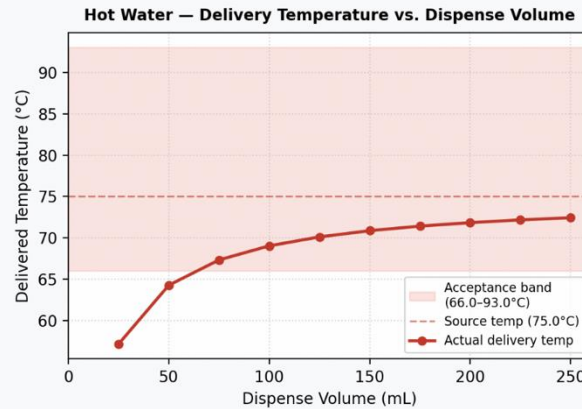
Fluid Transportation

Analysis

Throughput Analysis

Water Temperature	Throughput (mL / min)
Hot	765.3
Cold	756.0
Ambient	754.7

EPWD Line Volume & Thermal Mixing Analysis Purdue University — HuLC Phase 2



Water Quality and Filtration

SAF1

The system shall dispense water meeting NASA's potable water quality standards.

- NASA Potable Water Quality Standards:
 - Less than 50 CFU/mL of bacteria
 - Non-detectable amounts of Coliform
 - Less than 0.20 ppm I_2
- UV-C for microbial contamination
 - Aquisense PearlAqua Micro UV-C (NSF Class B rating)
 - 9,000-hour effective lamp life
- ACTEX Filter to reduce I_2
 - Water enters EPWD with 1-4 ppm I_2
 - 4,320 lbm; ~ 7 months of use (4 astronauts)
- 40 ppm I_2 flush
 - Handle microbial growth during dormancy
 - Dummy filter to ensure full decontamination



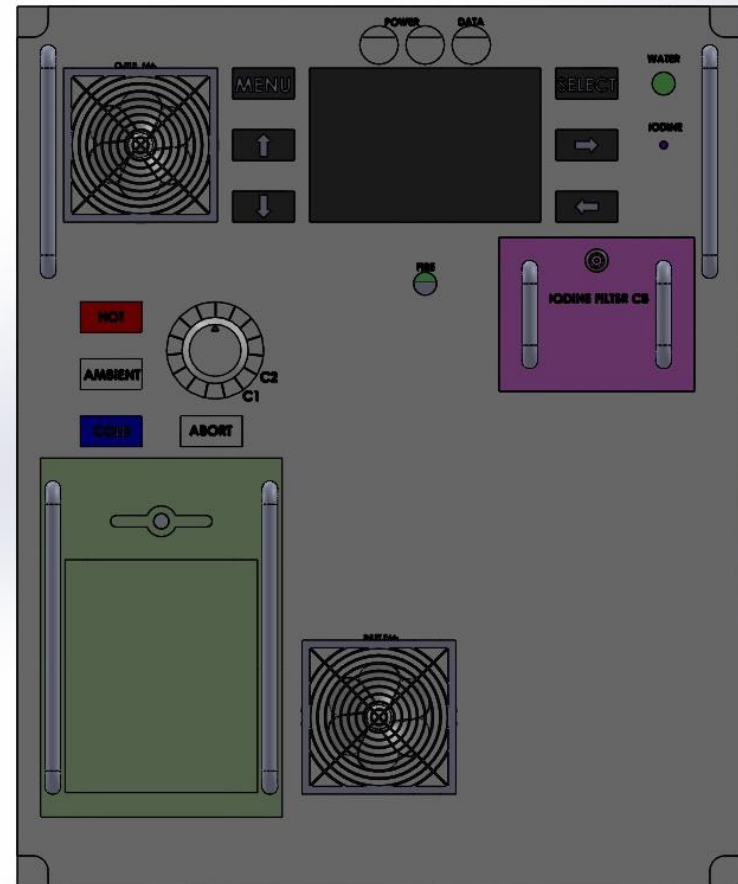
Micro UV-C
Aquisense Technologies

User Interface

STS1

The system shall provide the crew with real-time status updates.

