NASA/TM-20210013644
NESC-RP-01518

# Assessment of Biocide Impacts on Life Support (LS) and Extravehicular Activity (EVA) Architectures

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April 2021

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**Acknowledgments**

The assessment team would like to recognize the significant technical contributions of Robin Hetherington (JSC-ES411, Materials and Processes) and Anna Shipman (MSFC-HS11, student trainee). The team would also like to thank peer reviewers Tim Barth, Dan Dorney, Jon Holladay, Steve Gentz, Rex Graves, Dexter Johnson, Monsi Roman, Rick Russell, Steve Smith, and Tim Stephenson.



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# NASA Engineering and Safety Center
# Technical Assessment Report

# Assessment of Biocide Impacts on Life Support (LS) and Extravehicular Activity (EVA) Architectures

**February 18, 2021**

## Report Approval and Revision History

| | | |
|---|---|---|
| Approved: | *Original Signature on File* | 3/5/21 |
| | NESC Director | Date |

| Version | Description of Revision | Office of Primary Responsibility | Effective Date |
|---|---|---|---|
| 1.0 | Initial Release | Dr. Morgan B. Abney NASA Technical Fellow for Environmental Control/ Life Support | 2/18/2021 |

# Table of Contents

## List of Figures



## List of Tables

# Technical Assessment Report

## 1.0 Notification and Authorization

Mr. Walter Schneider, Project Manager for the Human Exploration and Operations Mission Directorate's (HEOMD) Advanced Exploration Systems (AES) Life Support Systems (LSS) project, requested an assessment to evaluate potable water system biocide options impacting Gateway, Human Lander Systems (HLS), Foundation Surface Habitat (FSH), and Exploration Command Module (ECM) missions. The assessment focused on identifying feasible biocide options, evaluating the impacts of their implementation on crew health, extravehicular activity (EVA) hardware, and LSS hardware, and conducting a trade on architecture options.

The key stakeholders for this assessment are Mr. Walter Schneider, AES LSS Project Manager; Ms. Miriam Sargusingh, Gateway, Habitation and Logistics Outpost (HALO), and HLS LSS Manager; Ms. Stephanie Johnston, HLS EVA System Manager; Mr. John Swatkowski, EVA Strategic Integration Lead; Mr. David Howard, Next Space Technologies for Exploration Partnerships (NextSTEP) Habitat LSS System Manager; and Dr. Moriah Thompson, Crew Health Lead.

## 2.0 Signature Page

Submitted by:

*Original Signature on File – 3/26/21*

Dr. Morgan B. Abney Date

Significant Contributors:

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| Mr. Kevin S. McCarley Date | Dr. Lance D. Delzeit Date |
| Ms. Eliza L. Montgomery Date | Dr. Michael Callahan Date |
| Dr. Martin S. Feather Date | Dr. Steven L. Cornford Date |
| Dr. Daniel B. Gazda Date | Dr. Spencer Williams Date |
| Mr. John W. Steele Date | |

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

## 3.0 Team List

| Name | Discipline | Organization |
|---|---|---|
| **Core Team** | | |
| Morgan Abney | NESC Lead | MSFC |
| Colin Campbell | EVA Portable LS | JSC |
| Kevin McCarley | Systems Engineering & Analysis | MSFC |
| Steven Cornford | Systems Engineering & Analysis | JPL |
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## 3.1 Acknowledgments

The assessment team would like to recognize the significant technical contributions of Robin Hetherington (JSC-ES411, Materials and Processes) and Anna Shipman (MSFC-HS11, student trainee). The team would also like to thank peer reviewers Tim Barth, Dan Dorney, Jon Holladay, Steve Gentz, Rex Graves, Dexter Johnson, Monsi Roman, Rick Russell, Steve Smith, and Tim Stephenson.

# 4.0 Executive Summary

On the International Space Station (ISS), product water from the Water Processing Assembly (WPA) is dosed with iodine to prevent unwanted microbial growth in the potable water system. This water is used in vehicle life support (LS) systems, in the extravehicular mobility unit (EMU), for crew consumption, and for crew hygiene activities. Long experience with iodine on ISS has shown that there are key technical challenges to using iodine as a biocide for Exploration. First, although iodine has been used to successfully control microbial growth in missions since the Apollo era, NASA's future missions are envisioned with much longer periods of dormancy during which water will remain stagnant and more prone to microbial growth. This is in contrast with experience to date, in which water flows through and out of the system, limiting the opportunity for microbial biofilm growth. Second, iodine cannot be ingested by the crew and must be removed prior to dispensing. This results in consumable mass and volume in the form of filters for iodine removal. Relatedly, missions beyond low Earth orbit will reduce the availability of spares due to increased logistics cost. Because iodine is removed prior to dispensing, portions of the hardware will have no biocide, putting them at greater risk of microbial growth. These sections will likely experience unwanted microbial growth during dormancy and require replacement, thus driving up sparing costs. Finally, there is interest in establishing international interoperability standards for exploration systems, including biocide compatibility. At present, Orion will use silver as a biocide. Certain international partners have selected or are considering the use of silver biocide in the potable water system. Iodine and silver are not compatible, and the exchange of water between systems using one or the other would require additional hardware to remove and/or add the complimentary biocide per the system exchange. As a consequence of these technical challenges, managers of future Exploration programs, such as Gateway, HALO, HLS, LSS, and the Deep Space Habitat, are considering silver-, bromine-, and chlorine- based biocides as alternatives to iodine.

Any changes to the baseline biocide will ultimately have an effect on the system designs for Exploration EMU (xEMU) and vehicle LS, and may affect crew health. In many cases, an advantage in one of these subsystems may introduce additional risk to another subsystem. For this reason, an architecture-level trade of various biocides was requested by the AES LSS Project.

The purpose of this study was to evaluate the impacts of multiple biocide solutions on LS, xEMU hardware, and crew health at subsystem and system levels in an effort to identify and prioritize biocide solutions for near- and long-term mission goals. The evaluation was limited to considerations of biocide substances that have either previously been used in spacecraft potable water systems or are undergoing assessments of their potential use. At present, these biocides include iodine and biocidal forms of silver, bromine, and chlorine. Finally, for this assessment, three mission scenarios were considered and set distinct timeline constraints on decision points. These scenarios included 1) the Exploration Command Module (ECM) flight in 2027 [ref. 13], 2) the Foundation Surface Habitat (FSH) flight in 2029, and 3) an unconstrained future mission in which the "best technical solution" would be preferred.

***Approach***

The study gathered information from scientific literature, historical NASA documents, and team expertise to complete six focused tasks:

Task 1: Identify and document available forms of biocidal silver, bromine, and chlorine.
Task 2: Identify and document the effects of biocides on crew health.

Task 3: Identify and document the effects of biocides on xEMU hardware and operations.
Task 4: Identify and document the effects of biocides on vehicle LS hardware and operations.
Task 5: Define architecture options (trade space) for implementation of biocides.
Task 6: Conduct a trade assessment on the architecture options.

Seven criteria and numerous subcriteria were used to trade architecture options. All impacts were combined at the architecture level and traded across 33 unique architecture options and mission assumptions. Because all the biocide options are in various stages of development for exploration missions, a full data set was not available to support a quantitative trade assessment. Instead, a qualitative set of trades were conducted at four discrete levels of optimism based on the team's assessment of the probability of development success for a given biocide architecture. The levels were *Pessimistic, Baseline, Likely, and Optimistic*. The selected trade criteria included:

1. Minimal Mass/Power/Volume Increase over State-of-the-art (SOA)
2. Minimal Schedule Increase over SOA
3. Minimal Cost Increase over SOA
4. Low Operational Complexity
5. Low Crew Health Risk
6. Low Maturation Risk
7. Minimal Sustaining Engineering

***Results***

The results of this study include (1) an assessment of each of the plausible biocide options and architectures against the criteria described; (2) extraction of a subset of the most promising options (i.e., top 10), robust with respect to uncertainties in the scores themselves; (3) identification of 56 development activities needed to address each of the unknowns associated with those promising architecture options; and (4) a prioritization of those development activities based on a combination of urgency and trade scores.

Specifically, the trade ranked two of the iodine-based architectures, the passive silver architecture, the electrolytic silver architecture, and four mixed iodine (for xEMU) and silver (for LSS) biocide architectures as the best for both the ECM and FSH missions, as well as the long-term best technical options. The assessment team then compiled a comprehensive list of development activities necessary to demonstrate the feasibility of each architecture. The combined data were used to construct a Development Prioritization Logic diagram offering a development pathway for the biocide architectures From the diagram, priority levels were assigned to the development activities based on the relative ranking of architecture options, the serial logic of specific activities, and the level of risk mitigation associated with the activity, with high-impact and/or long-lead activities given elevated priority. Seven activities were ranked as Tier 1 (i.e., to begin as soon as possible). Eight were ranked as Tier 2 (i.e., to begin as soon as funding and staffing can be made available). Finally, 11 were ranked as Tier 3 and 30 as Tier 4. In general, the Tier 3 and 4 activities ranked lower, as they were dependent on the successful outcomes of the higher-tiered tasks.

In summary, the goal of this assessment was to evaluate the impacts of iodine, silver, bromine, and chlorine-based biocides on crew health, xEMU hardware, and vehicle LS hardware, individually and at an architecture level. This was accomplished by analyzing how each subsystem was affected in seven areas: 1) mass, power, and volume; 2) schedule; 3) costs to develop from current state to flight hardware; 4) operational complexity; 5) crew impacts;

6) technology maturation; and 7) sustaining engineering. All impacts were combined at the architecture level and traded across 33 unique architecture options, with assumptions made at four discrete levels of optimism. Ultimately, none of the architecture options for Exploration have all the data necessary to fully understand the impacts in each area. Further, reduction in risks of a given biocide to one subsystem frequently showed equal or greater risks to the other subsystems. This necessitated a trade to minimize impacts across the entire architecture, rather than just at the subsystem level. The NESC recommendations take the form of a prioritization of those development activities. The assessment limited its consideration to the use of iodine and biocidal forms of silver, bromine, and chlorine, the motivation being that these substances have either previously been used in spacecraft potable water systems or are undergoing efforts to assess their potential use in such systems.

# 5.0 Assessment Plan

Identification and evaluation of the trade space for implementation of iodine-, silver-, bromine-, and chlorine-based biocides and their impacts on xEMU and LS water processing systems was requested by the HEOMD AES Project. The assessment was requested to help inform technology decisions that will affect Gateway/HALO/United States (U.S.) Habitat, HLS, Lunar Surface Systems, and Deep Space Habitat.

The original scope of the assessment involved four goals:

1. Identify available forms of biocidal silver, bromine, and chlorine.
2. Evaluate the effects of each biocide on crew health, xEMU hardware, and LS system hardware.
3. Define system architectures and concepts of operation (ConOps) for all viable solutions involving iodine-, silver-, bromine-, and chlorine-based biocides.
4. To trade architectures and rank solutions for Exploration implementation.

No changes were made to the scope during the assessment, and all six defined tasks were completed as planned with the exception of the schedule for Tasks 2 through 4. These tasks were delayed by approximately one month due to ISS on-orbit activities requiring the temporary redirection of core team members. The tasks and their objectives follow:

***Task 1: Identify and document available forms of biocidal silver, bromine, and chlorine (6 weeks).***

- Review the scientific literature, historical NASA documents, and recently initiated technology development efforts and compile a list of silver-, bromine-, and chlorine-based biocides and dosing approaches.
- Document the chemicals, their availability, their effective concentrations, their chemical properties, previous or current applications, lessons learned, and any known limitations on their use in potable water systems.

***Task 2: Identify and document the effects of biocides on crew health (3 months).***

- Use the list compiled in Task 1 to evaluate the effects of each biocide on crew health.
- Evaluate each across the range of concentrations for effective microbial control as well as above these limits to fully understand risks.
- Consider crew welfare, including taste and odor.

***Task 3: Identify and document the effects of biocides on xEMU hardware and operation (3 months).***

- Evaluate the effect of each biocide on components within the xEMU Portable Life Support System (PLSS) and the Liquid Cooling and Ventilation Garment (LCVG) that interface with water provided by the LS water system.
- Evaluate the effect of each biocide on components that may be exposed to the LS water system in relevant failure modes.

***Task 4: Identify and document the effects of biocides on LS hardware and operation (3 months).***

- Evaluate the effect of each biocide on systems, subsystems, and components within the vehicle LSS that interface with the LS water system.

- Evaluate the effect of each biocide on components that may be exposed to the LS water system in relevant failure modes.

***Task 5: Define architecture options (trade space) for implementation of biocides (1 month).***

- Review findings from Tasks 2 through 4 and define the architectures and ConOps for implementation of each biocide or combinations of biocides.
- Provide relevant data for each criteria of the trade study and document the technical, schedule, and cost impacts of each architecture on the subsystems, where possible.
- Eliminate any biocide options identified as having critical shortcomings (e.g., lethal to crew) from consideration in the trade.

***Task 6: Conduct trade on architecture options (2 months).***

- Define criteria, define metrics.
- Perform a trade study of the architectures identified in Task 5 using standard systems engineering methods.

Four technical interchange meetings (TIMs) were held to review the results of Task 1 (TIM #1), Tasks 2 through 4 (TIM #2), Task 5 (TIM #3), and Task 6 (TIM #4). TIMs #1 and #2 included the core assessment team and sponsors to ensure stakeholder concurrence. TIMs #3 and #4 included the core assessment team and key additional participants to review, refine, and update data and analyses. The additional participants included two xEMU team members who programmatically support the mobility unit development and were significant contributors to the overall success of the assessment.

Key stakeholders for the effort are shown in Table 1.

***Table 1. Assessment Stakeholders***

| Name | Title | Affiliation | Role |
|---|---|---|---|
| Walt Schneider* | AES LSS Project Manager | NASA Marshall Space Flight Center (MSFC) | Supporting, Receiving Results |
| Miriam Sargusingh+ | Gateway/HALO/HLS ECLSS System Manager | NASA Johnson Space Center (JSC) | Receiving Results |
| Stephanie Johnston | HLS EVA System Manager | NASA JSC | Receiving Results |
| John Swatkowski** | EVA Strategic Integration | The Aerospace Corporation | Receiving Results |
| David Howard | NextSTEP Hab ECLSS System Manager | NASA MSFC | Receiving Results |
| Moriah Thompson | Crew Health | NASA JSC | Receiving Results |

*Alternate Christine Stanley
+Gateway Deputy Mononita Nur, HALO Subsystem Manager Matt Johnson, HLS Alternate System Manager Larry Spector
**Deputy Natalie Mary

# 6.0 Problem Description, Background, Approach, and Results

## 6.1 Problem Description

Iodine ($I_2$) has been used since the Apollo era to control microbial growth in wetted portions of LS and EVA systems. However, because of the challenges experienced by ISS and incompatibility with water from international partners [ref. 1], along with the Exploration challenge of dormant periods between operations, NASA established a technology goal for a "single biocide that is stable long-term and safe for human consumption at biocidal concentrations" [ref. 2]. For these reasons, the AES LSS Water Processing Team baselined silver, the same biocide used in Russian water systems, as a biocide for Exploration missions. The team also continues to work with the Space Technology Mission Directorate (STMD) on new approaches using bromine and chlorine for possible infusion into future missions.

The Exploration EVA (xEVA) Team has baselined iodine for ISS demonstration and near-term Exploration missions. There is current work between xEMU and LS teams to study the effects of alternate biocides on xEMU hardware. However, because of the inherent interface between these systems, there remain significant concerns regarding the interactive effects of these chemicals, their effects on materials and hardware, and their impacts on near-term mission architectures [ref. 1]. This effort seeks to evaluate the impacts of multiple biocide solutions on LS, EVA, and crew health in an effort to identify the most promising solutions for both near- and long-term mission goals.

## 6.2 Background

Numerous systems within the ISS are impacted by the choice of biocide. For the purposes of this study, the assessment team explored the effect of a particular biocide or combination of biocides on the WPA's potable water distribution bus, LS systems interfacing with the WPA, PLSS hardware, EVA support hardware, logistics hardware, and individual crew members. Figure 1 shows the relative flow of potable water and wastewater among these. These systems and their interfaces are described in detail in the following subsections.

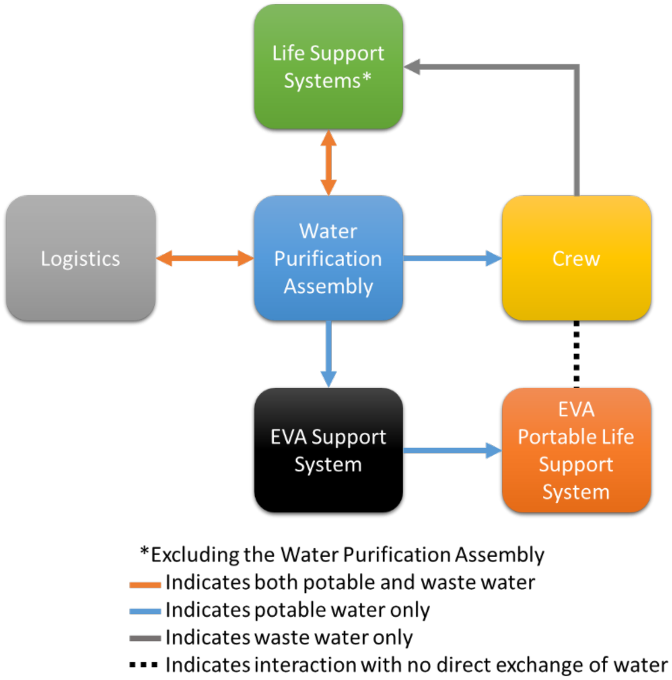


*Figure 1. Interactions Between ISS Systems and Potable and Wastewater*

### 6.2.1 Water Purification Assembly

The ISS WPA is designed to convert wastewater to potable water through a multi-step process, as shown in Figure 2. The first step in the process is the removal of air from the wastewater, followed by mechanical filtration to remove particulates, multifiltration to remove dissolved contaminants, catalytic oxidation to oxidize organics, gas separation to remove oxygen, and ion exchange to remove oxidation byproducts. Following the final ion exchange step, the resulting potable water is passively iodinated using an iodine resin. The product water is analyzed using a conductivity sensor and reprocessed if the conductivity is found to be beyond the acceptable limit. A microbial check valve (MCV) is used as a microbial barrier on the water reprocessing line to prevent microbial backgrowth from the wastewater side of the WPA to the high-purity water side. If the product water is within acceptable limits, it is stored in the product water tank. A second tank, called the accumulator, is used to further distribute potable water throughout the potable water bus. The potable water bus provides water directly to other LSSs, including the oxygen generation assembly (OGA) and the universal waste management system (UWMS); to the crew via the potable water dispenser (PWD); to the contingency water containers (CWCs) in support of logistic activities; and to EVA support systems via CWCs and the umbilical interface assembly (UIA). A secondary water quality analysis is conducted on the potable water using the total organic carbon analyzer (TOCA), which is also located off the potable water bus.

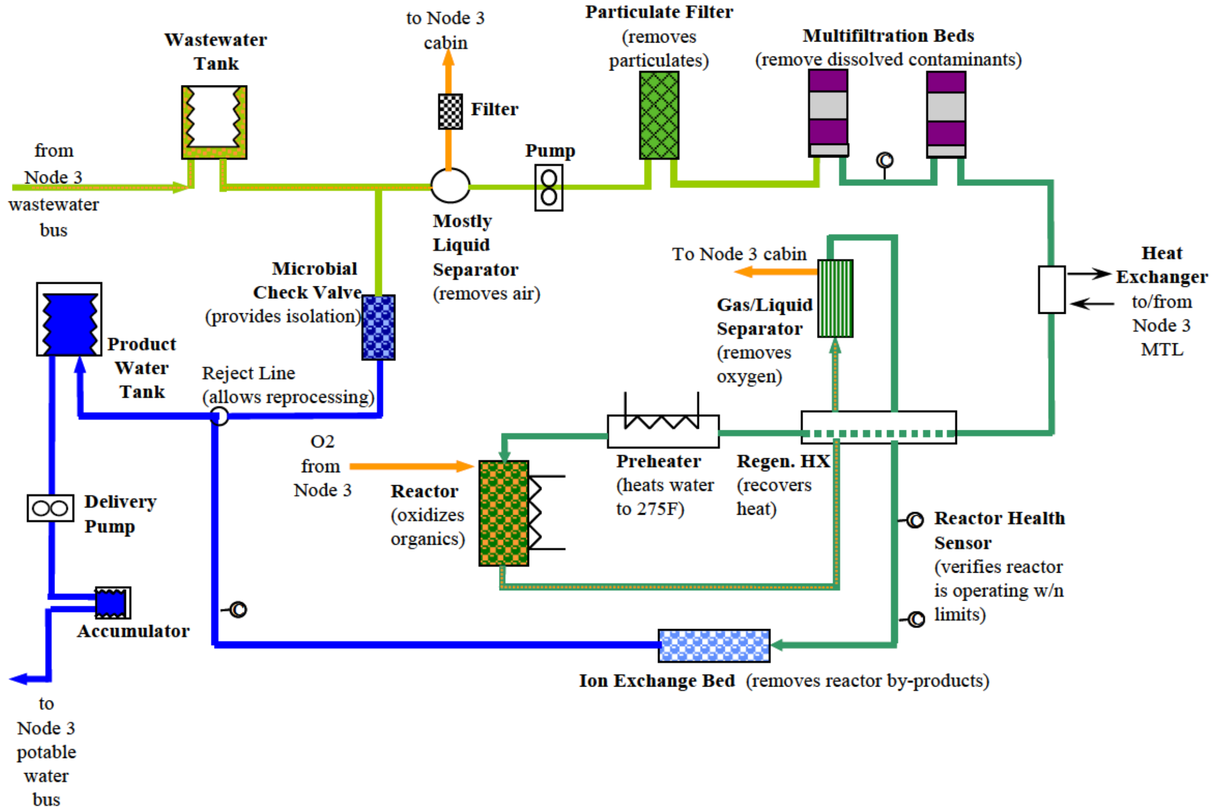


*Figure 2. Simplified WPA Schematic*

Because iodine is introduced into the system at the end of the ion exchange bed (IEB), only a limited portion of the WPA is wetted with iodinated water. The system schematic (Appendix E.5), shows three pressure sensors, a conductivity sensor, a gas sensor, six valves, a filter, a check valve, two tanks, a pump, and plumbing, all of which are exposed to the iodinated water. Each can be impacted by a change in the biocide. Further, MCVs are located at multiple locations throughout ISS to protect various hardware; a new biocide would require a new MCV design to continue to protect the required systems.

### 6.2.2 LSS Interfacing with WPA

Five main LS subsystems interface with the WPA, as shown in Figure 3 and Figure 4. Systems that provide wastewater to the WPA for processing include the urine processing assembly (UPA), the Sabatier reactor (when installed), and the cabin condensing heat exchanger (CHXR). Systems that accept potable water from the WPA include the UWMS and the OGA.