- LCD Screen
 - Detailed status pages for all systems
 - Maintenance instructions
 - Annunciations
 - Current operational status
- Ten buttons
 - LCD Screen Control (four arrows, select, menu)
 - Dispense Control (hot, cold, ambient, abort)
- Iodine filter access
- Amount dial
 - 25-250mL in 25mL increments
- Rehydration Station
 - Current system to avoid redesigning the food and water bag system

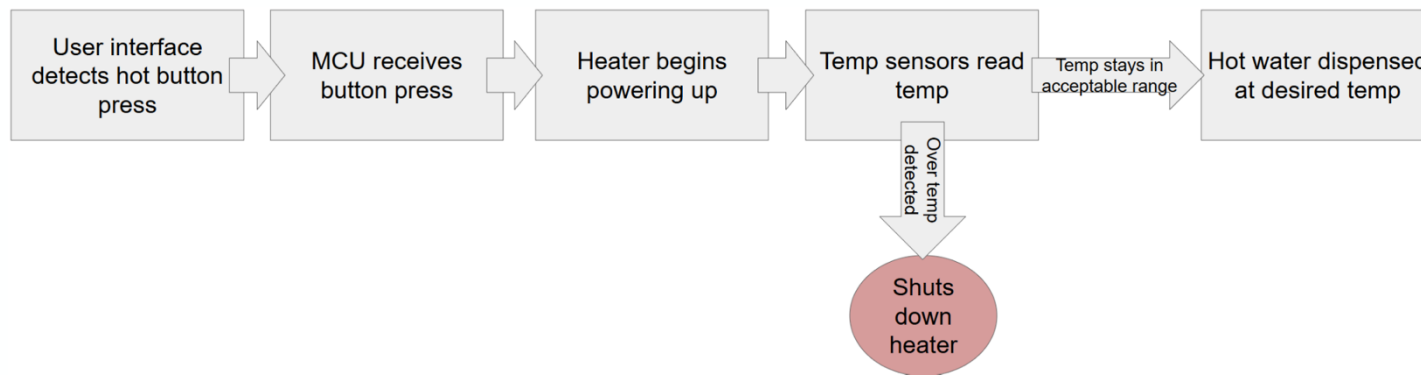


Command and Data Handling

STS1

The system shall provide the crew with real-time status updates.

- Integrates sensing, telemetry, fault management, and user interaction into a coordinated framework
- Main sensors: temperature, pressure, water quality
- Rad-hard components
- Health managed by watchdog supervision, continuous fault detection, isolation routines, and event logging
- Initiates preheating 600 seconds before “scheduled” mealtime
- Example state function:



Power Handling

INT1 The system shall be integrable with the HLS.

- Power system interfaces with EXPRESS rack 28 Vdc
- Separate high and low power loads for efficiency and protection
 - High-Power (Thermal Control System): inrush current limiting, EMI filtering, and electronic fuses
 - Low-Power: Dedicated DC/DC converters
- Rad-hard components
- Direct-to-load power architecture maximizes efficiency

Risk Analysis

Risk Analysis

Identification During Initial Design

Risk Number	Risk
2	Bubble formation during fluid transportation
4	Backflow
5	Thermal insulation failure
6	Fire
7	Over-freezing
8	Over-heating

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
		LIKELIHOOD				

Risk Analysis

Mitigation

Risk Number	Risk	Mitigation Technique
2	Bubble formation during fluid transportation	Capillary fluidic structures.
4	Backflow	Dual-check valve at inlet of EPWD.
5	Fire	Proper insulation, ensuring strong electrical connections, multiple temperature sensors feeding into CDH system, addition of a fire port.
6	Thermal insulation failure	Researching different insulation materials around pipes, using correct quantities of insulation
7	Over-freezing	Multiple temperature sensors feeding into CDH system.
8	Over-heating	Multiple temperature sensors feeding into CDH system.

Risk Analysis

Post Mitigation

Risk Number	Risk
2	Bubble formation during fluid transportation
4	Backflow
5	Thermal insulation failure
6	Fire
7	Over-freezing
8	Over-heating

CONSEQUENCE	5	4,6,8				
	4	5,7				
	3			2		
	2					
	1					
			1	2	3	4
		LIKELIHOOD				

Verification and Validation



School of Aeronautics
and Astronautics

Verification and Validation

Requirement Validation

Req. ID	Requirement	Verification
TMP1	The system shall be able to deliver between 25 and 250 mL of water between 4 °C and 93 °C within 10 minutes.	Thermal and fluid analyses
SAF1	The system shall dispense water meeting NASA's potable water quality standards.	Inclusion of heritage technologies
SAF3	The system shall not cause any harm to the user or HLS during usage or maintenance.	Risk mitigation
INT1	The system shall be integrable with the HLS.	Appropriate use of input assumptions; Minimal barriers to NASA adoption.