#### 6.2.2.1 LSS Providing Wastewater to the WPA

The UPA provides an initial purification step for urine through a distillation process. The product distillate, which contains no biocide, is stored in the wastewater tank for WPA processing.

The Sabatier reactor, when installed, recovers oxygen from metabolic carbon dioxide in the form of water. Product water from the chemical process is fed to the WPA wastewater tank after passing through an activated carbon/ion exchange (ACTEX) filter, located on the wastewater bus line, to remove impurities from the water stream.

The CHXR condenses water vapor from the circulating cabin air using a heat exchanger and stores the condensate in the WPA wastewater tank. The condensing surface of the heat exchanger has an integrated silver oxide biocide in its hydrophilic coating.

Because the UPA, Sabatier, and CHXR are neither exposed to nor impart biocide, a change in the biocide is not expected to affect these systems.

### 6.2.2.2 LSS Receiving Potable Water from the WPA

The UWMS, which includes the toilet, receives potable water from the potable water bus. An ACTEX filter located on the potable bus line removes the iodine biocide prior to introduction to the toilet. Before the UWMS was available, the crew used a Russian-provided toilet that used silver as the biocide from its secondary water source. This filter was originally required to remove iodine from the water to prevent the chemical reaction between iodine and silver that produces silver iodide precipitate. The UWMS adds pretreatment chemicals to the urine, including phosphoric acid and chromium trioxide. These are ultimately removed in the UPA. A new biocide could have one of two effects. First, if the biocide is compatible with the UWMS materials and the pretreatment chemicals, the ACTEX filter could be removed from the potable bus line to save logistic mass. However, if the biocide is not compatible with the UWMS or the pretreatment chemicals, the ACTEX filter would be required for Exploration missions. Depending on the biocide, a new material may be required in the ACTEX to ensure sufficient biocide capacity.

The OGA receives water from the potable bus line to be electrolyzed for oxygen production. At the OGA inlet, a de-iodination bed removes iodine biocide from the incoming water to protect the Nafion membranes in the unit. A bypass line allows feed water to be redirected to the wastewater bus in the event the OGA is unable to accept feed water during water flow. The bypass line connected to the Sabatier wastewater stream is outfitted with an MCV, which acts as a microbial barrier to prevent microbial growth from the wastewater side to the high-purity water side (i.e., protects the OGA feedwater loop).

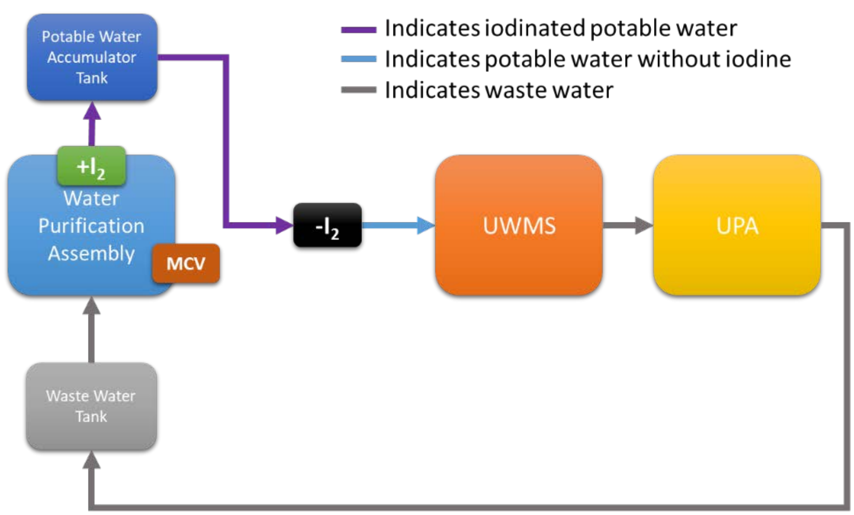


***Figure 3. WPA Interfaces with UWMS and UPA***
***Note: Iodine is added to the loop in the WPA and removed from the loop upstream of the UWMS.***

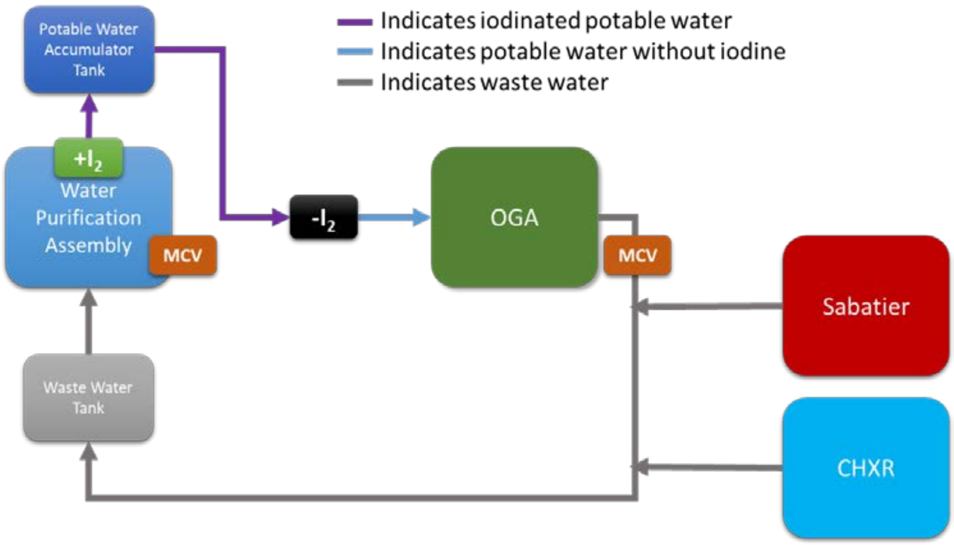


***Figure 4. WPA Interfaces with OGA, Sabatier, and CHXR***

*Note: Iodine is added to the loop in the WPA and removed from the loop upstream of the OGA. An MCV protects the OGA feed loop from contamination from the wastewater bus.*

A change in biocide from iodine could affect the OGA similarly to the UWMS. If the new biocide is compatible with OGA hardware, then the deiodination filter could be removed from the architecture. However, if not, the filter would need to remain and could require new materials to capture the new biocide.

### 6.2.3 xEMU System Description

The ISS EMU was originally designed for the Space Shuttle Program orbiter. For Exploration, the xEMU will be used. Multiple programs (e.g., Gateway, HLS, Foundation Surface Habitat, Exploration Command Module, Mar surface missions) have agreed to use the common xEMU design for all near-term applications. Two xEMUs must be delivered in 2023 for the Lunar 2024 and Gateway HLS applications. The xEMUs delivered in 2023 must be highly reliable, with minimal sparing immediately after delivery and also after a two-year quiescent period. Additionally, the ISS Demonstration xEMU is scheduled for delivery in 2023. It must be compatible with the ISS EMU sublimator, because water in the vehicle cooling loop is shared in the transition from the xEMU to ISS EMU to cover ISS contingency EVAs in the event of an xEMU failure during the demonstration. The ISS EMU uses a 1 to 4 parts per million (ppm) iodine biocide in the cooling loop. Although some preliminary development work continues to assess the effects and implications of using alternative biocides in the xEMU water loop, the xEMU design, which is well under way, has baselined iodine as the biocide of choice for these early exploration demonstrations and missions. The selection of iodine is driven by several factors, including the historical success of iodine in EMU, aggressive mission timelines, and the need for compatibility with contingency operations on ISS. For the purposes of this assessment, the xEMU is discussed rather than the EMU. The xEMU, shown schematically in Figure 5, operates in two modes, which are described in the following subsections.

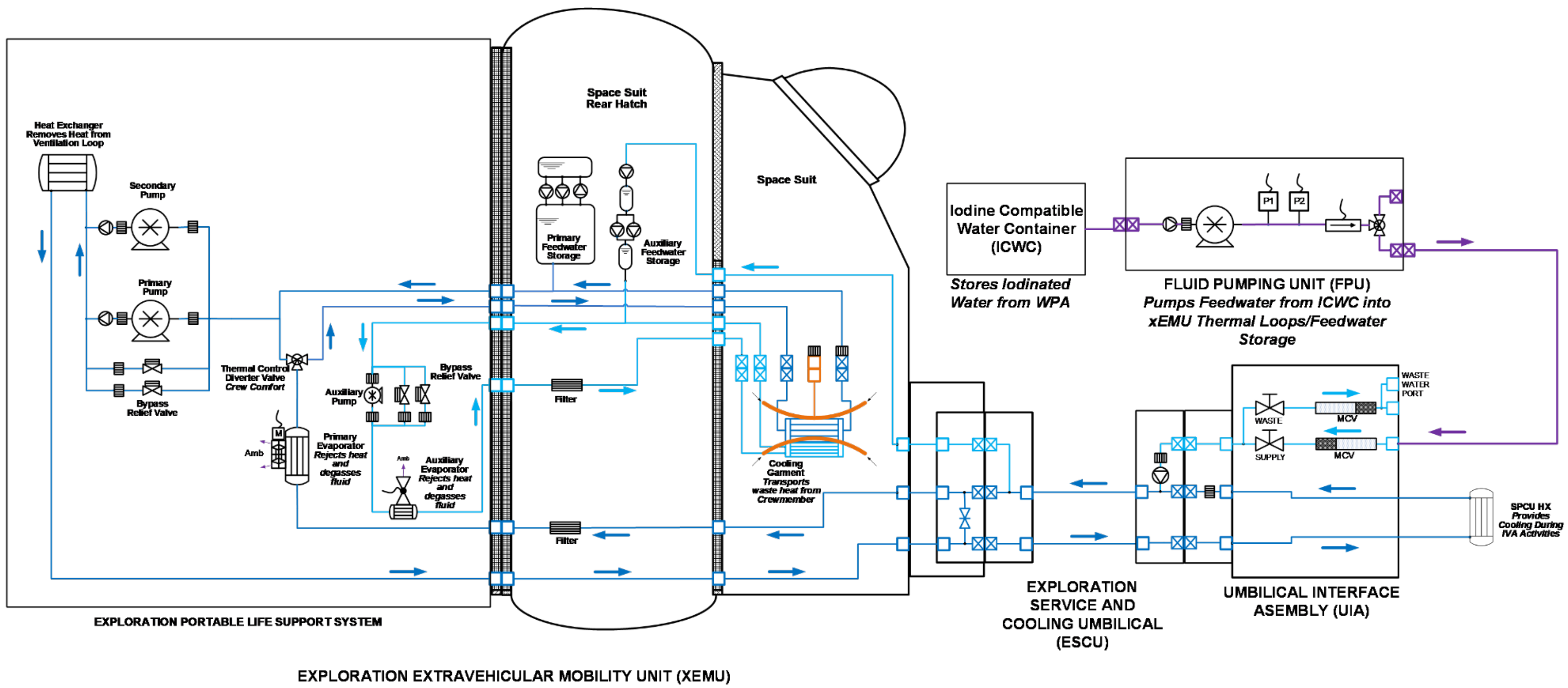


***Figure 5. xEMU Thermal Control Loop (TCL) Schematic***

*Note: Colored lines denote primary TCL (dark blue), auxiliary TCL (light blue), and water feed (purple).*

#### 6.2.3.1 Intravehicular Activity (IVA)

In this mode, the suit evaporator (i.e., spacesuit water membrane evaporator (SWME)), must perform several functions. The back-pressure valve is 10% open under IVA conditions. Water vapor is vented from the SWME at a negligible rate because cooling is not required. Free (i.e., undissolved) gas is vented from the TCL. Waste heat from metabolic processes and electronic components is removed via a cooling loop that pumps water out of the suit, through the umbilical, and across the vehicle heat exchanger. A gear pump recharges the TCL by supplying water from a reservoir to the TCL through the feedwater supply assemblies (FSAs). Reserve feedwater passes through an MCV in the vehicle interface panel and finally is introduced into the TCL where the iodine biocide is added.

#### 6.2.3.2 EVA

In this mode, the suit evaporator, which is a critical component in the xEMU TCL, must accommodate much larger thermal loads. The TCL will throttle the back-pressure valve to achieve a 50 °F fluid outlet temperature from the SWME. Vapor is vented at 0.5-3.0 pounds per hour (pph), where a ~1.2 pph vent rate is nominally expected from the 200 pph cooling fluid that is cooling the suit and crewmember. Volatile compounds are also vented through the SWME. Biocide concentration in the TCL as water is evaporated through the SWME is a significant concern and must be carefully considered when selecting a biocide. The xEMU starts an EVA with 10 pound mass (lbm) of usable water in the FSA and another 1-2 lbm distributed throughout the TCL. Upon completion of an EVA, the TCL is charged but the FSA is depleted and could be empty. If the FSA is empty upon EVA completion, non-volatile compounds will have been concentrated significantly in the operating TCL.

#### 6.2.3.3 xEMU System Operation

Water in the LCVG, which is circulated by a positive displacement pump, absorbs and removes waste heat from the spacesuit user and avionics systems as it moves throughout the Exploration Portable Life Support System (xPLSS). The warmed water is then pumped through the HX-440 or HX-540 evaporator, which removes heat through evaporative cooling into space vacuum. The heat rejection rate is controlled by a back-pressure valve. Inlet circulating water is evaporated at a rate of 2.6 pph (i.e., 1.3% of total circulating water) at the maximum achievable cooling rate and at 1.2 pph under nominal operating conditions. Evaporated cooling water is replaced from feedwater storage compliant bladders, which are located in the hatch of the rear entry suit volume, which will concentrates non-volatiles in the active portion of the TCL during an EVA. The FSA starts EVA with ~10 lbm usable water and collapses to near zero usable water by the end. Cooled liquid water exits the evaporators and is recirculated throughout the xPLSS and LCVG. TCL fluid is vaporized from the evaporators throughout an EVA and continues during subsequent IVA operations while the back-pressure valve is 10% open. Any volatile ionic biocide compound, biocide decomposition product, or reaction byproduct may enter the cabin during IVA operations or the airlock during depress/repress operations through the evaporators.

#### 6.2.3.4 xEMU Specific Biocide Considerations

The concentration rate of non-volatile compounds in the TCL must be carefully considered when selecting a biocide for the xEMU TCL application. The concentration of aqueous non-volatile species in the TCL will increase as reserve biocidal feedwater is supplied to the TCL. Many factors can affect the concentrating rate of non-volatile species during use, including aqueous reaction thermodynamics, reaction thermodynamics at the solid-liquid interface, redox reaction thermodynamics, and vapor pressure. In a separate effort, a comprehensive model is in development to predict the concentrating rate of non-volatile species in the TCL as a function of the biocide chemistry and wetted surfaces. Furthermore, evaporator fiber membranes are particularly sensitive to oxidant damage and precipitate fouling. External gear pumps are used in the xEMU TCL, but wetted journal bearings are susceptible to precipitate fouling due to tight tolerances. Finally, the TCL fine filters have limited surface area, which is an additional consideration with respect to precipitate formation, whether the precipitates are due to reaching the solubility limits of a candidate biocide or its corresponding counter-ion or due to products of corrosion that circulate in the water. For reasonable water quality, the filters offer an order of magnitude margin for pressure drop. However, they are not sized to consider a large precipitate load.

Areas of concern for the xEMU TCL application that were considered for this evaluation include:

- Effects of counter-ions and/or biocide degradation products (e.g., introduction of total organic carbon that can act as a microbial nutrient or impact water surface tension).
- Metallic and non-metallic material compatibility.
- SWME wettability/functionality, oxidation, water surface tension changes.
- Stability/life in solution with and without servicing (up to a 2-year quiescence period).
- Reactivity of biocide candidates with system material non-metallic extractables and corrosion products.
- Precipitate (e.g., biocide itself, corrosion products, and/or reactivity products) risks to high surface area membranes, fine metallic filters, high surface area heat exchanger surfaces, and tightly toleranced journal bearings for the external gear pumps.
- Integration/implementation of dosing methodology.

### 6.2.4 EVA Support Hardware (Vehicle Interface)

The EVA support hardware on ISS is the servicing, performance, and checkout equipment (SPCE) [ref. 3]. This equipment provides several functions, including EMU Don/Doff Assembly (EDDA), an EMU restraint for use by the crew during doffing and donning of the suit; the UIA, the only physical interface between the ISS Joint Airlock and the EMUs; the power supply assembly (PSA), to provide intravehicular power to the suit and the EMU battery charger; and the fluid pumping unit (FPU), to recharge EMU feed water.

On ISS, contingency water containers-iodine (CWC-Is), or iodine compatible water containers (ICWCs) are filled with iodinated potable water and connected to the FPU. This unit, shown schematically in Figure 6, provides controlled flow of potable water to the EMU feedwater bladders through the UIA. Within the UIA, additional biocide is added to the water via the biocide filter assembly (BFA), shown as MCV in the schematic, before filling the feed water bladders. A second BFA on the UIA wastewater outlet provides a microbial barrier between the wastewater and high-purity water sides.

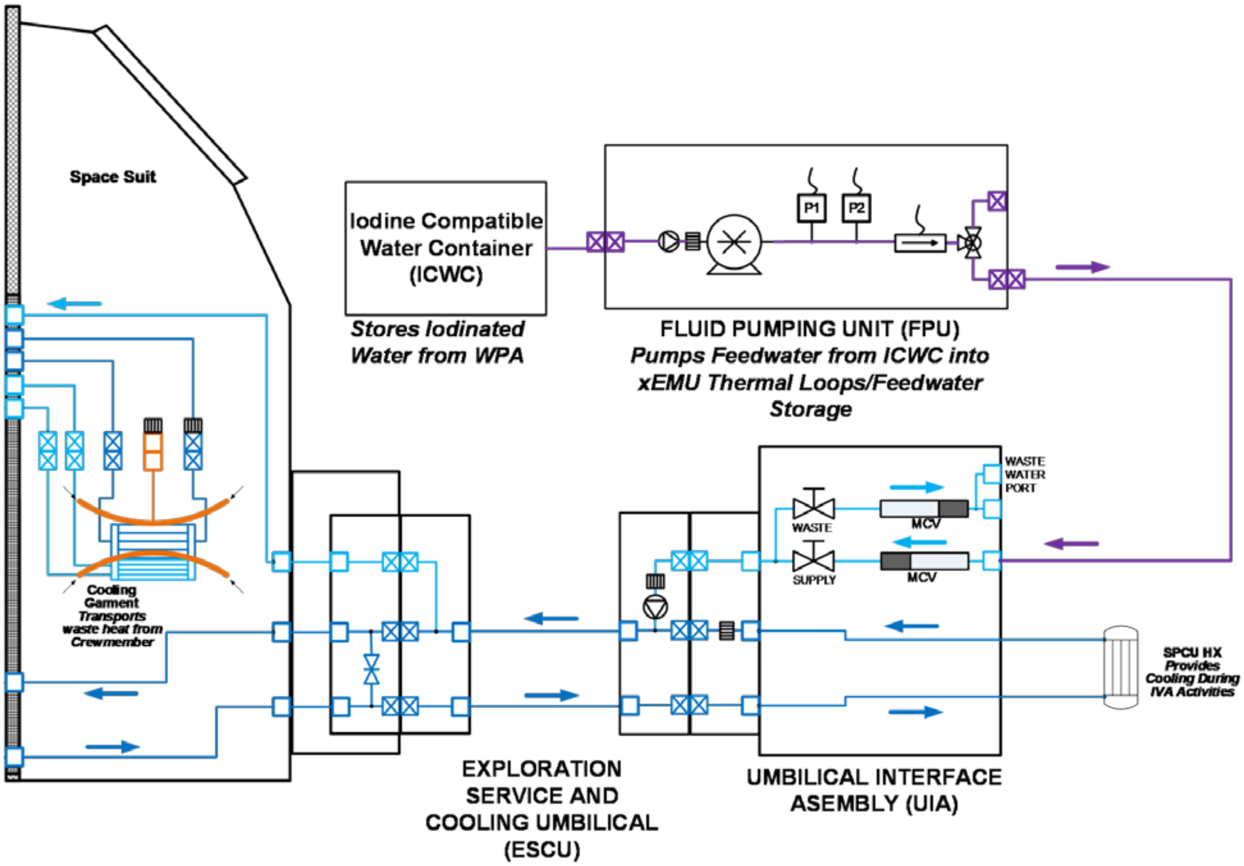


*Figure 6. EVA Support Hardware Schematic*

For Exploration, the xEMU team is targeting elimination of the BFA from the architecture based on the baseline assumption of iodine as the biocide and a direct, iodinated line from the potable water bus. Any changes in biocide will require compatibility with FPU components, UIA components, and the potential development of new BFA media.

### 6.2.5 Logistics Hardware

The water balance on ISS is partially maintained through the use of two types of CWCs. The containers can hold non-iodinated potable water, condensate water, or wastewater. The CWC-I can hold the same liquids as well as iodinated water. In cases of surplus, potable water or wastewater can be offloaded from the water system and stored in the CWCs. Stored or fresh potable water from the ground can also be provided to the water system from the CWCs. In operation, CWC-Is containing iodinated water can deliver it directly to the accumulator tank via a T-hose. Non-iodinated water can be added to the accumulator through the T-hose. However, in this case, the water is iodinated during introduction via an MCV. Depending on material compatibility, a new biocide may require a new construction material for the CWC.

When originally flown, the water recovery system contained a microbial shock kit (MSK), which provided a pump and MCV through which water could flow and shock the system in the event of contamination. The MSK was never used and was returned to ground in 2017. No shock capability is present on ISS [ref. 4]. For future missions, however, a shock kit is anticipated and would need to be designed for the new biocide.

#### 6.2.6 Crew

##### 6.2.6.1 Crew Hardware

Potable water for drinking and food preparation is provided to the crew via the PWD. This dispenser also provides water for payloads, hygiene towel hydration, water quality testing, and filling CWCs when necessary. A simplified flow diagram is shown in Figure 7 [ref. 5]. Water from the WPA accumulator is provided directly to the PWD via the potable water bus. Because the crew is unable to consume iodine biocide at levels greater than 0.20 ppm, iodine is removed from the water in the PWD on ISS. The iodine is removed prior to hot and ambient dispensing using an ACTEX/deiodination filter. The filter is limited by its capacity for iodine and must be replaced after filtration of 4,320 lbm of water (or ~7 months of on-orbit use) [ref. 5]. This leaves all lines and hardware downstream of the ACTEX without biocide, including the water heater, pressure/temperature sensors, and valves. Shortly after the initial launch of PWD, the unit experienced microbial contamination that was attributed to system stagnation prior to launch [ref. 6]. A flight rule was developed to prevent future contamination:

- <3 days of stagnation, no flush or sampling required.
- 3-13 days stagnant, small flush required but no sampling.
- 14-30 days stagnant, 1L of water is used to flush the ambient leg and 3L used to flush the hot leg. Ground and on-orbit analysis is required.
- >30 days stagnant, flushing required as well as additional sampling on the ground.

However, while microbial growth has been measured since nominal operation of the units began, no failures have occurred due to microbial growth in the volumes without biocide [O-1]. One theory is that the combined effects of 1) sterilization by the WPA catalytic oxidizer, 2) frequent flow of water through the unit's ambient lines, 3) high temperature in the unit's hot water lines, and 4) the removal of the majority of carbon (i.e., nutrient) sources via carbon filtration in the WPA prevents microbial growth from exceeding requirements (i.e., maximum 50 colony-forming units/milliliter bacteria, non-detectable coliform) [ref. 7]. This has led some to question whether a biocide is needed at all. While this assessment did not explore architectures that excluded a biocide, testing to evaluate the necessity of biocide in the potable water system, a study to review why and how biocide requirements are specified, and an update to the existing microbial control requirements for Exploration mission scenarios would answer this question.

Key concerns with the PWD for Exploration missions include the potential for microbial contamination in the volumes without biocide, potential contamination during dormancy, and the resupply impact of the PWD ACTEX and microbial filters. These three drivers have prompted the evaluation of alternate biocides. As such, a new biocide will have a significant effect on the Exploration PWD design. Depending on the biocide chosen, mass and volume improvements could result from the elimination of components, or changes to materials could have a positive or negative influence on mass and volume.

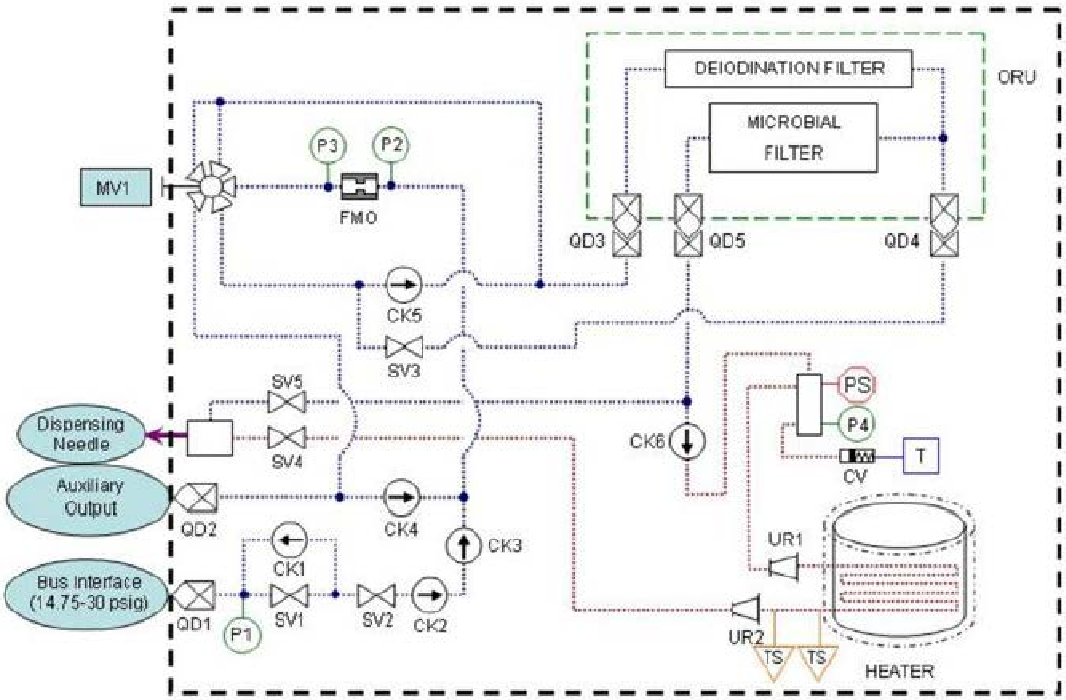


*Figure 7. PWD Simplified Flow Diagram*

### 6.2.6.2 Crew Health

The effect of chemicals on crew health has been determined for short- and long-term exposures on ISS. A key driver for evaluating new biocides is their acceptability for crew consumption. Iodine is known to cause medical issues at effective biocidal concentrations [refs. 14, 15]. Therefore, the crew is prohibited from nominally consuming iodine, necessitating removal in the PWD.

## 6.3 Approach

Six tasks were defined, with the goal of evaluating the impacts of multiple biocide solutions across the Environmental Control and Life Support System (ECLSS) architecture. Tasks 1 through 4 were independently conducted by task teams made up of a subset of the larger assessment team. Once complete, the results were reviewed at a TIM attended by the core assessment team and stakeholders. Task 5 was conducted by the full assessment team, with concurrence from stakeholders. Task 6 was conducted by the systems engineering team and reviewed with the full assessment team before outbriefing stakeholders. The detailed approach for each task is provided in the following subsections.

### 6.3.1 Task 1 Approach

The goal of Task 1 was to identify and document available forms of biocidal silver, bromine, and chlorine. These three species were selected for evaluation because they have previously been used in spacecraft potable water systems (e.g., silver) or there are ongoing efforts to assess their potential use in spacecraft potable water systems (e.g., bromine and chlorine). While other biocides are commonly used in terrestrial and spacecraft applications (e.g., based on amines, aldehydes, phenols, copper, zinc, or other chemical species), the scope of this task was limited to biocide systems based on silver, bromine, and chlorine.

The task team conducted a thorough review of scientific literature, historical NASA documents and reports, and NASA-funded new technology efforts. This team conducted internet searches and reviewed data sheets for commercially available products, compiling a list of silver-, bromine-, and chlorine-based biocide systems and dosing approaches. Those efforts identified 25 candidate biocide systems (i.e., 20 based on bromine or chlorine and 5 based on silver). After compiling the list of candidate biocide systems, the task team documented the specific chemicals, their availability, their effective concentrations, their chemical properties, previous and/or current applications, lessons learned, known limitations on their use in water systems, and development risks.

After compiling the list of available biocide systems and supporting information, the task team applied qualification criteria, defined by the assessment team as listed in Table 2 to determine whether any of the systems should be eliminated from further evaluation.

***Table 2. Biocide Qualification Matrix***

(Examples of outcomes are provided for reference only.)

| Criteria | Opt 1 | Opt 2 | Opt 3 |
|---|---|---|---|
| Must not introduce a known risk to crew health at effective biocide concentrations | | | |
| Must not require more than 3 years to begin flight demonstration/implementation | | | |
| Must be commercially available or can be made available quickly for evaluation in NASA ground systems. | | | |
| Must not be a Toxic Hazard Level 3 (storage or use) | | | |
| Must not degrade/become ineffective under storage conditions (non-use) for up to 3 years | | | |
| **Determination** | Disqualified | Obtain additional data | Qualifies for Tasks 2-4 |

| |
|---|
| **PASS** |
| **UNKNOWN** |
| **FAIL** |

Each biocide option was evaluated against each of the five criteria and designated “Pass” if sufficient data were available to confirm the criteria were met, “Unknown” if data were insufficient to adequately assess qualification, or “Fail” if data were available to prove the biocide did not meet the criteria. Any biocide with a single failing criteria was disqualified from consideration in Tasks 2 through 4. Any biocide with an “unknown” designation was flagged for additional evaluation. Any biocide that passed all criteria was taken forward for consideration in Tasks 2 through 4.

### 6.3.2 Task 2 Approach

The goal of Task 2 was to determine the potential health impacts of each candidate biocide during flight and if used as drinking water. This task comprised three basic subtasks:

a. An evaluation of the Toxicity Hazard Level (THL) per standard NASA procedure for chemical substances flown to ISS [ref. 8].

b. An assessment of potential short- and long-term health effects when water treated with the biocide is ingested.

c. A qualitative determination of the potential palatability of biocide-treated water.

Upon completion of each subtask, a scoring schema was developed to assess the viability of each candidate biocide based on the findings.

To support these subtasks, information on the toxicological and chemical properties of each candidate biocide was gathered using standard resources employed by JSC Toxicology. These include, but are not limited to: the U.S. National Library of Medicine's Pubchem database and its underlying datasets, the U.S. Environmental Protection Agency's (USEPA) Integrated Risk Information System, toxicological profiles from the Agency for Toxic Substances and Disease Registry (ATSDR), the Aggregated Computational Toxicology Resource (ACToR), the High Production Volume (HPV) chemical assessment programs conducted by the USEPA and the Organization for Economic Cooperation and Development (OECD), publicly available safety data sheets and other product materials, and Spaceflight Water Exposure Guideline (SWEG) documents as available. Any other available safety and hazard assessments were gathered.

The candidates as described were based on disinfection using iodine, silver, chlorine, and bromine. Iodine was considered as the baseline option. The possible delivery forms for silver included electrolysis, introduction of concentrated silver salts ($AgNO_3$), controlled release (AgCl or AgF), and ion bed exchange. The possible delivery forms for chlorine included di- and tri-chloroisocyanuric acid, sodium chlorite, chloramine-T, calcium hypochlorite, and chlorosuccinimide. The possible delivery forms for bromine included 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH), 1,3-dibromo-5,5-dimethylhydantoin (DBDMH), and a brominated resin (e.g., HaloPure BR).

For **Task 2.a**, standard procedures for the evaluation of THLs were followed to determine the potential impacts of a release of the candidate biocide as it would be delivered to a theoretical vehicle. The process for determining the THL is described in JSC 26895, Table 1 [ref. 8]. NASA toxicologists assimilate information on toxicological test data, physical properties, and application of a chemical substance to determine the THL of any chemical (e.g., liquid, solid, gas, particle, gel, particulates/powders) that will be sent to ISS. In many cases, data on the toxicological properties of a chemical substance is not available. At these times, the toxicologist may infer properties from similar substances, using expert judgment.

Biocides that were judged as THL 3 or 4 were eliminated from further consideration. All THL assessments in this exercise are considered preliminary, as the specific application, form, and ConOps for the biocide will dictate the final determination on safety.

For **Task 2.b**, two exposure scenarios were initially considered: 1) one-time exposure to 1L of water treated with the candidate biocide at its effective concentration (analogous to the off-nominal event in which ISS crew member Luca Parmitano ingested leaking water during an EVA in 2013), and 2) long-term consumption of water treated with the candidate biocide for drinking water. However, the second scenario became the driver for scoring of the biocide candidates under Task 2, as a lack of health effects from long-term consumption would be expected to absolutely preclude health effects from a one-time exposure.

The effective concentration of each candidate biocide was used as the exposure concentration in this scenario, and a toxicological assessment for possible adverse effects of exposure to 2 to 3.5L of water per day at this concentration was compiled. This level of consumption is consistent with terrestrial exposure guidelines [ref. 16], and the proposed intake [ref. 17] level for crew members during long-term exploration missions (i.e., to lessen the risk of developing kidney stones).

For **Task 2.c**, palatability of water treated with the candidate biocide was considered. To support this analysis, information on taste and odor thresholds for each substance was gathered from a variety of sources. This subtask is by its nature subjective, as taste and odor thresholds can vary widely among individuals.

Two rubrics were created to support scoring of the candidate biocides: 1) an all-encompassing rubric (AER), shown in Table 3, and 2) one comprised of four separate criteria: palatability (1-4), THL (0-4), long-term health effects (LTHE, 1-4), and data availability (1-3), provided in Appendix B. The maximum possible score for the AER is 5, and 15 for the aggregate rubric. The narrative description for individual criteria at each level is also provided in Appendix B. Each candidate was scored against these two rubrics and reported to the assessment core team.

***Table 3. Crew Health Biocide Evaluation Rubric***

| Score | Criterion Narrative |
|---|---|
| **5** | The best option in this criteria. No short- or long-term toxicological concerns (marginal), no palatability concerns, sufficient data is available to make a robust judgment. |
| **4** | Excellent option in this criteria. Minimal toxicological (marginal) and palatability concerns, available data is adequate. |
| **3** | Very good option in this criteria. Few negative factors that are easily accommodated. Potential for minor toxicity (critical) or palatability issues, available data is adequate. |
| **2** | Good option in this criteria. Has negative factors that can be accommodated, but with impacts. Potential for minor toxicity (critical) or palatability issues, or available data is insufficient for robust assessment. |
| **1** | Option is minimally acceptable in this criteria, but may require countermeasures. Has a number of negative factors that can be accommodated, but with significant impacts. Potential for serious, irreversible, or long-term toxicity (catastrophic), significant concerns with palatability, and/or little to no data availability. |
| **0** | Option is not acceptable in this criteria, one or more significant problems/impacts that cannot be accommodated within reason. One or more "showstoppers." High potential for serious, irreversible, or long-term toxicity (catastrophic), significant concerns with palatability, and/or little to no data availability. |

### 6.3.3 Task 3 Approach

The goal of Task 3 was to identify and document the effects of candidate biocides identified in Task 2 on xEMU hardware and operation. The candidate biocides fit into three categories: chlorine-, bromine-, and silver-based. Results were compared with iodine biocide, which is currently baselined for the xEMU application. This evaluation critically evaluated the compatibility of the candidate biocides for the xEMU application, as well as compatibility with wetted system materials. The candidate biocides were scored using 10 evaluation criteria:

a. Metallic material compatibility
b. Non-metallic material compatibility
c. Functional component risk
d. Aesthetics (e.g., odor)
e. Operational simplicity of implementation
f. Resource impact (e.g., up-mass, volume, power)
g. Sensing

h. System complexity
i. Driver for modification of an existing design
j. Programmatic impacts

Each biocide was scored numerically using a scale from 0 (i.e., option is not acceptable for use), to 5 (i.e., the best option for the application), as defined in Table 4.

***Table 4. xEMU Biocide Evaluation Rubric***

| Score | Criterion Narrative |
|---|---|
| **5** | The best option in this framework. A near-ideal design solution. |
| **4** | Excellent option in this framework. Few negative factors to be accommodated. |
| **3** | Very good option in this framework. Few negative factors that are easily accommodated. |
| **2** | Good option in this framework. Negative factors can be accommodated with impacts. |
| **1** | Option is acceptable in this framework. A number of negative factors can be accommodated with significant impacts. |
| **0** | Option is not acceptable in this framework. Multiple significant problems/impacts cannot be reasonably accommodated. |

The materials compatibility review is referenced peripherally in this section of the report and discussed in greater detail in Appendix C.

### 6.3.4 Task 4 Approach

The goal of Task 4 was to identify and document the effects of candidate biocides identified in Task 2 on the vehicle ECLSS hardware and operation. A list of nine operational considerations, shown in Table 5, were generated to evaluate the impacts of each biocide on the vehicle LS subsystem. A brief discussion of the operational considerations is provided.

***Table 5. Vehicle LS Operational Considerations for Potable Water Biocide***

| Item | Consideration |
|---|---|
| **1.** | Maintaining Biocide Control |
| **2.** | Dosing |
| **3.** | Operational Simplicity |
| **4.** | Mass to Implement |
| **5.** | Reliability |
| **6.** | Storage |
| **7.** | Compatibility |
| **8.** | Dormancy |
| **9.** | Technology Readiness |

***1. Maintaining Biocidal Control***

Maintaining effective biocide control has two elements. The first is whether the biocide will maintain microbial control at concentrations safe for crew to drink. If not, the biocide needs to be removed near the use point, leaving the most vulnerable section of the potable water system unprotected. The second is that the biocide maintains sufficient concentration of biocide effect microbial control.

***2. Dosing***

Credible options must be available for dosing the candidate biocides into the potable water system in the concentration range required for microbial control. For regenerative water recovery systems, this includes a way to dose the biocide on-orbit. Currently, there are two broad classes of dosing technology: active systems requiring power, such as electrolytic or a dose pump, and those that require no power (i.e., passive).

3. ***Operational Simplicity***

Refers to the complexity of the system hardware and operation. For example, a system that requires no additional hardware to remove the biocide prior to crew consumption, or systems that require no power vs. ones that do, are likely to have greater operational simplicity.

***4. Mass to Implement***

Is the predicted mass required to implement the biocide technology for a given mission? This mass refers to the infrastructure required to put the technology within the water system (e.g., media, housings, power), as well as to the consumable and/or replacement mass of the technology (e.g., spares) over the mission lifespan.

***5. Reliability***

Reliability is an estimation of the technology’s ability to deliver expected performance without unexpected failure and/or unplanned maintenance.

***6. Storage***

Storage refers to assessments of how the technology lends itself to the safe long-term storage of the biocide, up to 3 years targeted based on SOA.

***7. Compatibility***

An assessment that the biocide technology has compatibility with expected materials to be used in the potable bus and end users (e.g., PWD, OGA, urinal flush, EMU). In general, this will refer to a chemical compatibility such that the function of the biocide and/or system components (e.g., lines, valves, pumps) will not be negatively impacted by interactions with the biocide.

***8. Dormancy***

Assessment of dormancy refers to any expected change in behavior for the biocide and/or potable water system associated with quiescent periods where the water system is expected to be stagnate for up to a year on the Lunar surface and up to 3 years on the Martian surface. In general, this consideration can be associated with any long-term effects of the biocide on the system (e.g., corrosion effects, precipitation, loss of microbial control).

## 9. *Technology Readiness*

As typically used, technology readiness refers to an assessment of where in the development process the technology stands. As part of this assessment and the larger candidate biocide study, technologies with higher technology readiness levels (TRLs) are favored. In addition, work being done to improve the TRL of specific technologies is discussed.

Each of the operational considerations was evaluated qualitatively and assigned a corresponding color, as defined in Table 6.

***Table 6. Qualitative Scoring Definition for Vehicle LS Subsystem Operational Considerations***

| |
|---|
| **No issue and/or risk** |
| **Minimal issue and/or risk** |
| **Moderate issue and/or risk** |
| **Significant issue and/or risk** |

### 6.3.5 Task 5 Approach

Task 5 began with a review of biocide level scoring that the subject matter expert (SME) teams produced in Tasks 2, 3 and 4. Based on the review of this data, the chlorine biocide options were eliminated from further consideration during this assessment. A more detailed explanation for chlorine elimination is provided in Section 6.4.5. This decision was discussed with the SME team and stakeholders and was concurred with during TIM #2.

The remaining biocide options were organized into an initial set of architectures. These initial architectures were developed taking into account single and dual biocide options as well as key program-level milestones, creating near-, medium-, and far-term possible solutions. This initial set of architectures was based primarily on delivery form and presented to the assessment team at TIM #2. The list was discussed and updated during the TIM to the following architectures:

- $I_2$ (SOA modified for Exploration)
- Ag+
  - Electrolytic
  - Passive release (e.g., foam)
  - Concentrated salt solution
- OBr-
  - Concentrated solution
  - Passive release
- Dual biocides architectures
  - (I2 for xEMU and Ag+ electrolytic for LSS)
  - (I2 for xEMU and Ag+ controlled release for LSS)
  - (I2 for xEMU and Ag+ concentrated salt solution for LSS)
  - (I2 for xEMU and OBr- concentrated solution for LSS)
  - (I2 for xEMU and OBr- passive release for LSS)

Each of the listed architectures were evaluated from a ConOps perspective, with considerations such as dosing methods, crew time required, and sustainability. System-level design solutions, including the need for monitoring and pH control, were considered for each of the architectures.

This process resulted in the identification of the need to expand the original architectures to include pertinent design elements and considerations that would score differently against the evaluation criteria. This expanded list of architectures is defined in section 6.4.5.

With the expanded list of architectures developed, meetings were conducted with the SME teams to capture rationale for all scoring done during Tasks 2, 3, and 4. During these meetings, the scores from Tasks 2, 3, and 4 were mapped to the architecture level. Since Tasks 2, 3, and 4 used a different scoring schema in some cases, calibration was performed to unify all scores against a common schema. All score mapping and calibration was coordinated and concurred with by the SME teams.

### 6.3.6 Task 6 Approach

Task 6, conducting the trade study process, was initiated at the start of the assessment. The basic steps of an analytical hierarchy decision analysis process were presented to the assessment team at TIM #1 and presented with progress shown at each following TIM to keep focus on the trade study process. An overview of the process and completion milestones follows:

1. **Define the decision to be made, the problem to be solved, or the goal of the activity.** *(Completed, per NESC Review Board approval)*
2. **Define the trade space, a list of comparable, viable potential options/answers to the decision to be made or solutions to the problem to be solved.** *(Completed, TIM #1 deliverable)*
3. **Define the attributes or qualities the viable options will be evaluated against.** *(Completed, input to Tasks 2, 3, and 4)*
4. **Develop a scoring schema to use to rate the viable options against the Attributes**. *(Completed, input to Tasks 2, 3, and 4)*
5. **Score the options against each attribute – subject of TIM #2**. *(Completed in TIM #3, Outbrief of Crew Health Risk scoring at TIM #4 )*
6. **Define architectures and weighting factors if some attributes are more important to meeting the requirements/goals than others.** *(Task 5, Completed at TIM #2)*
7. **Conduct the trade and test the resulting recommendation.** *(Task 6, presented at TIM #4)*
8. **Document the process and the recommendation.** *(Task 7, presented at TIM #4 and in this report)*

In Task 1, viable biocide options were identified as described in Section 6.2.1 and evaluated and scored at the subsystem level in Tasks 2, 3 and 4. A scoring framework, as shown in Table 7, was developed by the systems engineering team and provided to the task teams for Tasks 2, 3 and 4. Each task team adapted the scoring schema for their specific subsystem, as described in Sections 6.3.2, 6.3.3, and 6.3.4.

*Table 7. Subsystem Level Biocide Scoring Framework for Tasks 2, 3, and 4*

| Stoplight Color | Numerical Score | Description<br>Feel free to rewrite to meet your specific criteria, this is a general guide. |
|---|---|---|
| Green | 5 | The best option in this criteria. A near ideal design solution. Example: reduces up mass compared to existing design solutions. |
| Green | 4 | Excellent option in this criteria. Almost no negative factors to be accommodated. Example: no additional up mass compared to existing design solutions. |
| Yellow | 3 | Very good option in this criteria. Few negative factors that are easily accommodated. Example: minimal increase in up mass compared to existing designs. |
| Yellow | 2 | Good option in this criteria. Has negative factors that can be accommodated, but with impacts. Example: moderate increase in up mass compared to existing designs. |
| Yellow | 1 | Option is acceptable in this criteria. Has a number of negative factors that can be accommodated but with significant impacts. Example: significant increase in up mass required but can be mitigated in other areas of system design and 'made to work'. |
| Red | 0 | Option is not acceptable in this criteria, one or more significant problems/impacts that cannot be accommodated within reason. One or more 'showstoppers'. Example: up mass increase cannot be accommodated. |

The evaluation criteria to be used to score the viable options at the architecture level was introduced at TIM #2 and updated during Task 5, resulting in the following:

1. **Criteria 1: Minimal Mass/Power/Volume Increase**
    a. New hardware added
    b. Hardware eliminated
    c. Hardware modified – material change
    d. Hardware modified – physical design change
    e. Hardware modified – approach change
    f. Resupply of:
        i. Hardware replacement parts/consumables
        ii. Consumables for dosing
        iii. "Fresh" biocide
        iv. Other consumables
    g. Dormancy operations supplies including:
        i. Hardware replacement parts
        ii. "Fresh" biocide
        iii. Other consumables
    h. Power

2. **Criteria 2: Minimal Schedule Increase**
    a. Added schedule for research/development (to achieve TRL 4)
    b. Added schedule for design of TRL 5 hardware
    c. Added schedule for fabrication of TRL 5 hardware
    d. Added schedule for testing of TRL 5 hardware
    e. Added schedule for iteration of TRL 5 hardware
    f. Add schedule for flight qualification
3. **Criteria 3: Minimal Cost Increase**
    a. Added cost for research/development to achieve TRL 4
    b. Added cost for design of TRL 5 hardware
    c. Added cost fabrication of TRL 5 hardware
    d. Added cost for testing of TRL 5 hardware
    e. Added cost for iteration of TRL 5 hardware
    f. Add cost for flight qualification
4. **Criteria 4: Operational Simplicity (Flight Ops/Crew Time and Frequency)**
    a. Crew interaction required vs. level of automation
    b. Monitoring/sensors required
    c. Special tools or equipment required
    d. Flexibility of timing of crew ops
    e. Reliability of system
    f. Robustness of system
5. **Criteria 5: Low Crew Health Risk**
    a. Physical and mental health
    b. Worst-case failure mode exposure impacts
    c. Long-term and long-duration exposure impacts
    d. Vaporization exposure impacts
    e. Aesthetics as they affect crew health
6. **Criteria 6: Low Maturation Risk**
    a. Level of fundamental research required
    b. Quantity of engineering design needed
    c. Quantity of health data needed
    d. Quantity of material compatibility data needed
    e. Quantity of functional ground test data needed
    f. Quantity of functional flight data needed
7. **Criteria 7: Sustaining Engineering**
    a. Costs of resupply of:
        i. Hardware replacement parts/consumables
        ii. Consumables for dosing
        iii. "Fresh" biocide
        iv. Other consumables
    b. Costs of dormancy operations supplies including:
        i. Hardware replacement parts
        ii. "Fresh" biocide
        iii. Other consumables

Note that during the scoring discussions with the SME teams, lower-level subcriteria were developed as needed to provide sufficient granularity to score important details in the architecture-level alternatives. Scoring schemas were developed for these subcriteria as needed. All lower level scoring was rolled up to the architecture evaluation criteria level and all scores were normalized to use the 0-5 scoring schema. This resulted in *Baseline* scores for criteria and all architectures.