Verification and Validation

Potential Prototype

Phase 1	Phase 2	Phase 3	Phase 4
<p>Piping and Flow Characteristics</p> <p>Description:</p> <ul style="list-style-type: none">• Complete piping layout• Full sensor suite included <p>Goal:</p> <ul style="list-style-type: none">• Better characterize fluid flow properties (dP analysis) <p>Results:</p> <ul style="list-style-type: none">• More accurate volume errors• More accurate inputs for thermal analysis	<p>Thermal System in Isolation</p> <p>Description:</p> <ul style="list-style-type: none">• Isolated thermal system <p>Goal:</p> <ul style="list-style-type: none">• Achieve more accurate information on thermal transfer <p>Results:</p> <ul style="list-style-type: none">• More accurate temperature errors• Refined power and control inputs• Analyze preheating time	<p>Controls, UX/UI, and Software State Logic</p> <p>Description:</p> <ul style="list-style-type: none">• Status screen, navigation interfaces, sensors <p>Goal:</p> <ul style="list-style-type: none">• Mature microcontroller, state, and UI software before full prototype integration <p>Results:</p> <ul style="list-style-type: none">• Verification of state machine behavior, safing actions, UI navigation, and a finalized alert set	<p>Full Prototype Integration</p> <p>Description:</p> <ul style="list-style-type: none">• Recreate EPWD's functional path with all major components <p>Goal:</p> <ul style="list-style-type: none">• TRL 5 <p>Results:</p> <ul style="list-style-type: none">• Better understanding of EPWD's behaviors / challenges