Because the majority of the architecture options included considerable unknowns, three additional sets of scores were generated: *Pessimistic*, *Likely*, and *Optimistic*. Starting with the *Baseline* scores, *Pessimistic* scores were generated by reviewing and eliminating all assumptions made in favor of a given architecture. This resulted in the lowest possible score for an architecture option. To generate the *Likely* scores, the unknowns for each architecture were reviewed and activities that could reduce the risk (i.e., provide answers for the unknowns) were generated. Engineering judgment was applied to each of the activities. If the team felt that an activity could reasonably be successful based on the data available today, then points were given for the appropriate criteria. This resulted in scores equal to or greater than *Baseline* scores, but relied on moderate optimism in engineering judgement. Finally, *Optimistic* scores were generated by assuming that all risk-reducing activities were successful and the appropriate points given for each criteria. This resulted in the highest possible scores for every architecture. Specific assumptions and variations between levels of optimism are provided in Appendix G.

Given the time-dependence for many of the architectures due to technology development, three mission scenarios were considered. The most near-term mission, the ECM, is due to fly in 2027. Historical experience with ECLSS systems suggests a delivery need date 2 years prior to flight. For the purposes of the trade, the assessment team assumed a 2025 need date, with increased risk identified beyond that. The mid-term mission, the FSH, is scheduled to launch in 2029, resulting in a need date of 2027. The third mission scenario was intended to be timeline-agnostic and targeted a “best technical solution” rather than the “best solution in the available time frame.”

Weighting factors were developed for criteria 1 through 6 with the evaluation teams during TIM #2 for the ECM and FSH missions, as shown in Table 8. For the “best technical solution” mission, criteria 2 (schedule), criteria 3 (cost), and criteria 6 (low maturation) were deemed irrelevant, as this approach would assume sufficient schedule and cost to adequately mature the required technologies. However, criteria 7 was added to consider the recurring costs of sustaining engineering for a mission architecture. The weighting factors as applied to “best technical solution” are provided in Table 8.

***Table 8. Criteria Weight Factors Applied to ECM, FSH, and “Best Technical Solution” Missions***

| # | Criteria | Weights Applied to ECM and FSH Missions (x) | Weights Applied to Best Technical Solution (x) |
|---|---|---|---|
| 1 | Minimal Mass/Power/Volume Increase | 2 | 2 |
| 2 | Minimal Schedule Increase | 1 | - |
| 3 | Minimal Cost Increase | 1 | - |
| 4 | Operational Simplicity | 2 | 2 |
| 5 | Low Crew Health Risk | 3 | 3 |
| 6 | Low Maturation Risk | 2 | - |
| 7 | Sustaining Engineering | - | 2 |

As a first-order check, the identified weighting factors were compared with a pair-wise comparison conducted with inputs from key stakeholders. The pair-wise comparison confirmed that the weighting factors developed during TIM #2 were appropriate, as shown in Table 9. A comparison of final scores using both sets of weighting factors is provided in Appendix G.

***Table 9. Trade Study Weighting Factor Validation for ECM and FHS Missions***

| # | Evaluation Criteria | TIM #2 Weighting Factors | Pair-wise Weighting Factors |
|---|---|---|---|
| 1 | Minimal Mass/Power/Volume Increase | 2 | 2 |
| 2 | Minimal Schedule Increase | 1 | 1 |
| 3 | Minimal Cost Increase | 1 | 0.5 |
| 4 | Operational Simplicity | 2 | 3 |
| 5 | Low Crew Health Risk | 3 | 4 |
| 6 | Low Maturation Risk | 2 | 2 |

Once *Baseline* trade scores were evaluated per the normalized architecture-level scoring, TIM #3 and TIM #4 were held to review the data and conduct a "gut check" of the outcomes. To facilitate comprehension of trade scoring results, Jet Propulsion Laboratory (JPL)-developed visualizations of those results were prototyped, and the most effective were shared with the core team. *Pessimistic, Likely,* and *Optimistic* scores were generated after TIM #4 and incorporated into the final results.

## 6.4 Results

Task 1 results were reviewed and discussed at TIM #1. This provided the input for Tasks 2-4, which were conducted in parallel. The initial results of Tasks 2-4 were reviewed and discussed at TIM #2. Tasks 5 and 6 were reviewed and discussed internally within the core team at TIM #3 and TIM #4 before outbriefing stakeholders. The results of each of the assessment tasks are described in the following subsections.

### 6.4.1 Task 1 Results

A total of 25 candidate biocide systems were identified during Task 1. Despite the relatively high number of candidate systems, it was determined that there were only three biocidally active species within the scope of this assessment: silver, hypochlorite, and hypobromite ions (**F-1**).

The biggest benefit of using a silver-, chlorine-, or bromine-based biocide in a spacecraft potable water system is that these ions are safe to consume at concentrations that effectively inhibit proliferation of microorganisms in the system. Using a biocide that can be consumed eliminates the need for biocide removal hardware.

The outcome of Task 1 is presented in two parts. The first summarizes the findings related to bromine- and chlorine-based biocide systems. These systems were grouped together due to their similarities. The second focuses on the silver-based systems and is limited to systems that rely exclusively on a silver ion to inhibit microbial growth. The raw data collected for all biocide precursors are detailed in Appendix A. The following sections provide summaries of that data.

#### 6.4.1.1 Cl/Br Biocides

Most of the halide biocides are biocidal due to their oxidative nature with the hypochlorous ($ClO^-$) and hypobromous ($BrO^-$) ions and their associated acidic form: HClO and HBrO (Eq. 1) being the biocidal species. One of two methods produces the biocidal species: the solvation of the ionic salt, or the hydrolysis of a halide-containing species (Eq. 2).

$$HOX \rightleftharpoons H+ + XO- \;;\; X = Cl \text{ or } Br \qquad \textit{(Eq. 1)}$$

$$R\text{-}X + H2O \rightarrow R\text{-}H + HOX \;;\; X = Cl \text{ or } Br,\ R = Cl,\ Br, \text{ or organic} \qquad \textit{(Eq. 2)}$$

For the halide biocides, a primary issue of concern is their oxidative power. Although their oxidative characteristic makes them strong, broad-spectrum biocides, it also makes them extremely corrosive to many materials including metals. The acidic form HOX, is generally considered to be more corrosive than the ionic form $XO^-$ due to the pH dependence of the electrochemistry. This is an issue because the potable water on the ISS is slightly acidic (i.e., around pH 5), and the pH of potable water during future exploration missions is expected to be similar.

Finally, XO- is degraded by heat and light. This issue, although minimized by the current water processing and xEMU designs, can still be an issue due to the long storage life requirement of an exploration mission.

Twenty unique bromine- and chlorine-based biocides were identified during literature reviews are provided in Appendix A. Qualification criteria, as defined in Table 2, were applied to each of the biocides. The results of the qualification process are shown in Tables 10 and 11 for bromine and chlorine, respectively. Results of qualification criteria applied to chlorine and bromine biocide precursors.

Several biocidal precursors were unable to meet the Qualification Criteria of Table 2 and were disqualified from consideration for Tasks 2 through 4. The halide gases ($Cl_2$, $Br_2$, BrCl, and $ClO_2$) are toxic and stored under pressure. If released, they would be volume-filling within the crew cabin area and pose an extreme health hazard, thereby failing to meet Qualification Criteria 4. NaOCl, Halazone, and $NH_2Cl$ do not meet Qualification Criteria 5 based on limited shelf life. 2,2-dibromo-3-nitrilopropionamide and 2-bromo-2-nitropropane-1,2-diol are not approved for potable water use and do not meet Qualification Criteria 2 and 4. Domiphen bromide, although containing Br, is an ammonium biocide, which fails to meet the Cl/Br biocide scope of this task.

Calcium hypochlorite, sodium chlorite, succinchlorimide, and Chloramine-T all met several of the qualification criteria but had at least one issue each that required further investigation. Finally, sodium dichloroisocyanurate; di- and trichloroisocyanuric acid; 1-bromo-3-chloro-5,5-dimethylhydantoin; 1,3-dibromo-5,5-dimethylhydantoin; poly-1-bromo-5-methyl-5(4’vinylphenyl)-dimethylhydantoin, and Umpqua’s Halogen-binding resin met all qualification criteria and were initially considered for evaluation within Tasks 2 through 4.

*Table 10. Results of Qualification Criteria on Bromine-based Biocide*

| Option | Criteria | | | | |
|---|---|---|---|---|---|
| | Must not introduce a known risk to crew health at effective biocide concentrations | Must not require more than 3 years to begin flight demonstration/ implementation | Must be commercially available or can be made available quickly for evaluation in NASA ground systems | Must not be a Toxic Hazard Level 3 (storage or use) | Must not degrade/ become ineffective under storage conditions (non-use) for up to 3 years |
| Halogen-binding Resin (Umpqua) | PASS: released 0.5-4 mg/L Br over lifetime | PASS: currently at TRL 3 entering Phase II SBIR | PASS: is in NASA-funded testing | PASS | UNKNOWN: but probably remains effective if packaged and kept dry |
| Poly-1-bromo-5-methyl-5 (4'-vinylphenyl) Hydantoin (HaloPure BR) | PASS: 0.1-0.5 mg/L Br released | Unknown: Commercial bead filter product, should be largely plug-n-play | PASS | PASS | UNKNOWN: At least 2-year shelf life with desiccant, no data for 3 years |
| 1-bromo- 3-chloro- 5,5-Dimethylhydantoin (BCDMH) | PASS: max 9 mg/L | UNKNOWN | PASS | UNKNOWN: Contact dermatitis potential at certain concentrations, LD50 (rat, oral) = 1390 mg/kg | PASS: 3 years |
| 1,3-Dibromo-5,5-Dimethylhydantoin (DBDMH) | PASS | UNKNOWN | PASS: Sigma | LD50 (rat, oral) = 250 mg/kg | PASS: 3 years |
| Bromine ($Br_2$) | Not Evaluated | Not Evaluated | Not Evaluated | FAIL: Stored/compressed Bromine gas | Not Evaluated |
| Bromine Monochloride (BrCl) | Not Evaluated | Not Evaluated | Not Evaluated | FAIL: Toxic gas | Not Evaluated |
| 2,2-Dibromo-3-Nitrilopropionamide | UNKNOWN: Not yet tested for potable water use | UNKNOWN: Requires FDA approval first | PASS: Sigma and Dow/Aquacar | UNKNOWN: Requires FDA approval first | UNKNOWN: but probably remains effective if packaged and kept dry |
| 2-bromo- 2-nitropropane-1,3-diol | UNKNOWN: Not yet tested for potable water use | UNKNOWN: Requires FDA approval first | PASS: Sigma | UNKNOWN: Requires FDA approval first | UNKNOWN: but probably remains effective if packaged and kept dry |
| Domiphen Bromide | Out of scope | | | | |

*Table 11. Results of Qualification Criteria on Chlorine-based Biocide*

| Option | Criteria | | | | |
|---|---|---|---|---|---|
| | Must not introduce a known risk to crew health at effective biocide concentrations | Must not require more than 3 years to begin flight demonstration/ implementation | Must be commercially available or can be made available quickly for evaluation in NASA ground systems | Must not be a Toxic Hazard Level 3 (storage or use) | Must not degrade/become ineffective under storage conditions (non-use) for up to 3 years |
| Sodium dichloroisocyanurate | PASS: 1 mg/L | UNKNOWN | PASS: Aquatab | LD50 (Rat, oral) = 1670 mg/kg lowest published lethal dose (man, oral) = 3570 mg/kg | PASS: 3-5 years |
| Di- and Tri-chloroisocyanuric acid | PASS: max 30 mg/L | UNKNOWN | PASS: Sigma | LD50 (Rat, oral) = 406 mg/kg (Tri); for di-, refer to sodium dichloroisocyanurate | PASS: Indefinite if stored in cool, dry place |
| Sodium chlorite | PASS: 0.7 mg/L | UNKNOWN | PASS: Sigma | LD50 (rat, oral) = 165 mg/kg | PASS: based on reassay date on VWR certificate of analysis |
| Chloramine-T | PASS: 0.5-2.0 mg/L | UNKNOWN | PASS: Sigma | LDLo (rat, oral) = 935 mg/kg | PASS: tablets (Difisin) have at least 3-year shelf life |
| Calcium hypochlorite (Ca(OCl)2) | UNKNOWN: EPA-approved for emergency potable water disinfection (5 mg/L) | UNKNOWN | PASS: Sigma | Lowest published toxic dose (man, oral) = 143 mg/kg LD50 (rat, oral) = 850 mg/kg | PASS: 3-5 years |
| Chlorosuccinimide | PASS | UNKNOWN | PASS: Sigma | LD50 (rat, oral) = 1212 mg/kg LDLo (rat, oral) = 2700 mg/kg | UNKNOWN: probably, structure similar to hydantoin |
| Chlorine dioxide ($ClO_2$) | Not Evaluated | Not Evaluated | Not Evaluated | FAIL: Toxic (like Cl gas) | Not Evaluated |
| Chlorine ($Cl_2$) | Not Evaluated | Not Evaluated | Not Evaluated | FAIL: Stored/compressed Chlorine gas | Not Evaluated |
| Monochloramine ($NH_2Cl$) | Not Evaluated | Not Evaluated | Not Evaluated | Not Evaluated | FAIL: unable to store – must be mixed real-time from ammonia and chlorine |
| Sodium hypochlorite (NaOCl) | UNKNOWN: EPA-approved for emergency potable water disinfection (~6-8 mg/L) | UNKNOWN | PASS: Sigma | Lowest published toxic dose (woman, oral) = 1000 mg/kg LD50 (mouse, oral) = 5800 mg/kg | FAIL: low shelf life at 20 C; pentahydrate form can last 1+ years at 7 C |
| Halazone | PASS: typical dose 4 mg/L | UNKNOWN | PASS: Sigma | LDLo (rat, oral) = 3500 mg/kg LD50 (rat, oral) = 2000 mg/kg | FAIL: 5-6 months unopened, 3 days upon opening bottle |

#### 6.4.1.2 Silver Biocides

While some studies have attributed biocidal properties to other forms of silver, it is widely accepted that the active biocidal form is the silver ion ($Ag^+$). Biocide systems based on the silver ion have been used in terrestrial and spacecraft water systems and have been demonstrated to be effective against planktonic and sessile bacteria, fungi, and viruses. Multiple modes of biocidal action have been reported for the silver ion. These include:

- Disruption of cellular function by binding to thiol (-SH) and amine ($-NH_x$) functional groups on proteins and enzymes.
- Inhibition of the electron transport chain.
- Accumulation in cellular membranes, causing damage and leading to lysis.
- Interference with transport across cellular membranes.
- Promoting production of reactive oxygen species (ROS).

In addition to the benefits mentioned in Section 6.4.1 for non-iodine biocides, silver has the added benefit of maintaining a common biocide with international partners.

While there are advantages to using silver ion as a biocide in spacecraft water systems, there are also well-documented challenges (see Appendix A). The most notable of these is stability. Silver ion is an electrochemically active species with a standard reduction potential of + 0.80 V vs. the normal hydrogen electrode. This is significantly more positive than the reduction potentials of other metals commonly found in spacecraft water systems. When solutions containing silver ions come in contact with materials that contain metals with lower reduction potentials, the silver ion will deposit on the material and oxidize the metals in the underlying surface. Another notable challenge to using silver ions in spacecraft water systems is that silver salts tend to be non-volatile. While this can help minimize losses due to evaporation, it also means that silver ions will concentrate in an evaporative system (e.g., xEMU cooling loop). This can cause material compatibility issues and, in extreme cases, could result in precipitation which can occlude fluid channels and cause failures in components with tight tolerances resulting in Criticality 1R catastrophic loss of heat rejection during an EVA.

Five candidate biocide systems based on silver ion were identified during Task 1. Since the active biocidal species (i.e., silver ion) is the same for all systems, each option below represents a different approach to adding silver ions to solution. The five candidate systems were: Injection of Silver Salt Solutions, Controlled Release of Silver Ions, Electrolytic Generation of Silver Ions, Ion Exchange, and Nanoparticle Impregnated Materials. A list of references for these systems is provided in Appendix A. The qualification criteria defined in Table 2 were used to evaluate each of the systems. The results of that evaluation are shown in Table 122.

Of the silver-based systems identified and evaluated during Task 1, only Nanoparticle Impregnated Materials were eliminated from further consideration based on the qualification criteria in Table 1. After reviewing the available literature, the assessment team had concerns that the SOA for the materials was not sufficiently mature to begin a flight demonstration within 3 years. There were also concerns about the long-term stability of the impregnated materials. Since this system failed to meet qualification criteria 3 and 5, it did not proceed for further evaluation in Tasks 2 through 4.

The other four silver-based candidate biocide systems met all or most of the qualification criteria and were identified for evaluation within Tasks 2 through 4. As shown in Table 122, Controlled

Release of Silver Ions, Electrolytic Generation of Silver Ions, and Ion Exchange all had unknowns listed for at least one qualification criteria. While some data may have been missing for these candidate systems, the task team felt the risk was sufficiently low, or the missing data could be generated, so the Controlled Release of Silver Ions, Electrolytic Generation of Silver Ions, and Ion Exchange systems were advanced for further evaluation.

*Table 12. Results of Qualification Criteria on Silver-based Biocide*

| Option | Criteria | | | | |
|---|---|---|---|---|---|
| | Must not introduce known risk to crew health at effective biocide concentrations* | Must not require more than 3 years to begin flight demonstration/ implementation | Must be commercially available or can be made available quickly for evaluation in NASA ground systems | Must not be a Toxic Hazard Level 3 (storage or use) | Must not degrade/ become ineffective under storage conditions (non-use) for up to 3 years |
| Injection of Ag Salt Solutions (AgF/$AgNO_3$) feasible based on storage concentration | PASS: Target concentration = 100-400ug/L | PASS: Already implemented—manual, would want to develop an automated approach | PASS: Commercially Available | PASS | PASS: Stable in syringes > 7 years |
| Controlled Release Silver | PASS: Target concentration = 100-400ug/L | PASS: In development by ELS Technologies via Phase II SBIR, and through KSC internal development | PASS: In NASA-funded testing | PASS | UNKNOWN: But vendor claims compatible with various sterilization techniques including UV and gamma irradiation (so probably OK for 3 years) |
| Electrolytic Generation of Silver | PASS: Target concentration = 100-400ug/L | PASS: Current Phase II SBIR with Reactive Innovations | PASS: Commercial uses in swimming pools, hospitals, etc. Commercial product = Electro-Katadyn | PASS | UNKNOWN: Appears to be rugged, but replacement anodes are available—suggests necessary replacement |
| Ion Exchange IX Bed/Cartridge | PASS: Target concentration = 100-400ug/L | Unknown: Would require development for implementation—no one currently on contract. Challenges in controlling release need to be solved. | PASS: AphaSan and AgIon - surface coatings, zeolite-based systems that rely on exchange of Na+ with Ag+ | PASS | UNKNOWN: But should be stable given chemical/ mechanical make-up |
| Nanoparticle Impregnated Materials | PASS: Target concentration = 100-400ug/L | FAIL: Not sufficiently developed and characterized | UNKNOWN: Commercially available options, but none that have been tested and approved | UNKNOWN: conflicting reports | FAIL: Available data shows no product that will not degrade |

#### 6.4.1.3 Task 1 Outcomes

Following the full review of bromine, chlorine, and silver biocides, 15 biocides, plus iodine, were selected for review (**F-2**) by the Task 2, 3, and 4 teams. Nearly all of the biocides had unknowns to be evaluated, as shown in Table 13.

***Table 13. Biocides Selected for Evaluation in Tasks 2, 3, and 4***

| # | Option | Biocide | Remaining Unknowns |
|---|---|---|---|
| 1 | Iodine-binding resin (Umpqua) – State-of-the-art | $I_2/I^-$ | None |
| 2 | Halogen-binding resin (Umpqua) | OBr- | Stability |
| 3 | Poly-1-bromo-5-methyl-5(4' -vinylphenyl)hydantoin (HaloPure BR) | OBr- | Flight Readiness, Stability |
| 4 | AgF salt solution | Ag+ | None |
| 5 | $AgNO_3$ salt solution | Ag+ | None |
| 6 | Controlled Release (AgCl) | Ag+ | Stability |
| 7 | Electrolytic generation of silver | Ag+ | Stability |
| 8 | Ion exchange IX bed/cartridge | Ag+ | Flight Readiness, Stability |
| 9 | 1-bromo- 3-chloro- 5,5-dimethylhydantoin (BCDMH) | OBr- | Flight Readiness, THL 3 |
| 10 | 1,3-Dibromo-5,5-Dimethylhydantoin (DBDMH) | OBr- | Flight Readiness, THL 3 |
| 11 | Sodium dichloroisocyanurate | OCl- | Flight Readiness, THL 3 |
| 12 | Trichloroisocyanuric acid, (and dichloroisocyanuric acid) | OCl- | Flight Readiness, THL 3 |
| 13 | Sodium chlorite | OCl- | Flight Readiness, THL 3 |
| 14 | Chloramine-T | OCl- | Flight Readiness, THL 3 |
| 15 | Calcium hypochlorite (Ca(OCl)2) | OCl- | Crew Health, Flight Readiness, THL 3 |
| 16 | Chlorosuccinimide | OCl- | Flight Readiness, THL 3, Stability |

### 6.4.2 Task 2 Results

#### 6.4.2.1 Task 2a: Toxicity Hazard Level

The THL for each biocide candidate was assessed per standard procedures [ref. 8]. None of the biocide candidates constituted a THL greater than 2.

Iodine has a history of use on ISS and is generally flown as embedded in a wetted resin. The nature of this product led the assessment team to conclude that exposure to the eye is not plausible for the resin particle, and this format was judged to be a THL 0.

Four delivery methods for silver in the xEMU have been proposed: a) introduction of silver salts ($AgF/AgNO_3$), b) controlled release, c) electrolytic generation of silver, and d) ion bed exchange. Ion bed exchange and controlled release are similar from an exposure perspective, especially in the context of setting a THL.

Concentrated silver nitrate (CASRN 7761-88-8) can cause severe eye damage that may cause blindness [refs. 9 and 10]. Silver nitrate at 5-50% causes permanent eye damage with dose-dependent effects that include marked edema and bloody discharge from the conjunctiva. Similar effects are seen whether the silver nitrate is in liquid or solid form. These effects are consistent with a THL assignment of 2, indicative of long-term effects and significant tissue damage.

Much less toxicological information is available on silver fluoride (CASRN 7775-41-9) in the proposed implementation. While generally assessed as a THL 0, the assessment team viewed the chemical as a THL 1 based on available data for the specific technology. Further, a report from the U.S. Coast Guard [ref. 18] indicates that the substance is irritating to eyes and skin. This is consistent with a THL of 1 or 2.

Electrolytic generation of silver involves a solid silver electrode, and in that form silver (e.g., silver-plated on steel) would be judged a THL 0. However, the electrolyte solution may require a separate toxicological assessment.

Similarly, the use of silver embedded in a matrix (e.g., polymer or resin for controlled release or ion bed exchange), regardless of the silver compound used, would be expected to present a THL of 0, assuming that particulate matrices are flown wetted. If dry particulates that were impregnated with silver nitrate were to be flown, a worst case scenario would result in a THL 2.

Chlorinated isocyanuric acid conjugates were assessed as a THL 1 as a worst case, as they cause relatively minor, reversible eye irritation in rabbits. Chloramine-T was also judged to be a THL 1, while the severe eye and skin effects that can be caused by sodium chlorite and calcium hypochlorite amount to a THL 2. Chlorosuccinamide is a THL 2, as it carries a risk of blindness following eye exposure.

All three brominated candidates were assessed as a THL 2, as they are understood to cause irreversible eye damage. HaloPureBR, if flown wetted, might be evaluated differently as exposure to the eye in such a scenario would be considered unlikely.

To reiterate, none of the hazardous effects associated with an in-flight release of the biocide candidates constitutes a THL of greater than 2. Thus, each of the candidates can be considered as having passed this criterion (**F-3**). It is relatively common for NASA and external payload providers to launch THL 2 substances to ISS for safe use them safely on-orbit.

As noted, all THL assessments in this exercise should be considered preliminary, as the specific application, form, and concept of operations for the biocide will dictate the final determination on safety.

#### 6.4.2.2 Task 2b: Long-Term Health Effects

No identified candidate biocides are expected to cause significant long-term health issues **(F-4).** However, some biocides are lacking detailed data on long-term exposures and were given lower scores for data availability on that basis. The potential impacts of long-term exposure to silver are best understood in a spaceflight context, as the SWEG is available [ref. 11].

Assuming that iodine will be removed prior to consumption, it would pose no health risk under a long-term exposure scenario. If exposure to small volumes of iodinated water were to occur infrequently and rarely, it would be unlikely to pose a risk to short- or long-term health.

Chlorine is used in municipal water disinfection, and numerous chemical risk assessments and safety values are available. Consumption of chlorine at the effective concentration is not expected to pose a risk to crew health in the short or long term. The chemical substances that impart chlorine to the water (e.g., isocyanuric acid, succinamide, chloramine-T) are not expected to pose a long-term health risk, but no concrete data are available.

Bromine as a disinfecting agent for drinking water has been examined, and available assessments [refs. 19, 20, 21] indicate that no long-term health effects would be expected from consuming brominated water at the effective concentration. However, a SWEG will be necessary if bromine proves a viable option for spaceflight (**F-5**). Similar to chlorinated substances, the candidate brominated substances (e.g., dimethylhydantoins) would not be expected to carry significant risk for long-term health effects.

For the sake of clarity, the risk of renal stone development could be considered a long-term health risk related to reduced water consumption. However, the scope of this subtask is such that it relates only to exposure to the candidate biocides as opposed to potential secondary effects. The risk of renal stone development is discussed further in relation to Task 2C (Palatability) and in Appendix B.

#### 6.4.2.3 Task 2c: Palatability

Consumption of water treated with silver, chlorine, or bromine is expected to pose some palatability issues for crew members. In particular, chlorine and bromine have pungent odors that may be noisome, though there is evidence of adaptation [ref. 22] for chlorinated water. Disinfection of drinking water through chlorination has a history in developed countries, and its palatability is better understood. However, chlorine levels in treated drinking water fall as they approach the point of consumption, per design of municipal infrastructure. Bromine may pose a larger palatability concern. Silver has been consumed on the Russian segment of ISS, and its palatability issues appear to be manageable based on its continued use. Iodinated water also has palatability issues with taste at the effective concentration, but for the purposes of this exercise it was assumed that iodine would be removed prior to consumption.

The palatability of brominated water constitutes a data gap, as there are no systematic data to support a robust judgment (**F-6**). There is currently no data on whether crew would encounter palatability concerns that would affect their consumption rate. The primary concern would be falling consumption leading to an increased risk of renal stones in crew members on long-term exploration missions (e.g., Lunar or Mars).

#### 6.2.4.4 Scoring

Scoring for crew health impacts is shown in Table 14. The candidate biocides that were assigned the highest scores were iodine (5/5, 15/15), and silver from electrolysis (5/5, 14/15) or controlled release/ion exchange (5/5, 14/15). Two of the chlorinated candidates (isocyanuric acid conjugates (4/5 and 12/15)) scored high, though all of the chlorinated and brominated candidates received lower scores in the aggregate rubric for palatability. Brominated candidates scored lowest (3/5, 10-11/15) because of higher THLs, poor palatability, and data availability scores.

*Table 14. Crew Health Scores for Candidate Exploration Biocides*

| Candidate | AER (0-5) | Aggregate (1-15) | Palatability (1-4) | Toxicity Hazard Level (0-4) | Long-term Health Effects (1-4) | Data Availability (1-3) |
|---|---|---|---|---|---|---|
| **Iodine** | 5 | 15 | 4 | 4 | 4 | 3 |
| **Silver** | | | | | | |
| Electrolytic silver | 5 | 14 | 3 | 4 | 4 | 3 |
| Slow release silver | 5 | 14 | 3 | 4 | 4 | 3 |
| AgF | 4 | 13 | 3 | 3 | 4 | 3 |
| AgNO3 | 4 | 12 | 3 | 2 | 4 | 3 |
| **Chlorine** | | | | | | |
| Sodium diisocyanura | 4 | 12 | 2 | 3 | 4 | 3 |
| Di- and tri-chloroiso | 4 | 12 | 2 | 3 | 4 | 3 |
| Sodium chlorite | 3 | 11 | 2 | 2 | 4 | 3 |
| Chloramine-T | 3 | 10 | 2 | 3 | 3 | 2 |
| Calcium hypochlorit | 3 | 11 | 2 | 2 | 4 | 3 |
| Chlorosuccinamide | 3 | 10 | 2 | 2 | 4 | 2 |
| **Bromine** | | | | | | |
| BCDMH | 3 | 10 | 2 | 2 | 4 | 2 |
| DBDMH | 3 | 10 | 2 | 2 | 4 | 2 |
| HaloPureBR | 3 | 11 | 2 | 2 | 4 | 3 |

Detailed scoring and narrative rationales for the scores are available in Appendix B. Alternative approaches to scoring were considered, including the use of a pass-fail criterion for THL, as the original scope had been to exclude any candidate which was assigned a THL of 3 or 4. It is common on ISS to fly substances that are assigned THLs of 2.

In summary, none of the candidates for exploration biocides in system and drinking waters carry significant toxicological concerns based on the assumptions as described and the ConOps as characterized. The primary discriminator is palatability. Chlorine and bromine as disinfectants appear to carry palatability concerns.

### 6.4.3 Task 3 Results

The evaluated criteria for the candidate biocides were scored by xEMU sub-team members using the scoring definitions in Table 4. The scores for each evaluated criteria per candidate biocide are shown in Table 15.

*Table 15. xEMU Subsystem Scoring Results*

| Candidate | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 16) Iodine / Triiodide | 4 | 4 | 4 | 1.7 | 5 | 4 | 5 | 5 | 4.3 | 5 |
| 5) Ionic silver (flow-through IX bed) | 2 | 2.8 | 2 | 5 | 3.3 | 4 | 3 | 3.7 | 2.7 | 1.3 |
| 6) Bromine/Tribromide | 0.6 | 0.6 | 1.8 | 1.7 | 4.3 | 4 | 5 | 4 | 2.7 | 3.3 |
| 4) Ionic silver (electrolytic) | 2 | 3 | 2 | 5 | 2.3 | 3 | 2 | 2 | 2 | 2.7 |
| 3) Controlled release salt solution (silver) | 2 | 2.8 | 2 | 5 | 4 | 2 | 2 | 1 | 2 | 2.7 |
| 2) Silver nitrate (AgNO3) salt solution | 2 | 2.8 | 1.6 | 5 | 2.7 | 2 | 2 | 2.3 | 2 | 2 |
| 7) Poly-1-bromo-5-methy;-5 (4'-vinylphenyl) hydantoin (HaloPure BR) | 0.6 | 0.4 | 1.2 | 3.3 | 3.7 | 3 | 4 | 2.7 | 1.3 | 2 |
| 1) Silver fluoride (AgF) salt solution | 1.2 | 1.6 | 1.2 | 5 | 2.3 | 2 | 2 | 2.3 | 1.3 | 2 |
| 9) 1,3-Dibromo-5,5-dimethylhydantoin (DBDMH) | 0.2 | 0.4 | 0.6 | 2.7 | 3.7 | 3 | 4 | 2.7 | 1.3 | 2 |
| 13) Chloramine-T | 0.8 | 1.6 | 0.4 | 2.7 | 3.7 | 3 | 4 | 3 | 0 | 0.3 |
| 15) Chlorosuccinimide | 0.8 | 1.6 | 0.4 | 2.7 | 3.7 | 3 | 4 | 3 | 0 | 0.3 |
| 10) Sodium dichloroisocyanurate | 0.8 | 1.6 | 0.4 | 1.7 | 3.7 | 3 | 4 | 3 | 0 | 0.3 |
| 8) 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH) | 0.2 | 0.4 | 0.6 | 2.3 | 3.7 | 3 | 4 | 2.7 | 0.7 | 0.7 |
| 11) Trichloroisocyanuric acid (and dichloroisocyanuric acid) | 0.8 | 1.6 | 0.4 | 1 | 3.7 | 3 | 4 | 3 | 0 | 0.3 |
| 14) Calcium hypochlorite ($Ca()Cl)_2$) | 0.8 | 1.6 | 0.4 | 1 | 3 | 2 | 2 | 1 | 0 | 0.3 |
| 12) Sodium chlorite ($NaClO_2$) | 0.8 | 1.6 | 0.4 | 1 | 3 | 2 | 2 | 1 | 0 | 0.3 |

Cumulative scores for each biocide and related comments are shown in Table 16. Sixteen biocides were evaluated for the xEMU TCL application, based on 10 evaluation criteria using a numerical scoring process. The baselined biocide for this application (i.e., iodine/triiodide) accumulated the highest score, which was expected considering the design, operation, and material selections for the xEMU evolved with the use of this biocide as a requirement. In general, silver-based biocides scored relatively well, but present significant design challenges and degradation risks in the xEMU TCL, including rapid biocide loss, materials compatibility, and increased operational complexity with increased risk of acute (catastrophic) failure of the thermal loop function during EVA (**F-7**). In general, chlorinated and brominated biocides scored lower and present substantial materials compatibility risks that would drive significant design challenges for the xEMU as outlined in Appendix C (**F-8**).

*Table 16. Hierarchy of Candidate Biocides for xEMU, from Highest to Lowest Cumulative Score*

| Candidate | Score | Comments |
|---|---|---|
| Iodine/Triiodide | 42 | Effective biocide, EMU/xEMU experience, system designed with this biocide as baseline, minimal program impact, may not support the "single biocide" for future water systems goal |
| Ionic Silver (flow-through bed) | 29.8 | Effective, broad-range biocide, minimal system complexity, but immature technology |
| Bromine/Tribromide | 28 | Existing flow-through bed technology, minimal system complexity |
| Ionic Silver (electrolytic) | 26 | Effective, broad-range biocide, technology under development through NASA |
| Controlled Release Salt Solution (silver) | 25.5 | Counter-ion or complex not identified with this candidate |
| Silver Nitrate ($AgNO_3$) Salt Solution | 24.4 | Additional materials compatibility risk due to the counter-ion |
| Poly-1-bromo-5-methyl-5 (4'-vinylphenyl) hydantoin | 22.2 | Materials compatibility and system complexity risks and challenges |

| | | |
|---|---|---|
| Silver Fluoride (AgF) salt solution | 20.9 | Additional materials compatibility risk due to counter ion |
| 1,3-Dibromo-5,5-dimethylhydantoin (DBDMH) | 20.6 | Materials compatibility and system complexity risks and challenges |
| Chloramine-T | 19.5 | |
| Chlorosuccinimide | 19.5 | |
| Sodium dichloroisocyanurate | 18.5 | |
| 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH) | 18.3 | |
| Trichloroisocyanuric acid (and dichloroisocyanuric acid) | 17.8 | |
| Sodium chlorite ($NaClO_2$) | 12.1 | |
| Calcium hypochlorite ($Ca(OCl)_2$) | 12.1 | |

### 6.4.4 Task 4 Results

Table 17 contains a compiled summary of a preliminary assessment of biocide impacts on the LS potable water system across the areas of consideration outlined. The results are qualitative only and color-coded according to the level of perceived of risk in development and/or implementation. The dark green squares indicate areas of no perceived issue and/or risk, light green indicates a minimal issue or risk, yellow is a moderate issue or risk, and red indicates an area perceived to be of significant issue or risk.

***Table 17. Preliminary Assessment Matrix for Vehicle LS Subsystem Operational Considerations***

| Biocide | Maintain Conc. | Dosing | Simplicity | TRL | Mass | Reliability | Storage | Material Comp. | Dormancy |
|---|---|---|---|---|---|---|---|---|---|
| Iodine | | | Requires ACTEX | | | | | | |
| Silver | Plating | | | | | | | | |
| Bromine | | | | | | | | | |
| Chlorine | | | | | | | | | |

Although a quantitative evaluation was not attempted, iodine has the fewest perceived issues or risks associated with its implementation. This result would be expected, as iodine is the SOA and many of the challenges associated with this technology are known. Based on ISS experience, there is a solid understanding of the technology for dosing, TRL, mass, and storage. A disadvantage of iodine is that it can be reactive with metal surfaces found in the LSS, potentially resulting in the loss of the biocidal form over time. In addition, iodine is known to adsorb onto non-metallic surfaces, resulting in biocide effectivity losses. Maintaining the biocide can be an issue, especially during dormancy. In addition, from a LS perspective, iodine is highly undesirable for future missions due to the requirement for its removal prior to human consumption. This requirement leaves the most vulnerable section of the water system without a residual biocide at or near the use point. This is the section of the system where the crew interfaces with the water system, and it is therefore most susceptible to contamination due to contact with the dispensing needle by crew, food, and drink bags. Similarly, the lack of biocide in this section of the system presents a significant issue/concern, especially related to transition of the water system into dormancy.

Silver is an effective biocide, consumable at biocidal concentrations. This has the potential to save mass, volume, and logistics over iodine, as additional hardware is not required to remove the biocide prior to use. In addition, being consumable, silver can be carried as a residual through to the entire water system from its introduction prior to storage to the use point. This provides an additional layer of protection for the system during use and for transition into dormancy. Finally, silver offers the potential for a common biocide, as Russia currently uses silver as a biocide as well as a number of other international partners. However, silver is known to deposit on surfaces. This would require development to ensure plating does not reduce concentration below the minimum inhibitory concentration (MIC) or affect the function of components in the potable bus. Similarly, work to establish and verify the dosing method is necessary.

Bromine is also an effective biocide, though it has not been fully researched to characterize compatibility with potable water or EMU applications. Similarly, the biocidal efficacy of bromine needs to be understood as a function of pH, to ensure buffering will not be needed at the pH level expected for the potable water system. Additionally, the dosing technology[1], though promising, is still under way. There may also be issues with palatability and, although not expected to be an issue, a formal SWEG has not been established to ensure bromine will be accepted as a consumable biocide. Finally, robust materials selection and possibly pH buffering/monitoring may be required to prevent corrosion (**F-9**).

Chlorine is not a desirable alternative because there is no current means for dosing, and because concerns exist about long-term storage and materials compatibility (**F-10**).

Based on this assessment, the preferred ordering for the potable water LS perspective would likely be silver > bromine > iodine > chlorine. (**F-11**)

### 6.4.5 Task 5 Results

The initial architectures from TIM #2 were expanded as described in Section 6.3.5. As mentioned, concerns with chlorine dosing, material compatibility, and storage challenges identified in Tasks 3 and 4 led the core team and stakeholders to unanimously agree to eliminate chlorine and chlorine-based architectures from further investigation within this assessment. If future consideration of chlorine is desirable, then more testing is needed on material compatibility, dosing, and other identified shortcomings. The resulting architecture options are listed in Table 18, with a brief description of each.

[1] Unpublished data.

*Table 18. Architecture Option List*

| # | Description |
|---|---|
| 1 | $I_2$ with design change to PWD to achieve iodine removal at or closer to nozzle |
| 2 | $I_2$ with replaceable “end leg” of PWD as a consumable |
| 3 | Electrolytic Silver |
| 4 | Electrolytic Silver + monitoring |
| 5 | Passive Release Silver (ELS or Foam) |
| 6 | Passive Release Silver + monitoring |
| 7 | Concentrated Salt Solution Silver |
| 8 | Concentrated Salt Solution Silver + monitoring |
| 9 | 1,3-Dibromo-5,5,dimethylhydantoin (DBDMH) solution (cleaved by hydrolysis) |
| 10 | DBDMH solution + buffer |
| 11 | DBDMH solution + buffer + monitoring (OBr- & pH) |
| 12 | Umpqua Passive Release |
| 13 | Umpqua Passive Release + buffer |
| 14 | Umpqua Passive Release + buffer + monitoring (OBr- & pH) |
| 15 | HaloPur BR Passive Release |
| 16 | HaloPur BR Passive Release + buffer |
| 17 | HaloPur BR Passive Release + buffer + monitoring (OBr- & pH) |
| 18 | $I_2$ for xEMU & Electrolytic Silver for vehicle LS |
| 19 | $I_2$ for xEMU & Electrolytic Silver + monitoring for vehicle LS |
| 20 | $I_2$ for xEMU & Passive Release Silver (ELS or foam) for vehicle LS |
| 21 | $I_2$ for xEMU & Passive Release Silver + monitoring for vehicle LS |
| 22 | $I_2$ for xEMU & Concentrated Salt Solution Silver for vehicle LS |
| 23 | $I_2$ for xEMU & Concentrated Salt Solution Silver + monitoring for vehicle LS |
| 24 | $I_2$ for xEMU & DBDMH solution for vehicle LS |
| 25 | $I_2$ for xEMU & DBDMH solution + buffer for vehicle LS |
| 26 | $I_2$ for xEMU & DBDMH solution + buffer + monitoring (OBr- & pH) for vehicle LS |
| 27 | $I_2$ for xEMU & Umpqua Passive Release for vehicle LS |
| 28 | $I_2$ for xEMU & Umpqua Passive Release + buffer for vehicle LS |
| 29 | $I_2$ for xEMU & Umpqua Passive Release + buffer + monitoring (OBr- & pH) for vehicle LS |
| 30 | $I_2$ for xEMU & HaloPur BR Passive Release for vehicle LS |
| 31 | $I_2$ for xEMU & HaloPur BR Passive Release + buffer for vehicle LS |
| 32 | $I_2$ for xEMU & HaloPur BR Passive Release + buffer + monitoring (OBr- & pH) for vehicle LS |
| 33 | $I_2$ Exploration PWD with shortened non-biocide legs and no “dead legs.” Otherwise ISS-like. |

### *Option 1: $I_2$ with Design Change to PWD to Achieve Iodine Removal at or Closer to Nozzle*

The Option 1 architecture assumes ISS-like application of iodine in the xEMU and LSS systems, with two exceptions. First, for Exploration, the xEMU team is targeting removal of the bacteria filtration assembly in the UIA, which would eliminate biocide dosing between the LSS and xEMU systems. Potable water would be directly transferred from LSS to xEMU without separate processing. Second, to address the potential issue of microbial growth in the non-iodinated portion of the PWD, this architecture assumes that the ACTEX/deiodination filter is moved from its location upstream of the water heater, adjacent to the dispensing needle where the crew obtains water. The benefit of this approach is that all volumes of the potable water system without biocide will be eliminated except the dispensing needle. This architecture requires demonstration of a new iodine removal media that is effective at the elevated temperatures of crew "hot" water.

***Option 2: I2 with Replaceable "End Leg" of PWD as a Consumable***

The Option 2 architecture assumes ISS-like application of iodine in the xEMU and LSS systems, with two exceptions. As mentioned in Option 1, Exploration xEMU architecture will target removing the iodine removal/redosing system at the interface between the LSS and EMU. Option 2 will also eliminate the need for separate processing between the two systems. Second, Option 2 will involve a PWD design that allows the non-biocided volume to be removed and replaced as needed. The key benefit is that in the event of dangerous microbial contamination and/or growth, those volumes can be discarded and a pre-disinfected replacement installed. This also provides a solution for dormancy in which a wetted PWD is removed prior to placing the LSS in dormancy, and a fresh or refurbished PWD is installed upon crew return.

***Options 3-8: Common Silver Biocide Architecture Considerations***

There are three common architectural changes for all silver-based biocide architectures. First, the deiodination filter in the PWD would be eliminated. Second, a microbial check valve that generates silver (MCV-Ag) would be required to replace the iodine MCV (MCV-$I_2$) used in locations throughout the ISS architecture. Third, ACTEX filters at the inlet of the OGA and UWMS would require evaluation of their performance in capturing $Ag^+$. It should be noted that silver removal media has been flown on ISS, but design modifications may be required to provide sufficient protection for downstream components.