Project Management



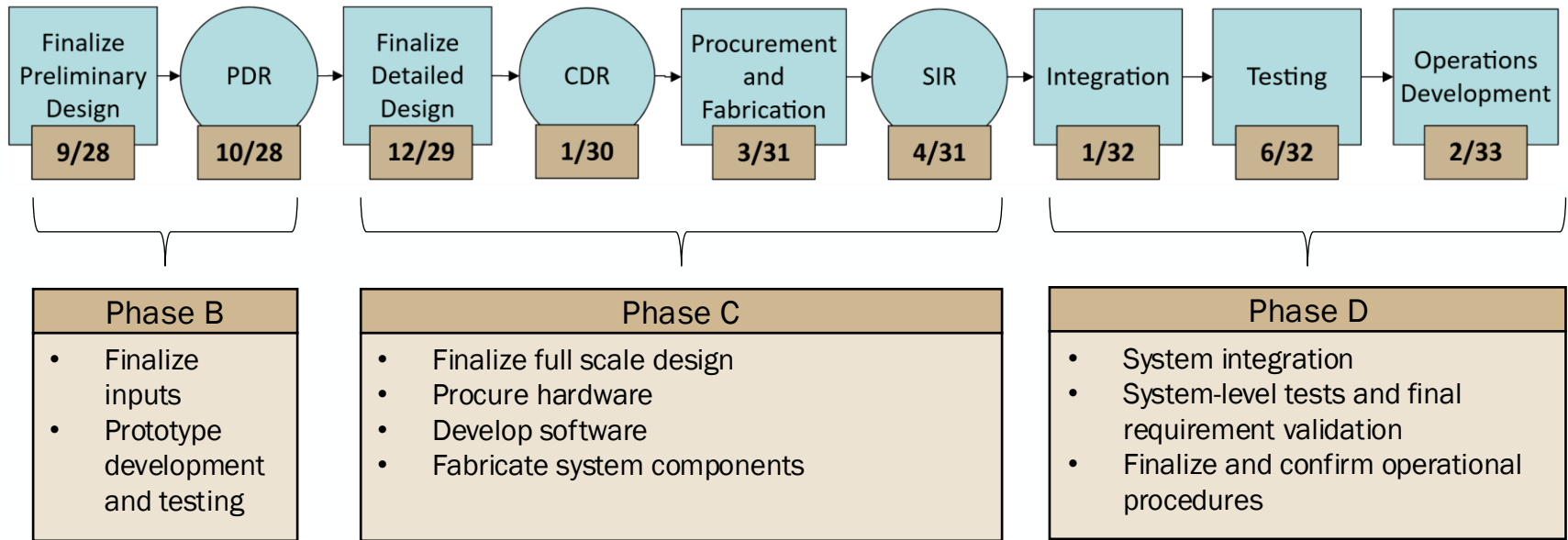
School of Aeronautics
and Astronautics

Cost

- NASA Project Cost Estimating Capability Tool
- First Pound Cost analysis

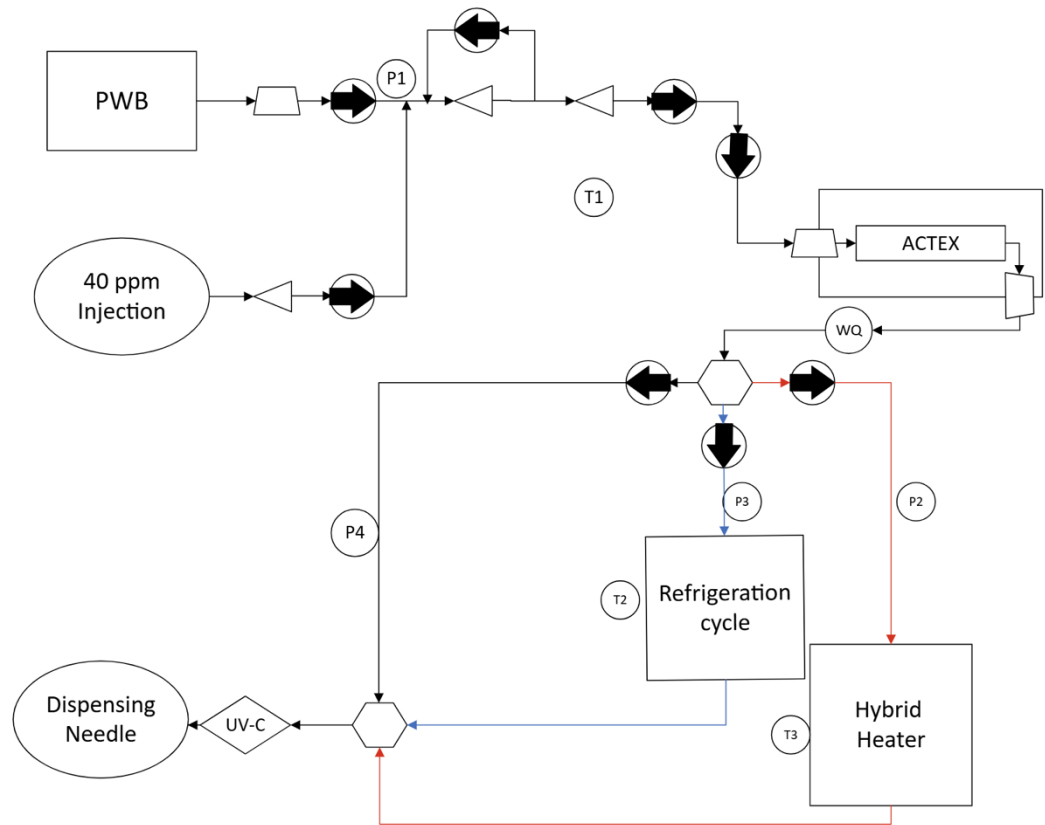
Budget Category	Estimated Costs (Millions of \$)
Design and Development	9.10
System Test Hardware	3.40
Recurring	2.60
Personnel	4.47
Manufacturing	7.55
Margin (30%)	8.14
Total Costs	35.26