During review of the ongoing efforts to develop silver technology, it was observed that current studies largely focus on the depletion of silver in solution in contact with different materials. However, the analysis and impact of silver on metallic and non-metallic materials is noted and largely ignored (**O-2**). More data are needed to understand where and under what conditions plating forms on the internal components, what type and degree of degradation can be expected, and what system changes would be required to prevent or adequately mitigate the degradation.

***Option 3: Electrolytic Silver***

JSC engineers have developed a custom-designed silver electrolysis dosing system [ref. 12]. In this architecture, the iodine resin would be removed from the existing IEB and the electrolytic silver dosing hardware would be placed in-line and downstream. The unit requires a power supply (low wattage) and controller.

***Option 4: Electrolytic Silver with Silver Monitoring***

Option 4 is identical to Option 3 with the added capability of silver monitoring. One concern with silver approaches is the risk of silver plating throughout the system. A monitor would provide a measurement of biocide concentration at one or more locations within the system. The monitor would require a power supply and controller that may or may not be combined with the electrolysis unit controller. This architecture assumes active, real-time control of the electrolytic silver hardware to modify silver ion generation based on the results of the silver monitor. It is assumed that the monitor will require periodic calibration.

*Option 5: Passive Release Silver*

In Option 5, the architecture assumes elimination of the iodine resin in the IEB and downstream integration of a passive release silver system. Two options are in development, including a silver chloride foam at Kennedy Space Center (KSC) and a Small Business Innovative Research (SBIR) contract with ELS Technology made from a solid-phase reagent. Because of the passive nature of these approaches, it is assumed they would provide the primary dosing and serve as the MCV-Ag to replace the MCV-$I_2$ application. It is also assumed that the chloride counter-ion will be changed to a counter-ion more compatible with materials as part of continuing development by both KSC and ELS.

*Option 6: Passive Release Silver with Silver Monitoring*

Option 6 is identical to Option 5, with the added capability of silver monitoring. As mentioned, the monitor would require a power supply, controller, and periodic calibration. For this architecture it was assumed that the monitor would be used to provide active control of biocide in solution. Therefore, a secondary approach would be required in the event additional silver dosing was required.

*Option 7: Concentrated Silver Salt Solution*

Option 7 assumes that a silver salt solution is used to actively meter biocide into the water system. This approach requires dosing hardware (e.g., reservoir, pump, and metering valve) and an associated controller.

*Option 8: Concentrated Silver Salt Solution with Monitoring*

Option 8 is identical to Option 7, with the added capability of silver monitoring. As mentioned, the monitor would require a power supply, controller, and periodic calibration. For this architecture it was assumed the monitor would provide active control of biocide in solution.

*Options 9-17: Common Bromine Biocide Architecture Considerations*

There are three common architectural changes for all bromine-based biocide architectures. First, these architectures assume the deiodination filter in the PWD can be eliminated. Second, a MCV that generates hypobromite (MCV-Br) will be required to replace the iodine MCV (MCV-I2) used in locations throughout the ISS architecture. Third, ACTEX filters at the inlet of the OGA and UWMS will need to be evaluated for their performance in capturing bromine. It is possible that new materials or design modifications would be required to provide sufficient protection for downstream components.

*Option 9: DBDMH Solution*

Option 9 assumes DBDMH solution is metered into the system similar to the way a silver salt solution would be in Options 7 and 8 (e.g., reservoir, pump, and metering valve) with an associated controller.

*Option 10: DBDMH Solution with Buffer*

Based on the effective pH range of bromine as a biocide and concerns with unbuffered bromine causing corrosion, Option 10 assumes that DBDMH is co-introduced with a buffer in solution. Further, this option assumes that the biocide is effective in the LS water system pH range.

### *Option 11: DBDMH Solution with Buffer and Monitoring*

Option 11 is identical to Option 10 with the added capability of monitoring. This assumes bromine and pH monitoring are required for successful implementation of the architecture. Additionally, a controller is assumed to provide active, real-time control of biocide concentration based on monitoring results.

### *Option 12: Umpqua Passive Release Bromine*

An SBIR contract is ongoing with Umpqua Research Company to develop a bromine-based resin similar to their iodine resin used in MCV-I2 and the ISS IEB. Option 12 assumes that the Umpqua Passive Release Bromine resin would be a direct replacement for the iodine resin for the IEB and MCVs.

### *Option 13: Umpqua Passive Release Bromine with Buffer*

Option 13 is identical to Option 12, with the exception that buffer is co-produced with bromine during flow-through of the bromine resin material.

### *Option 14: Umpqua Passive Release Bromine with Buffer and Monitoring*

Option 14 is identical to Option 13, with the added capability of monitoring. This assumes bromine and pH monitoring are required for successful implantation of the architecture. However, to have active control to introduce additional biocide, a secondary active dosing approach would be required.

### *Option 15: HaloPur BR Passive Release*

Option 15 is identical to Option 12 except that HaloPur BR passive release material is used instead of the Umpqua material.

### *Option 16: HaloPur BR Passive Release with Buffer*

Option 16 is identical to Option 13 except that HaloPur BR passive release material is used instead of the Umpqua material.

### *Option 17: HaloPur BR Passive Release with Buffer and Monitoring*

Option 17 is identical to Option 14 except that HaloPur BR passive release material is used instead of the Umpqua material.

### *Options 18-32: Mixed Biocides*

Results from subsystem evaluation of the biocides showed a distinct advantage for xEMU hardware to use iodine. For Options 18-32, the architectures assumed two biocides were used across subsystems: iodine for xEMU and Options 3-17 for the vehicle LSS. This added complexity when considering integration of the two subsystems. Specifically, these architecture options added the BFAs into the UIA architecture to 1) remove vehicle LSS biocide and add iodine biocide for feed water to the xEMU water bladders and 2) remove iodine biocide and add vehicle LSS biocide for wastewater returning to the vehicle LSS.

### *Option 33: Exploration PWD with Shortened Non-biocide Legs and No "Dead Legs," Otherwise ISS-like*

Option 33 is being pursued by the ISS Program based on observations of ISS hardware. Specifically, the PWD is known to have "dead legs" where water does not routinely flow.

Concerns with microbial growth in these legs led to a redesign effort to eliminate tubing that was no longer required as part of PWD operations. This architecture assumes iodine biocide in an ISS-like configuration following removal of the PWD dead legs.

Data from Tasks 1-4 were compiled, assumptions documented, and scores normalized for each of the seven criteria described. An important note is that none of the architecture options for Exploration have the data necessary to understand the impacts in each area. Assumptions were made based on current understanding of the technology and engineering judgement on the likelihood of development activity success **(O-3)**. A summary of baseline scores for each criteria are shown in Table 19. Specific subsystem scores and detailed assumptions for each value can be found in Appendix F.

## Table 19. Summary of Criteria Scores for All Biocide Architectures

| Option # | Description | 1: Minimal M/P/V Increase | 2: Minimal Schedule Increase | | | 3: Minimal Cost Increase | 4: Operational Simplicity | 5: Low Crew Health Risk | 6: Low Maturation Risk | 7: Sustaining Engineering |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | ECM Mission (2027) | FSH Mission (2029) | Best Technical | | | | | |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 4 | 2 | 3 | 0 | 5 | 3 | 5 | 2 | 4 |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 3 | 2 | 3 | 0 | 5 | 3 | 5 | 3 | 3 |
| 3 | Electrolytic Silver | 3 | 1 | 2 | 0 | 3 | 2 | 5 | 2 | 4 |
| 4 | Electrolytic Silver + Monitoring | 2 | 0 | 2 | 0 | 2 | 2 | 5 | 2 | 4 |
| 5 | Passive Release Silver (ELS or Foam) | 4 | 0 | 2 | 0 | 4 | 2 | 5 | 1 | 4 |
| 6 | Passive Release Silver + Monitoring | 1 | 0 | 2 | 0 | 2 | 2 | 5 | 1 | 3 |
| 7 | Concentrated Salt Solution Silver | 2 | 1 | 2 | 0 | 3 | 2 | 4 | 2 | 3 |
| 8 | Concentrated Salt Soln Ag + Monitoring | 1 | 0 | 2 | 0 | 2 | 2 | 4 | 2 | 3 |
| 9 | DBDMH Solution | 2 | 0 | 2 | 0 | 3 | 2 | 3 | 1 | 3 |
| 10 | DBDMH Solution + Buffer | 2 | 0 | 2 | 0 | 3 | 2 | 3 | 1 | 3 |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | 1 | 0 | 1 | 0 | 1 | 2 | 3 | 1 | 2 |
| 12 | Umpqua Passive Release | 3 | 1 | 2 | 0 | 5 | 2 | 3 | 1 | 3 |
| 13 | Umpqua Passive Release + Buffer | 3 | 1 | 2 | 0 | 5 | 2 | 3 | 1 | 3 |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | 1 | 0 | 1 | 0 | 2 | 2 | 3 | 1 | 2 |
| 15 | HaloPur BR Passive Release | 3 | 1 | 2 | 0 | 5 | 2 | 3 | 1 | 3 |
| 16 | HaloPur BR Passive Release + Buffer | 3 | 1 | 2 | 0 | 5 | 2 | 3 | 1 | 3 |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | 1 | 0 | 1 | 0 | 2 | 2 | 3 | 1 | 2 |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 2 | 1 | 2 | 0 | 2 | 4 | 5 | 2 | 4 |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | 2 | 0 | 2 | 0 | 1 | 2 | 5 | 2 | 4 |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | 2 | 2 | 3 | 0 | 3 | 4 | 5 | 1 | 4 |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | 1 | 0 | 2 | 0 | 2 | 2 | 5 | 1 | 3 |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | 2 | 0 | 2 | 0 | 2 | 4 | 4 | 2 | 3 |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | 1 | 0 | 2 | 0 | 1 | 2 | 4 | 2 | 3 |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | 2 | 0 | 2 | 0 | 2 | 3 | 3 | 1 | 3 |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | 2 | 0 | 2 | 0 | 2 | 4 | 3 | 1 | 3 |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 0 | 1 | 0 | 1 | 2 | 3 | 1 | 2 |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 4 | 2 | 3 | 0 | 4 | 4 | 3 | 2 | 3 |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | 4 | 1 | 2 | 0 | 4 | 4 | 3 | 2 | 3 |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 0 | 1 | 0 | 1 | 2 | 3 | 1 | 2 |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 4 | 1 | 2 | 0 | 4 | 4 | 3 | 1 | 3 |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | 4 | 1 | 2 | 0 | 4 | 4 | 3 | 1 | 3 |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 0 | 1 | 0 | 1 | 2 | 3 | 1 | 2 |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 2 | 5 | 5 | 0 | 5 | 2 | 5 | 3 | 2 |

### 6.4.6 Task 6 Results

The final trade evaluation evolved throughout the process. Initially, baseline scores were generated based on available data for each architecture option and its corresponding technologies. A closer evaluation examined the role uncertainty and technical immaturity played in the scoring. New scores were generated by re-evaluating each architecture option from a pessimistic perspective, an optimistic (i.e., likely) perspective, and a highly optimistic perspective. These data were combined for comparison within individual missions and in their entirety for cross-mission comparisons. The top 10 ranked options in each category were compared to identify architectures that were consistent regardless of technical maturity and that represented better options with additional development and/or risk reduction. Similarly, the bottom 10 ranked options in each category were compared to help identify options with the lowest comparable advantages. Technical activities to address risks and technical immaturity were collected and mapped to individual architectures. This resulted in a list of highest impact activities. The results of each of these activities follow.

#### 6.4.6.1 Architecture Scores and Sensitivity Analysis

Using the scoring equations defined in Section 6.3.6, baseline scores for each architecture were calculated for two mission scenarios and the "Best Technical" option, as shown in Figure 8.

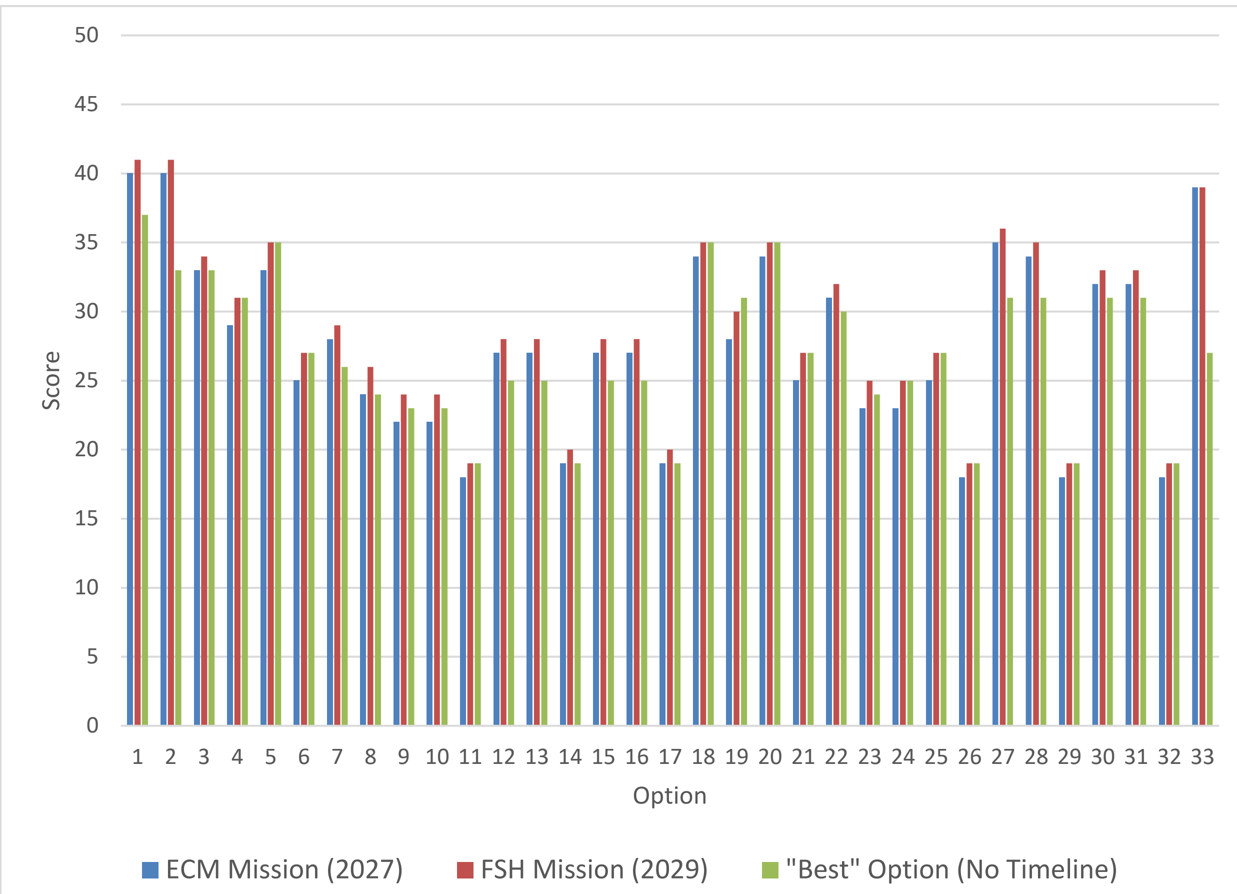


*Figure 8. Baseline Scores for ECM (2027) and FSH (2029) Missions and "Best Technical" Option*

During discussions of the baseline results, it appeared the scores were potentially influenced by assumptions made for unknowns. While every effort was made to be consistent in assumptions across all architectures, there was concern that varying levels of optimism and pessimism when making assumptions about technical unknowns could skew the data. To evaluate this, each architecture option was re-evaluated and *Pessimistic*, *Likely*, and *Optimistic* scores were generated as described in Section 6.3.6. A complete table of scores can be found in Appendix G. Figure 9, Figure 10, and Figure 11 show the scoring spread for each mission based on various levels of optimism in scoring unknowns. The error bars help to visualize the sensitivity of the scores to scoring error or to lack of data. Blue dots represent *Baseline* data, the assessment team’s best estimate of the current state. Red dots represent *Likely* data, the best estimate of the most likely outcome of development efforts. The bottom black lines represent *Pessimistic* data, which assumes everything goes wrong (i.e., current estimates are not conservative enough). The top black lines represent *Optimistic* data, which assumes everything goes right (i.e., current estimates are extremely conservative). As can be seen, there are some architectures where favorable outcomes in unknowns could have a dramatic effect on final score. However, the overall trend in architecture ranking (i.e., top 10 vs. bottom 10) is consistent despite assumptions. This provides confidence that optimism/pessimism was consistently scored across the architecture options and that errors in scoring had no significant impact on the overall outcome of the trade. (**F-12**).

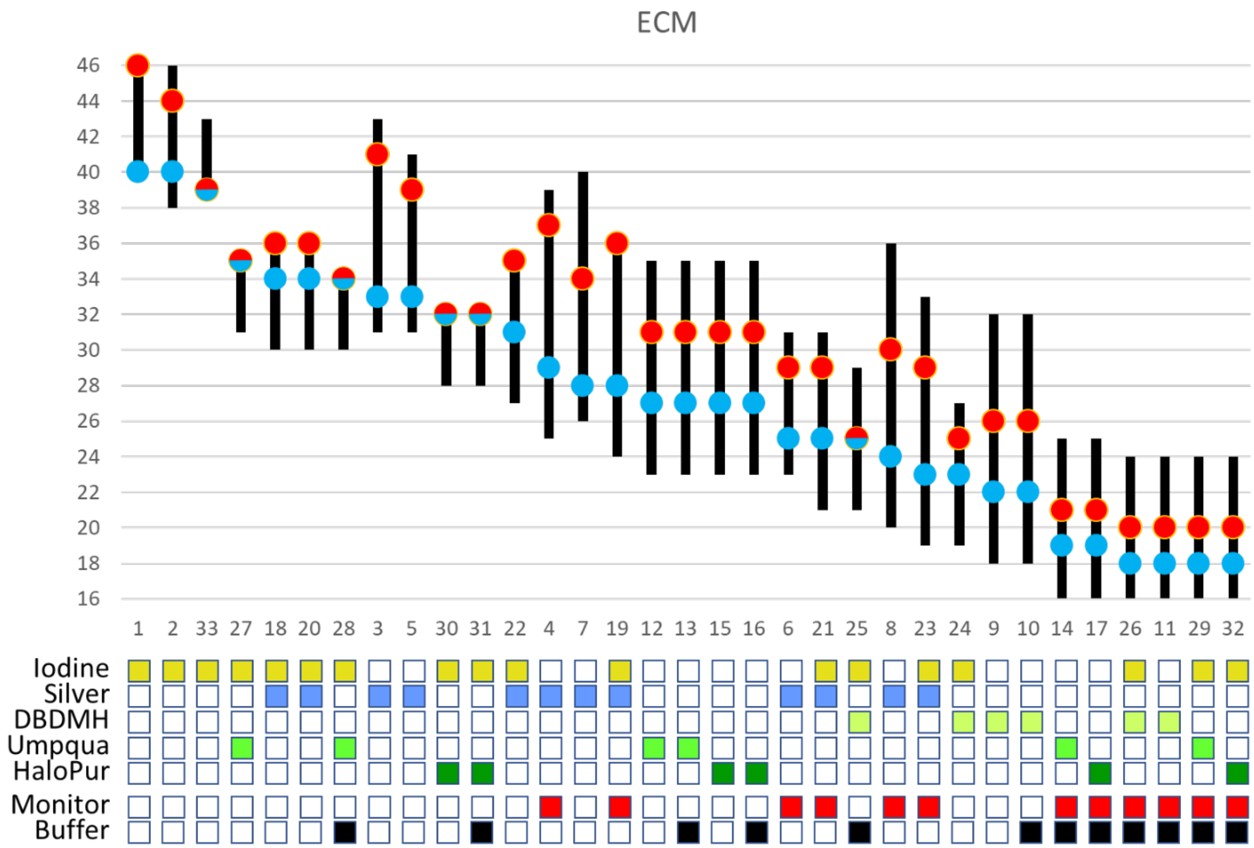


***Figure 9. ECM Scoring Sensitivity Distribution***

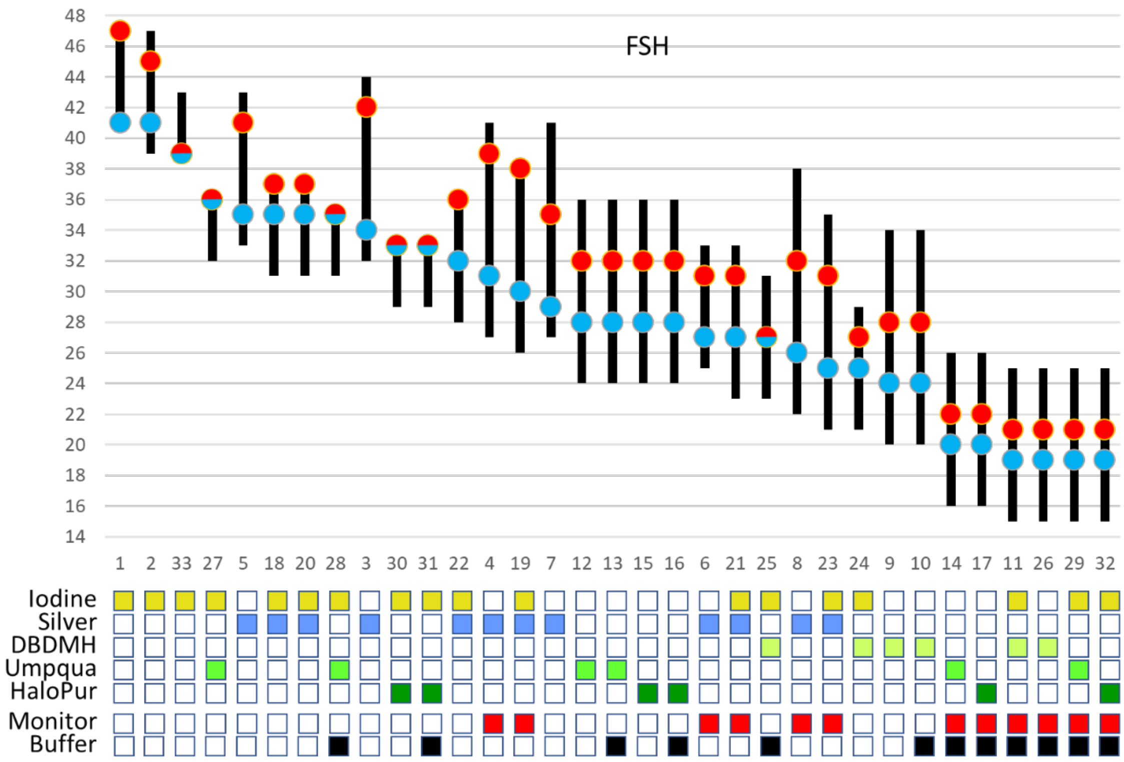


*Figure 10. FSH Scoring Sensitivity Distribution*

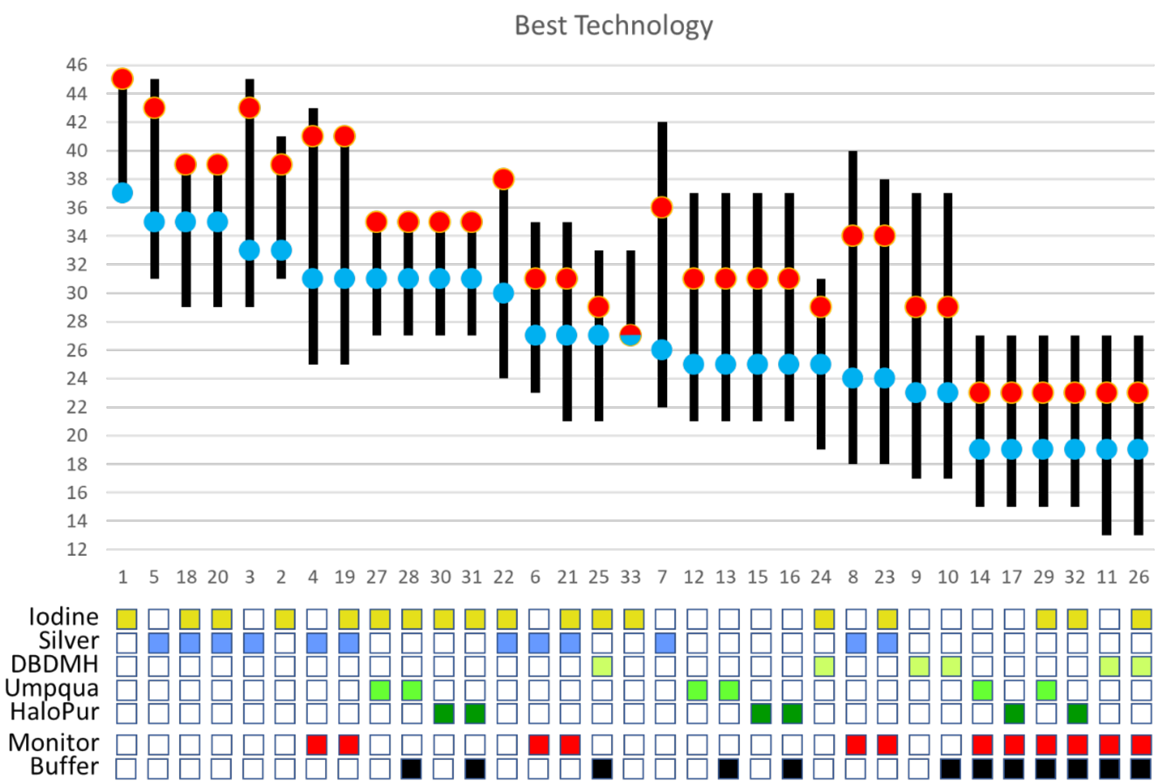


*Figure 11. Best Technology Scoring Sensitivity Distribution*

### 6.4.6.2 Schedule and Cost Impacts for ECM and FSH Missions

Figure 12 helps visualize the influence of cost and schedule on ECM and FSH mission trades. Because of the near-term deadline for hardware on-dock (i.e., December 2026) for ECM, 21 of the 33 architecture options were non-viable. An additional seven architectures would require authority to proceed (ATP) before June 2021 to meet the current schedule (**F-13**). If any of these options is targeted for inclusion on ECM, then development activities should begin immediately. The remaining five architecture options were all listed within the top five options per baseline scores.