Schedule



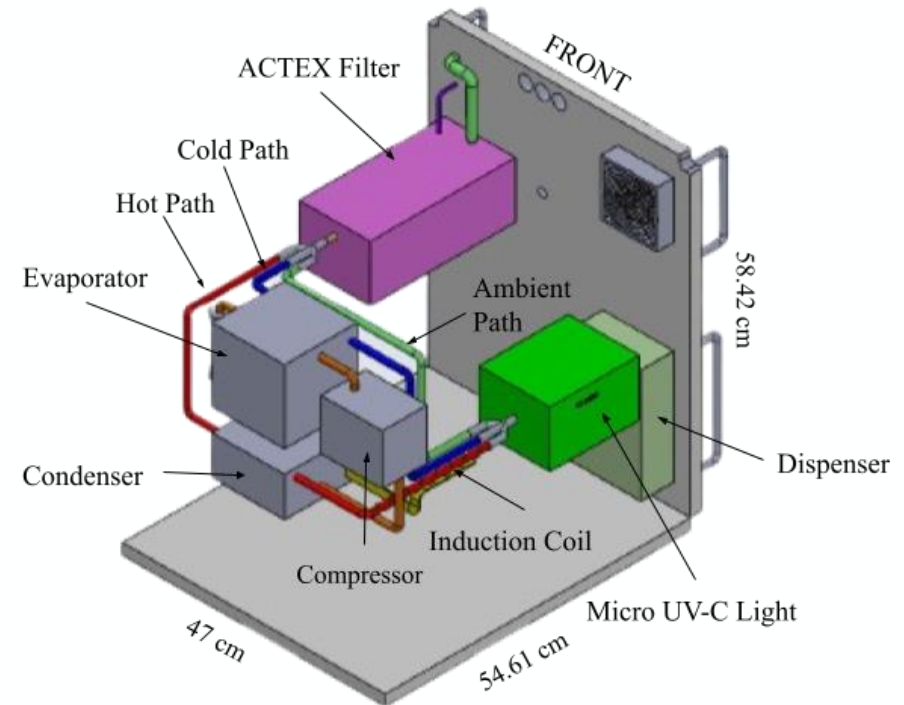
Areas for Future Improvement

- Limitation: Pipe volume between thermal elements and dispenser causes temperature errors.
- Potential Solutions:
 - Purge water
 - Optimize for higher cost to be put on distance away from dispenser
 - Genetic algorithm



Conclusion

- Designed the Enhanced Potable Water Dispenser with a cooling capability and an enhanced user interface
- Conducted analyses on key aspects of the design:
 - Thermal performance
 - Water flow
- Risk Mitigation
- Imagined how a potential prototype could advance understanding of the EPWD



Thank You

Backup Slides

System Engineering Backup



School of Aeronautics
and Astronautics

Deliver Water Safely

SAF1	The system shall meet NASA potable water quality standards.
SAF3	The system shall be double-fault tolerant for any hazard that puts the user or Human Lander in harm.
SAF4	The system shall enter into a safe state in the event of power loss, over-temperature, or valve malfunction.
SAF5	The system shall prevent over-temperature water delivery above 96° C.
SAF6	The system shall not put the user in harms way during nominal operations.
SAF7	The system shall not put the user in harms way during maintenance.

Deliver Both Hot and Cold Water for Daily Food and Beverage Needs

TMP1	The system shall deliver water that is capable of reaching a temperature range of [4, 93]° C.
TMP2	The system shall deliver water at a temperature within 5% of the acceptable bounds.
TMP3	The system shall prevent nucleation of the water.

Efficiency / Throughput

EFF1	The system shall be able to produce up to 250 mL of water at desired temperature within 600 seconds.
------	--

Minimal Cleaning / Easy to Maintain

MTN1	The system shall not need routine maintenance less than every 6 months.
------	---

Interface with HLS / Other Systems

INT1	The system shall interface successfully with other systems on board the Human Lander.
INT2	The system shall not affect any other systems upstream of the water intake.
INT3	The system shall be compatible with current ISS rack or mounting interfaces.
INT4	The system shall interface with current NASA food and water vessels.

Design for Cislunar, Lunar, and Martian Environments

ENV1	The system shall be operable in zero/micro-gravity, Lunar gravity, Martian gravity, Earth gravity.
ENV3	The system shall be able to withstand the launch forces required to reach the Moon or Mars.
ENV4	The system shall be able to withstand 240 (TBR) micro sieverts per hour.
ENV5	The system shall prevent dust intake during lunar or Martian operations.

Full Budget

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

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 Shock-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			

Thermal Control Backup



School of Aeronautics
and Astronautics

Thermal Control

Cooling Trade Study

- Design 3 chosen – no tank is crucial for system success

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 pump)	7 (Contact limited)	10 (Maximum ΔT)
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

Thermal Control

Slide 11

10-minute justification:

- Beats baseline xPWD system
- Feasible goal, no time loss for astronauts
- Achieves goal of “on-demand” hot and cold-water delivery

Trade study values:

- Based primarily on driving requirements, other requirements do not carry as much weight because of decreased importance
- Time, reliability, and temperature stability are primary functions and needs of system