The on-dock deadline for FSH was assumed in December 2028. All the proposed architecture development efforts fell within this targeted timeline. However, 6 of the 32 options would require ATP by March 2021 (i.e., fiscal year (FY)21); 11 would require ATP in FY22; and 11 in FY23 (**F-14)**.

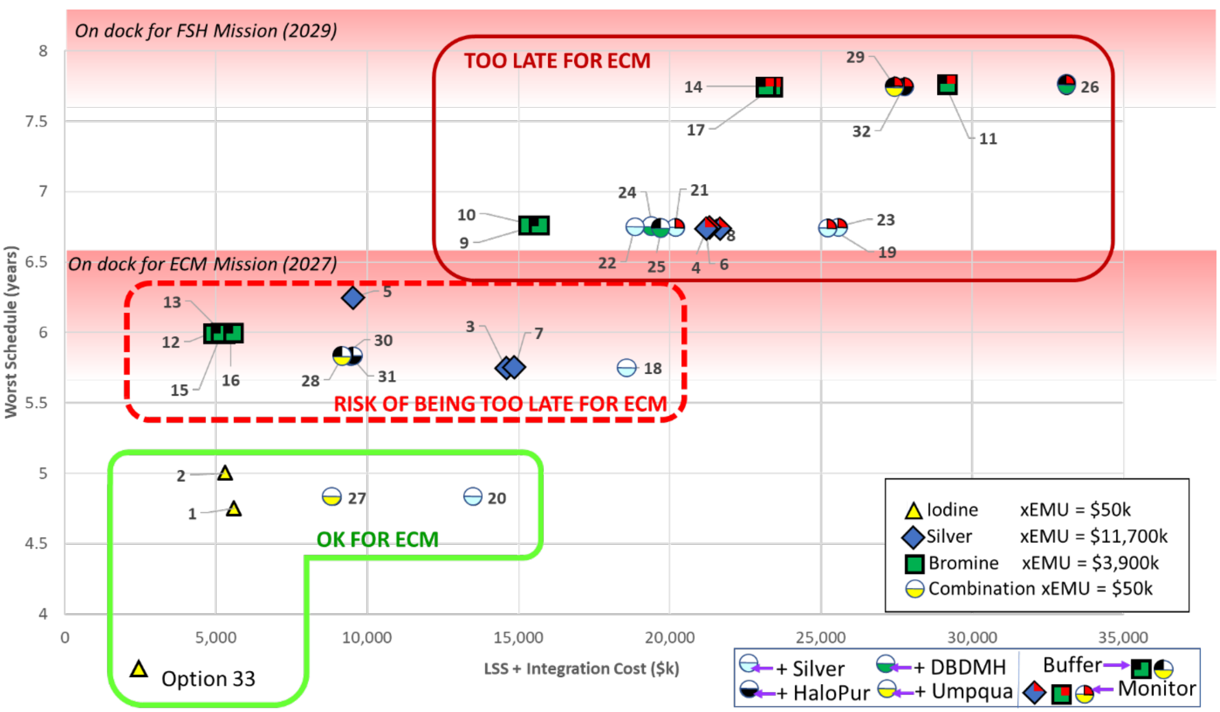


*Figure 12. Influence of Schedule and Cost on Architecture Options*

### 6.4.6.3 Top 10 Architectures

The baseline scoring effort resulted in the same 11 architectures (i.e., two tied for the 10$^{th}$ spot) in the top 10 for the ECM and FSH missions. While the top 10 for "Best Technical" option included those same 11 architectures, 2 more were included due to a 6-way tie for eighth position. The ranks of each of the top 10 options for each mission are shown in Table 20. Schedule impacts are denoted through color coding, where orange and yellow indicate funding required in FY21 and FY22, respectively, to meet mission timelines. Grey indicates the required ATP date has passed, and "DNR" indicates the option did not rank in the top 10.

***Table 20. Baseline Ranking of Top 10 Architectures for Each Mission Scenario***

Note: Architecture Options 4 and 19 did not rank (DNR) in the top 10 for either ECM or FSH missions. Architecture Option 33 DNR for Best Technical. Orange blocks indicate required ATP in FY21. Yellow block indicates required ATP in FY22.

| Option | Description | Ranking | | |
|---|---|---|---|---|
| | | ECM Mission (2027) | FSH Mission (2029) | Best Technical |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 1 | 1 | 1 |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 5 | 5 | 2 |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | 5 | 5 | 2 |
| 5 | Passive Release Silver (ELS or Foam) | 8 | 5 | 2 |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 1 | 1 | 5 |
| 3 | Electrolytic Silver | 8 | 9 | 5 |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 4 | 4 | 7 |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | 5 | 5 | 7 |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 10 | 10 | 7 |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | 10 | 10 | 7 |
| 4 | Electrolytic Silver + Monitoring | DNR | DNR | 7 |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | DNR | DNR | 7 |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 3 | 2 | DNR |

Once complete, the resulting analysis provided 12 sets of top 10-ranked architecture options (i.e., three mission scenarios multiplied by four levels of optimism) as shown in Table 21. Across all 12 sets, there were a total of 18 mission architectures **(F-15)**. Six architecture options were ranked in the top 10 of all 12 sets (i.e., Options 1, 2, 3, 5, 18, and 20). This suggests that these architectures are relatively robust against skewed assumptions based on lack of data or technical immaturity **(F-15a)**. One architecture option was ranked in 9 of the 12 sets (i.e., Option 33) and was more favorable across all levels of optimism, but only for near-term missions **(F-15b)**. This suggests schedule and cost are driving favorability. One architecture option was ranked in 8 of the 12 sets (i.e., Option 27) and was more favorable when more pessimistic assumptions were made. If more optimism was applied across all architecture options, then Option 27 no longer ranked in the top. This suggests the approach has relatively lower technical risk overall, but does not trade as well if riskier technologies are successful **(F-15c)**. Two architecture options were ranked in 7 of the 12 sets (i.e., Options 4 and 19). These options were more favorable when more optimism was applied to the assumptions. This suggests higher technical risk, but also higher payoff if successful **(F-15d)**. Three architecture options were ranked in 6 of the 12 sets (i.e., Options 28, 30, and 31). Like Option 27, these scored higher when assumptions were more pessimistic, suggesting lower technical risk, but less payoff at the architecture level **(F-15e)**. The other five architecture options were ranked in fewer than 4 of the 12 sets (i.e., Options 7, 8, 22, 9, and 10) **(F-15f)**. All five appeared only when higher levels of optimism were assumed, suggesting the highest risk approaches. Further, even when ranked, they were at the lowest end of the top 10, suggesting lower relative payoff compared with the other options.

***Table 21. Tabulation of Sets in Which an Architecture Option Scored in the Top 10***

Note: Shaded boxes indicate the architecture scored in the top 10 for that mission and level of optimism. Gray indicates the architecture did not rank in the top 10. Box color indicates relative quantities of top 10 rankings (green=most, yellow=middle, red=fewest). The infinity symbol refers to the Best Technical Option.

| **# Top 10 Ranks** | **Option** | **Description** | **Pessimistic** | | | **Baseline** | | | **Likely** | | | **Optimistic** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ECM | FSH | ∞ | ECM | FSH | ∞ | ECM | FSH | ∞ | ECM | FSH | ∞ |
| All 12 | 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | | | | | | | | | | | | |
| | 2 | I2 with Replaceable "end leg" of PWD as a consumable | | | | | | | | | | | | |
| | 3 | Electrolytic Silver | | | | | | | | | | | | |
| | 5 | Passive Release Silver (ELS or Foam) | | | | | | | | | | | | |
| | 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | | | | | | | | | | | | |
| | 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | | | | | | | | | | | | |
| 9 of 12 | 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | | | | | | | | | | | | |
| 8 of 12 | 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | | | | | | | | | | | | |
| 7 of 12 | 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | | | | | | | | | | | | |
| | 4 | Electrolytic Silver + Monitoring | | | | | | | | | | | | |
| 6 of 12 | 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | | | | | | | | | | | | |
| | 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | | | | | | | | | | | | |
| | 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | | | | | | | | | | | | |
| 3 of 12 | 7 | Concentrated Salt Solution Silver | | | | | | | | | | | | |
| | 8 | Concentrated Salt Soln Ag + Monitoring | | | | | | | | | | | | |
| 2 of 12 | 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | | | | | | | | | | | | |
| 1 of 12 | 9 | DBDMH Solution | | | | | | | | | | | | |
| | 10 | DBDMH Solution + Buffer | | | | | | | | | | | | |

The effect of changing levels of optimism on ranking and overall score for each mission scenario is shown in Figure 13.

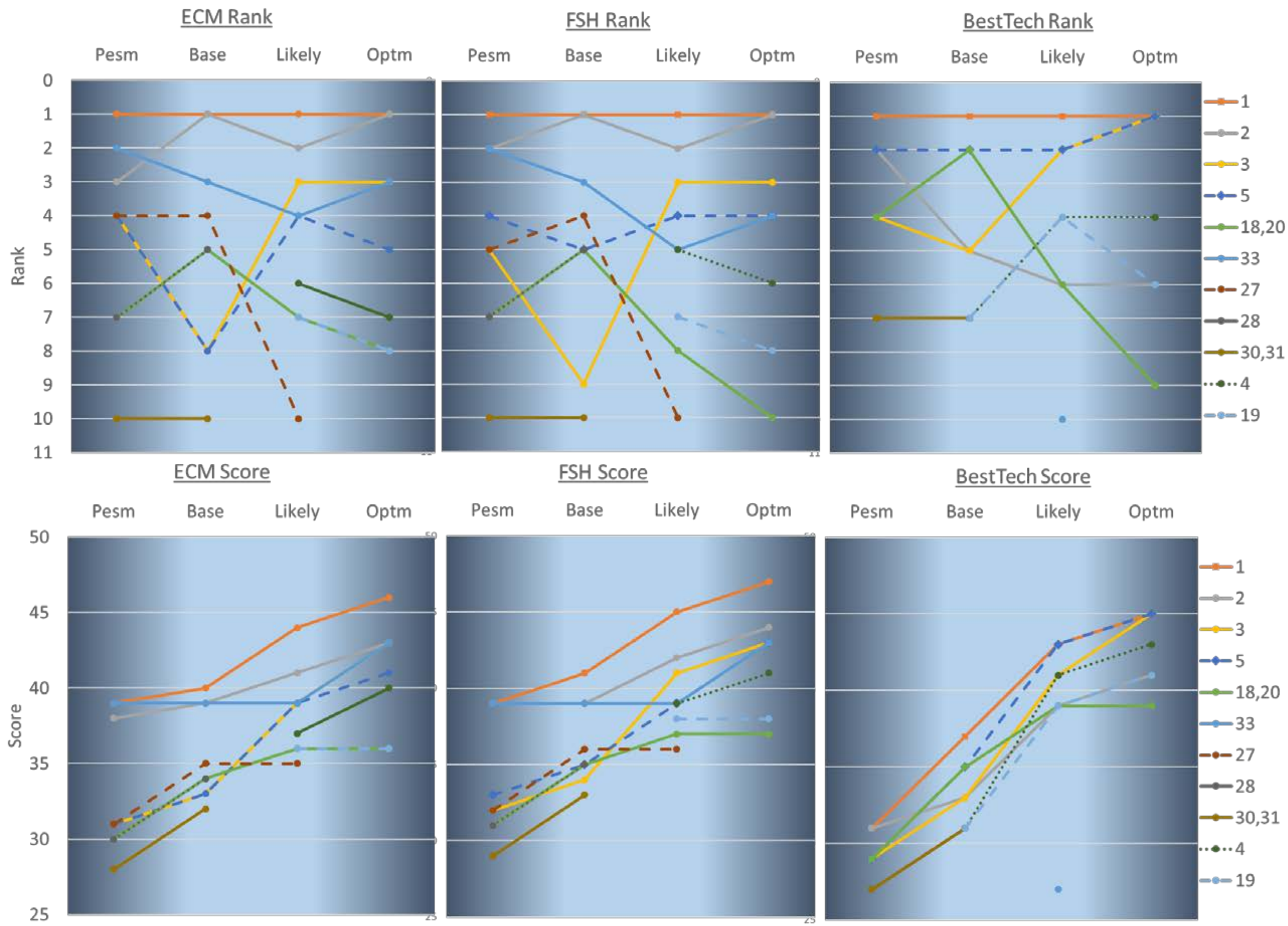


*Figure 13. Ranking and Raw Scores of Top 10 Biocide Architectures for Three Mission Scenarios*

#### 6.4.6.4 Bottom 10 Architectures

The bottom 10 biocide architecture options were evaluated as a comparison to the top 10. Six options consistently scored lowest across all missions and levels of optimism, as shown in Table 22.

***Table 22. Bottom 10 Architecture Options Across all Scenarios***

| Option # | Description |
|---|---|
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| 26 | I2 for xEMU &DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring |

These are all the options within the trade space that involve bromine biocide and bromine/pH monitoring (**F-16**).

#### 6.4.6.5 Development Activity Mapping

During compilation of the technical data for each subsystem and biocide option, a list of development activities was generated to address each unknown as it was identified. A total of 56 unique activities were compiled (**F-17**) and is provided in Appendix G. Each of the activities was mapped to specific architecture options. In many cases, a single activity answered questions for multiple architectures (e.g., Activity 1: Complete testing of iodine to evaluate material compatibility and long-term functional compatibility with SWME polypropylene membrane maps to the 18 architecture options where iodine is used as the biocide in the xEMU). Figure 14 shows the highest-impact development efforts to address top 10 architecture options. The bars are color-coded to denote which options benefit from the activity (i.e., green, yellow, and red as defined in Table 21).

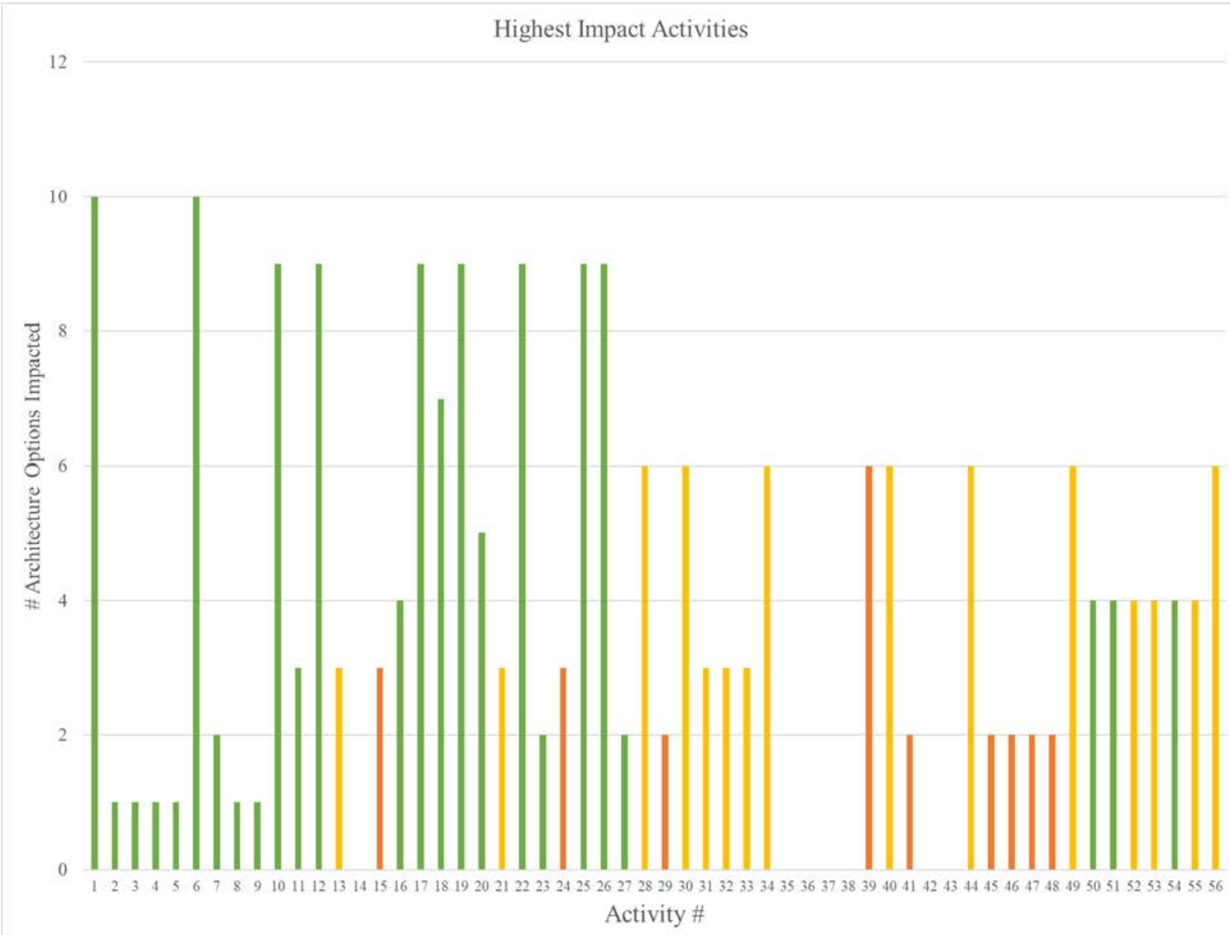


*Figure 14. Highest-Impact Activities for Top 10 Architecture Options*

#### 6.4.6.6 Activity Prioritization

Based on the observed scores across all levels of optimism and each mission scenario, a development prioritization logic diagram was generated, as seen in Figure 15. The Development Prioritization Logic serves to show how linear development might be accomplished based on the trade study scores for the top 10 options across all scenarios evaluated (i.e., 18 architecture options). However, it is reasonable to assume that risk mitigation might be accomplished by funding high-impact activities for options lower in the logic diagram. To differentiate between the relative priorities of activities based on both factors, activities are mapped to each option and separated into four tiers per the logic diagram flow. Tier 1 activities are the highest priority and should begin as soon as possible. Tier 2 activities are of high priority and should begin when funding and personnel can be spared. Tier 3 activities are medium priority and should occur when data from Tier 1 and Tier 2 activities justify proceeding. Tier 4 activities are lowest priority and should occur when data from Tier 3 activities justify proceeding.

The logic diagram began with Option 33 because it is the baseline for Exploration. This option (i.e., Exploration PWD eliminating dead legs) scored in the top 3 for ECM and FSH missions across all levels of optimism, but was less favorable for Best Technical due to the high anticipated mass replacement for dormancy (**F-18**). Activities mapping to Option 33 are shown in yellow below the orange diamond in Figure 15. Underlined activities are funded. For Option 33, Activity 1 is funded.

- **Activity 1**: Testing iodine material compatibility with the new SWME membrane material.

Activities that will be needed to adequately prove the feasibility of Option 33 and remain unfunded include:

- **Activity 6**: Conduct testing to assess iodine effectivity when exposed to metals-of-design over time (i.e., does iodine change to non-biocidal form?).
- **Activity 7**: Conduct testing to evaluate iodine depletion rates over time in a stored water system.
- **Activity 8**: Conduct testing and analysis to determine the sections of PWD that require replacement (vs. replacing the entire assembly) for microbial control during nominal operation.
- **Activity 9**: Conduct test and analysis to determine the sections of PWD that require replacement (vs. replacing the entire assembly) for microbial control after periods of dormancy.

Activities 1, 6, 7, 8, and 9 are required to adequately demonstrate successful implementation of Architecture Option 33 **(F-19**). Further, Activities 8 and 9 are of particular importance as they will determine what alternative paths should be pursued per the logic diagram. Activities 1, 6, 7, 8, and 9 should be prioritized as Tier 1 activities.