Thermal Control

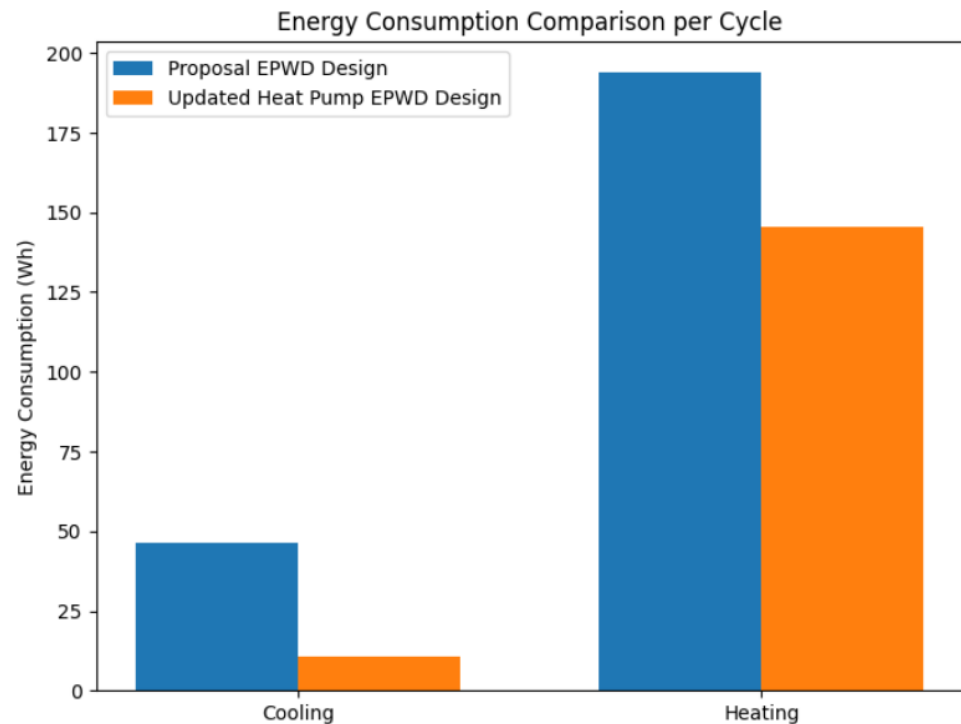
Slide 12-13

Heat Ratio, Values for Cooling vs. Heating:

Heating : Cooling Ratio

Proposal = 4.15

Updated = 13.39



Thermal Control

Slide 13-14

Thermal Load on Environment Calculations

Waste Heat:

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:

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

Thermal Control

Slide 13-14

Subsystem 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:

$$Q = m * c_p * \Delta T \quad (1)$$

$$P = \frac{Q}{\Delta t} \quad (2)$$

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

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

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
 $c_p = 4.184 \frac{kJ}{kg \cdot K}$
 $\Delta T_{max} = T_{max} - T_{min} = 18^\circ C - 4^\circ C = 14^\circ C = 14K$
 $t_{expected} = 600 s$

Equations:

$$Q = m * c_p * \Delta T \quad (1)$$

$$P = \frac{Q}{\Delta t} \quad (2)$$

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

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

With estimated 20% Losses for Mini Refrigeration Cycle:

$$P_{max} = 236 W$$

Thermal Control

Slide 13-14

Lumped Capacitance Calculations

Subsystem 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 Control

Slide 13-14

Thermal Resistance Calculations

Subsystem 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

$L = 0.0005 \text{ m}$

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:

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

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

Thermal Control

Slide 13-14

Subsystem 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:

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

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

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 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: $COP_h = 1.33$

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:

- $W_{cool} = 168.57 \text{ kJ}$
- $W_{heat} = 700 \text{ kJ}$
- $W_{comp} = 37.67 \text{ kJ}$
- $Q_{rejected} = 157.33 \text{ kJ}$
- $Q_{lost,net} = 472.67 \text{ kJ}$
- $W_{heat,net} = 525.19 \text{ kJ}$

System Layout Backup

Genetic Algorithms

Optimization of Component Location

A genetic algorithm is an optimization method inspired by natural selection that iteratively evolves a population of candidate designs, using selection, crossover, and mutation to identify the configuration that best satisfies a defined fitness function.

Fitness Function

The genetic algorithm minimizes a weighted objective function:

$$J = w_1\Delta P + w_2L_{pipe} + w_3V_{dead} + w_4P_{overlap} + w_5P_{thermal}$$

where:

ΔP = total pressure loss

L_{pipe} = total pipe length

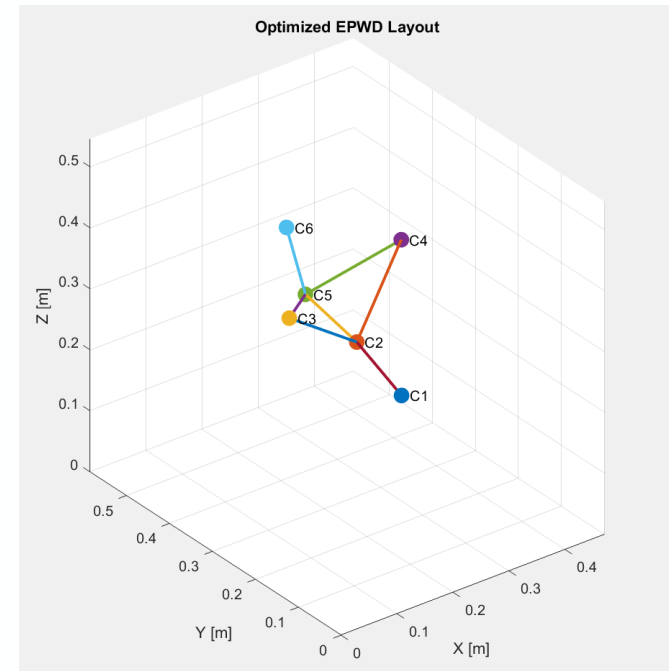
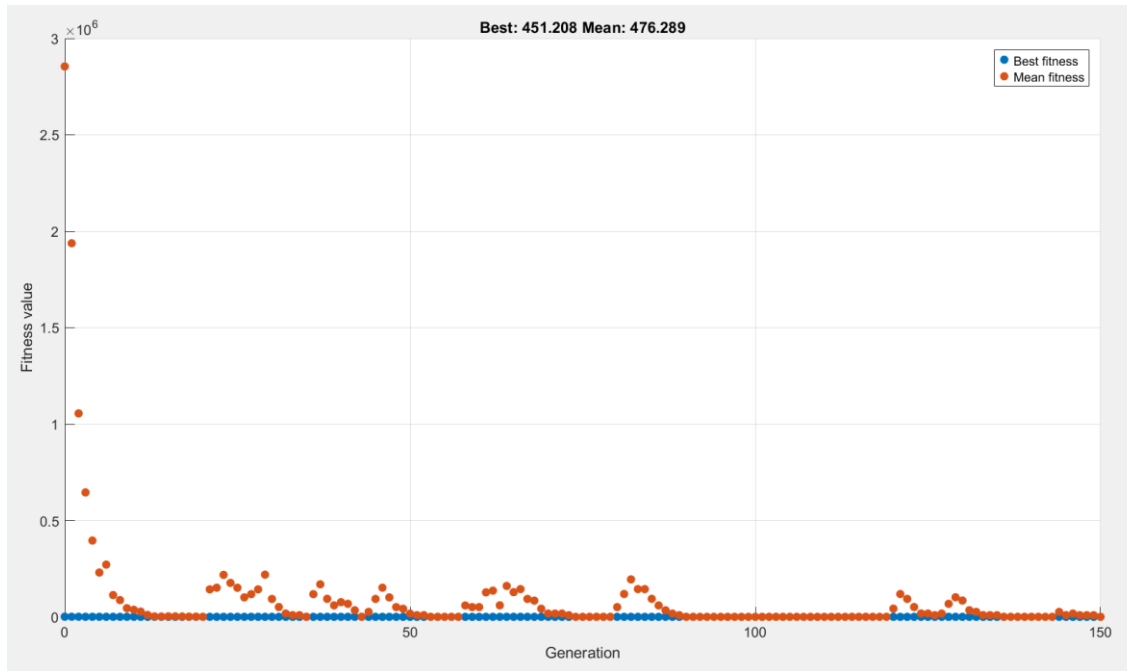
V_{dead} = stagnant/dead-zone volume

$P_{overlap}$ = component overlap penalty

$P_{thermal}$ = thermal interference penalty

Genetic Algorithms

Optimization of Component Location



Line Lengths

Section	Length [cm]
Hot	84.65
Cold	61.46
Ambient	50.43
Other	68.49