In the case of Option 33, the biggest concern is that unacceptable microbial growth will occur in the non-biocided leg of the PWD during dormant periods. However, no data exist to demonstrate the types, quantity, or rates of microbial growth during a dormant mission scenario. Even in the *Optimistic* set, the best case assumption was that a PWD would last for more than one mission. However, if Activity 9 shows that the microbial growth is within acceptable limits, or if it can be mitigated without complete replacement of the PWD, that option then ranks first across all mission scenarios and levels of optimism. If Activities 6-9 are shown to have favorable outcomes, then it follows that at an architecture level the best outcome will have been achieved for near-term missions. However, if unacceptable microbial growth is observed during crewed periods (i.e., Activity 8 yields unfavorable results) or during dormant periods (i.e., Activity 9 yields unfavorable results) as expected, then Options 1 or 2 may provide the necessary engineering solution.

Option 1 (i.e., remove iodine at or near PWD dispensing needle) consistently ranked first in all evaluated scenarios (**F-20**), but proving the feasibility will require completion of:

- **Activity 2**: Conduct a literature review of iodine removal media that is as efficient with “hot” water as the SOA media is with cold water.

If Activity 2 is successful, follow-on studies should be conducted in Activities 3 and 4:

- **Activity 3**: Conduct test to evaluate reliability of “hot water” iodine removal media for long-term “hot” water applications.
- **Activity 4**: Conduct test to evaluate robustness of “hot water” iodine removal media for long-term “hot” water applications.

Because Activity 2 will drive the need to conduct Activities 3 and 4, Activity 2 should be prioritized at Tier 1 and Activities 3 and 4 at Tier 2.

Option 2 (i.e., replacement of PWD leg as a consumable) varied from ranking first to ranking sixth. However, the outcome of Activity 9 drives the necessity of pursuing Option 2 (**F-21**). Therefore,

- **Activity 5**: Develop a new design for the PWD end leg. Should be prioritized as a Tier 2 and pursued only if warranted by the outcome of Activity 9.

The development activities described are required to close gaps for each of these architectures. If none of these activities are successful, then the technical data will have shown that a biocide is needed throughout the potable water system and to the crew members, thus necessitating a new (non-iodine) biocide for Exploration.

The development activities described are required to close gaps for each of the iodine-only architecture options. If the described activities have unfavorable outcomes, then the architecture option is ultimately disqualified based on technical data and the development prioritization logic jumps to a non-iodine biocide option. Another possible outcome, independent of the technical activities, is that a programmatic decision may be made that the crew shall have biocided water to drink to mitigate any risk to crew health from uncontrolled microbial growth combined with the risk of having the crew at significantly greater distances from Earth and timely mission abort scenarios. If this were to occur, then the development prioritization logic would similarly jump to a non-iodine biocide option (**O-4**).

Ultimately, if iodine is shown to be unacceptable for Exploration, then the data shows that the next logical solutions are Options 3 (i.e., Electrolytic Silver) and 5 (i.e., Passive Release Silver). Twelve activities map to these options.

- **Activity 20**: Evaluates xEMU flush processes for mitigating risks with silver. This activity will drive the feasibility of using silver in the TCL and could ultimately force a mixed-biocide option or bromine option (**F-22**). Priority: Tier 1.
- **Activity 12**: Develops a MCV-Ag for implementation into the system. This technology is needed for Options 3 and 5, along with the next six options in the top 10 (**F-23**). Priority: Tier 2.
- **Activity 25**: Conducts an evaluation of LS balance of plant components compatibility with silver plating. Although a goal of this assessment was to conduct a thorough materials review of xEMU and vehicle LSS components for material compatibility with all biocides, the Task 4 team was unable to obtain the necessary component-level data to fully assess the hardware (**F-24**). Activity 25 seeks to conduct a more in-depth analysis of ISS-heritage hardware to determine materials of construction and evaluate compatibility with silver biocides. Priority: Tier 2, because this is a LSS design driver.
- **Activity 23**: Seeks to identify a passive silver release material with a more compatible counter-ion than AgCl, the material used in the current development hardware. Material compatibility analysis showed considerable concerns with the chloride counter-ion in the system (**F-25**). Priority: Tier 2.

The remaining activities that map to Options 3 and 5 (i.e., Activities 10, 16-19, 22, 26, and 27) provide necessary information, but may be deemed unnecessary based on the outcomes of the Activities in Tier 1 and 2 (**F-26**). Priority: Tier 3.

- **Activity 10**: Identify silver-removal media for OGA protection and complete design modifications to replace I2 media in OGA IEB.
- **Activity 16**: Conduct robustness testing of electrolytic silver dosing hardware (e.g., long-term operation contaminant impacts, corrosion impacts).

- **Activity 17**: Conduct reliability testing of silver biocide technology: long-term operation.
- **Activity 18**: Conduct reliability testing of silver biocide technology for continuous vs. intermittent operation.
- **Activity 19**: Conduct reliability testing of silver biocide technology for dormancy impacts.
- **Activity 22**: Develop and test silver-compatible tubing due to the high surface-to-volume ratio and anticipated plating.
- **Activity 26**: Conduct testing to evaluate rate and effects of silver biocide depletion during water storage.
- **Activity 27**: Conduct testing to determine the quantity of Cl- released with passive AgCl approaches and evaluate systems material compatibility.

If Options 3 and/or 5 prove successful, then these represent the best outcomes after the iodine architectures. If both options fail, the next logical approach depends on the reason for failure:

- If failure is due to silver incompatibility with xEMU hardware and operations, then the next logical approaches per the trade results are Options 18 (i.e., I2 for xEMU and Electrolytic Silver for LS) and 20 (i.e., I2 for xEMU and Passive Ag for LS) (**F-27**). In this case, only three additional activities are required beyond those conducted in support of Options 33, 1, 2, 3, and 5. Priority: Tier 3, pending the outcome of Activity 20.
    - **Activity 50**: Conduct kinetic and breakthrough testing of silver capture media (to inform confidence in media).
    - **Activity 51**: Conduct testing to evaluate effect of Ag + I2 mixing at various concentrations to determine worst-case scenario for media failure and biocide mixing.
    - **Activity 54**: Conduct testing to collect silver absorption/desorption data to predict filter lifetime/replacement schedule.
- If failure is due to a need for active control (vs. passive control) of the biocide concentration, then Option 4 (Passive silver dosing with monitoring) is the next logical step in development (Option 4 is Option 3 with monitoring) (**F-28**). Three additional activities are then required to implement Option 4.
    - **Activity 11**: Complete silver monitor development. While significant testing is required before system developers know whether it is required, the long lead warrants early funding. Priority: Tier 2, but at a relatively low level of effort compared with the other Tier 2 activities.

    The next two activities are dedicated to the operational considerations of a monitor. Priority: Tier 4, pending confirmation that the monitor is required for silver biocide implementation.

    - **Activity 13**: Conduct testing to inform silver monitor/sensor ConOps for dormancy (e.g., determine whether sensor remains in place, requires removal and/or replacement).
    - **Activity 21**: Conduct testing of silver monitor to inform ConOps: required frequency of calibration and required tools and consumables.
- If failure is simply because the silver dosing technologies in Options 3 and 5 could not be made to adequately function or one criteria was significantly impacted (e.g., significant growth in mass/power/volume estimates that result in a change in trade outcome), then the trade suggests bromine biocide be explored for vehicle LSS per Options 27 (i.e., I2 for

xEMU and Umpqua Br Passive for LS), 28 (i.e., I2 for xEMU and Umpqua Br Passive + buffering for LS), 30 (i.e., I2 for xEMU and HaloPur Br Passive + buffering for LS), and 31 (i.e., I2 for xEMU and HaloPur Br Passive + buffering + monitoring for LS). In these bromine-based options, xEMU hardware continues to use iodine as the biocide per the trade results (**F-29**).

As mentioned, in some cases risk mitigation might be accomplished by funding high-impact activities for options further down the logic diagram. One critical test for bromine-based biocide options is palatability. If bromine biocide results in crew members being unwilling to consume necessary quantities of water, then no amount of technology development will eliminate the risk (**F-5**). Therefore, Activity 28 should be prioritized as Tier 2 to determine the feasibility of all bromine architecture Options 9-17 and 24-31 as soon as reasonably possible. Further, if the results of Activity 28 are favorable, then it will be necessary to begin Activity 56 immediately thereafter (i.e., Tier 3) due to the long lead-time associated with approval for a new SWEG.

- **Activity 28**: Conduct bromine palatability testing.
- **Activity 56**: Develop SWEG for bromine biocide.

This trade suggests that bromine-based architectures are not warranted until Options 33, 1, 2, 5, and 3 have proven infeasible (**F-30**). Until data from other activities (e.g., Activity 28) demonstrate the feasibility and necessity of pursuing a bromine option, then bromine-related activities should be prioritized as a Tier 4. These activities include:

- **Activity 29**: Conduct testing and/or analysis to determine whether sensors in the xEMU backplate use Hastelloy for housing material or sensing material. Identify new sensors/sensor materials if necessary.
- **Activity 30**: Conduct testing and analysis to determine the mass/volume ratios of bromine biocide salt solutions and passive solutions and their predicted resupply rates.
- **Activity 31**: Conduct testing and analysis to identify acceptable buffer for bromine in the water system.
- **Activity 32**: Develop and test buffer-introduction approaches for bromine biocide solutions and buffer resupply rate.
- **Activity 33**: Conduct testing to evaluate long-term stability of buffer with bromine in xEMU and LSS systems.
- **Activity 34**: Identify bromine-removal media for OGA protection and complete design modifications to replace I2 media in OGA IEB.
- **Activity 35**: Develop and test OBr-monitor/sensor.
- **Activity 36**: Adapt existing pH monitor technology or develop new pH monitor technology for space.
- **Activity 37**: Conduct testing to inform bromine and pH monitor/sensor ConOps for dormancy (e.g., determine whether sensors remain in place, require removal and/or replacement).
- **Activity 38**: Develop secondary dosing method if architecture requires active control of bromine or buffer concentration and the primary dosing method is passive.
- **Activity 39**: Conduct testing and redesign of biocide passive release bromine-dosing system for passive release applications and bromine-based MCV.

- **Activity 40**: Conduct reliability testing of bromine biocide technology for long-term operation.
- **Activity 41**: Conduct testing to evaluate impacts of OBr- only and OBr- with buffer on xEMU thermal loop and components.
- **Activity 43**: Conduct testing to evaluate simultaneous and independent bromine and buffer depletion rates in stagnant and flowing systems.
- **Activity 45**: Conduct testing of OBr- uptake in LCVG tubing (e.g., ethylene vinyl acetate) and determine effect on material life.
- **Activity 46**: Conduct testing to evaluate byproducts/counterions produced from hydantoin bromine biocide.
- **Activity 47**: Complete testing of OBr- to evaluate material compatibility and long-term functional compatibility with SWME polypropylene membrane.
- **Activity 48**: Develop a bromine hydantoin dosing system.
- **Activity 49**: Conduct testing to evaluate shelf-life of bromine biocides and buffer.
- **Activity 52**: Conduct kinetic and breakthrough testing of bromine capture media.
- **Activity 53**: Conduct testing to evaluate effect of Br/OBr- + I2 mixing at various concentrations to determine worst-case scenario for media failure and biocide mixing.
- **Activity 55**: Conduct testing to collect Br/OBr- absorption/desorption data to predict filter lifetime/replacement schedule.

Similarly, all silver-based activities not specifically addressed map to options that scored lower in the trade. For this reason, the remaining silver biocide-based activities should be prioritized as Tier 4. These include:

- **Activity 14**: Develop secondary dosing method if architecture requires control of silver concentration and the primary dosing method is passive.
- **Activity 15**: Conduct testing and analysis to determine the mass-to-volume ratios of silver biocide salt solutions, passive solutions, and electrolytic solution and predicted resupply rates.
- **Activity 24**: Develop a salt dosing system for silver salt solutions.
- **Activity 44**: Conduct reliability testing of silver biocide technology for dormancy impacts.

Finally, the Bottom 10 analysis showed the same six architectures at the bottom of all scenarios evaluated. Based on this, bromine and pH monitoring should be prioritized as Tier 4 and revisited only if all other bromine approaches fail to yield a feasible solution.

- **Activity 42**: Conduct testing of Br and pH monitors/sensors to inform ConOps: required frequency of calibration and required tools and consumables.

#### 6.4.6.7 Summary

The goal of this assessment was to evaluate the impacts of iodine-, silver-, bromine-, and chlorine-based biocides on crew health, xEMU hardware, and vehicle LS hardware individually and at an architecture level. This was accomplished by analyzing how each subsystem was affected in seven areas: 1) mass, power, and volume; 2) schedule; 3) development costs from current state to flight hardware; 4) operational complexity; 5) crew impacts; 6) technology maturation; and 7) sustaining engineering. All impacts were combined at the architecture level and traded across 33 unique architecture options and mission assumptions. Because for exploration missions all of the biocide options are in various stages of development, data were unavailable to support a quantitative trade assessment. Further, because of system interdependencies, the assessed benefits of a given biocide to one subsystem frequently resulted in an equal or higher level of assessed risk to the others. Therefore, a qualitative set of trades were needed to minimize the impacts across the entire system architecture and at four discrete levels of optimism, based on the team's assessment of the probability of development success.

Ultimately, the trade ranked two iodine architectures, passive silver, electrolytic silver, and mixed iodine (for xEMU)/silver (for LSS) biocide architectures the highest for FSH and ECM missions, the long-term best technical option.

Ranking of the technologies and criteria data were used to create a development prioritization logic diagram (Figure 15). The assessment team compiled a comprehensive list of development activities necessary to demonstrate feasibility of each architecture, mapped activities to the appropriate architectures, and identified priority levels for each activity. Priority levels were based on the relative ranking of options, the serial nature of the logic diagram, and risk mitigation for those activities with high impact or long lead times. Seven activities were ranked at Tier 1 and should begin as soon as possible. Eight activities were ranked at Tier 2 and should begin as soon as funding and staffing can be made available. Eleven activities were ranked at Tier 3 and 30 at Tier 4. These activities should occur depending on successful results from higher-tier activities.

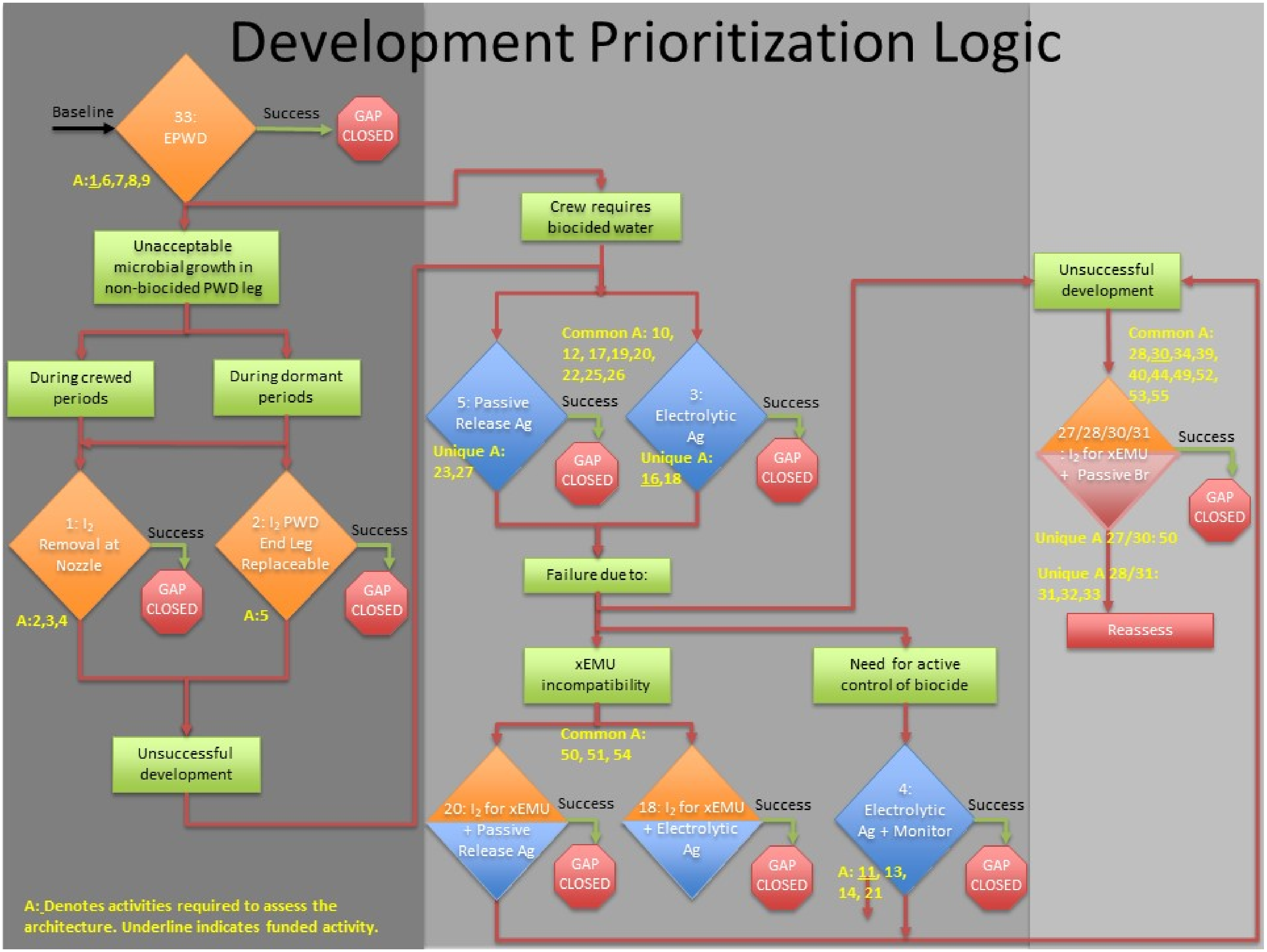


***Figure 15. Development Activity Prioritization Logic Diagram***

# 7.0 Findings, Observations, and NESC Recommendations

## 7.1 Findings

The following findings were identified:

***Task 1***

***F-1.*** Three biocidally active species, in addition to the baseline iodine, were identified within the scope of this assessment: silver ion, hypochlorite ion, and hypobromite ion.

***F-2.*** Fifteen new biocide candidates were identified as potential solutions in a spacecraft application.

***Task 2***

***F-3.*** None of the hazardous effects associated with an in-flight release of the 16 biocide candidates constitutes a THL of greater than 2, resulting in acceptable risk for short-term exposure.

***F-4.*** A preliminary assessment suggests that none of the 16 candidate biocides pose significant issues for long-term health when implemented as described.

***F-5.*** Development of a SWEG will be required to implement bromine biocide in human flight systems.

***F-6.*** Palatability of brominated water constitutes a data gap, as there are no systematic data to support the crew's willingness to consume adequate quantities over long-duration missions.

***Task 3***

***F-7.*** Silver-based biocides present significant design challenges and degradation risks in the xEMU TCL, which include rapid biocide loss, materials compatibility, and increased operational complexity with increased risk of acute (i.e., catastrophic) failure of the thermal loop function during EVA.

***F-8.*** Chlorinated and brominated biocides present substantial materials compatibility risks that would drive significant design challenges for the xEMU.

***Task 4***

***F-9.*** Robust materials selection and possibly pH buffering/monitoring may be required to prevent corrosion in the vehicle LSS when using a bromine biocide.

***F-10.*** Chlorine is not a desirable biocide in the vehicle LSS because there is no current method for dosing combined with significant concerns over long-term storage and materials compatibility

***F-11.*** From a vehicle LSS perspective, the preferred ranking of biocides based on system requirements, system goals, available data, and engineering judgment would be silver > bromine > iodine > chlorine.

***Task 6***

***F-12.*** Sensitivity to relative optimism and pessimism in assumptions does not significantly change the outcome of the architecture ranking.

***F-13.*** Of the 33 architectures evaluated, 21 are not viable for implementation on ECM due to required timeline (e.g., 7 architectures must have ATP by June 2021 to be viable).

***F-14.*** All 33 architectures are viable for implementation in FSH based on schedule.
To remain viable architectures from a schedule perspective:

- Six require ATP by March 2021 (CY21).
- Eleven will need to be initiated in FY22, and another 11 in FY23.

***F-15.*** Eighteen of the 33 architecture options ranked in the top 10 of all missions and levels of optimism:

a. Options 1, 2, 3, 5, 18, and 20 ranked in the top 10 in all 12 evaluated scenarios, suggesting that these architectures are relatively robust against skewed assumptions based on lack of data or technical immaturity.

b. Option 33 ranked in the top 10 in 9 of 12 evaluated scenarios and was favorable across all levels of optimism, but only for near-term missions, suggesting schedule and cost are driving favorability.

c. Option 27 ranked in the top 10 in 8 of 12 evaluated scenarios and was more favorable when pessimistic assumptions were made, suggesting relatively lower risk overall, but less payoff if all technologies are equally successful.

d. Options 4 and 19 ranked in the top 10 of 7 of 12 evaluated scenarios and were more favorable when optimistic assumptions were made, suggesting higher technical risk, but higher architecture-wide payoff if successful.

e. Options 28, 30, and 31 ranked in the top 10 in 6 of 12 evaluated scenarios and were more favorable when pessimistic assumptions were made, suggesting lower risk overall, but less payoff at the architecture level.

f. Options 7, 8, 22, 9, and 10 ranked in the top 10 in fewer than 4 of 12 evaluated scenarios. All appeared in the top 10 only when the highest optimism was applied, suggesting the highest risk approaches.

***F-16.*** The six architecture options that involve bromine biocide and bromine/pH monitoring consistently scored lowest for all evaluated scenarios.

***F-17.*** A total of 56 unique development activities were identified as necessary to address knowledge and development gaps for the evaluated architecture options.

***F-18.*** Option 33 scored in the top 3 for ECM and FSH missions across all levels of optimism, but was less favorable for best technical option due to the high spares replacement mass for dormancy.

***F-19.*** Activities 1, 6, 7, 8, and 9 are required to adequately demonstrate successful implementation of Architecture Option 33.

***F-20.*** Option 1 was consistently ranked first in all evaluated scenarios, but requires Activity 2 to be completed to prove feasibility.

***F-21.*** The outcome of Activity 9 drives the necessity of pursuing Option 2.

***F-22.*** Activity 20, which evaluates xEMU flush processes for mitigating risks with silver, will drive the feasibility of using silver in the TCL and could ultimately force a mixed-biocide or bromine option.

***F-23.*** Options 3 and 5, along with the next six options in the top 10, require a MCV-Ag for implementation into the system.

***F-24.*** The Task 4 team was unable to obtain the necessary component-level data to assess the material compatibility of all components.

***F-25.*** The top identified passive release silver biocide option is based on AgCl with documented material compatibility concerns.

***F-26.*** Activities 10, 16 through 19, 22, 26, and 27 provide necessary information for demonstrating Options 3 and 5, but may be deemed unnecessary based on the outcomes of Tier 1 and Tier 2 activities.

***F-27.*** If failure of Options 3 and 5 is due to silver incompatibility with xEMU hardware and operations, then the next logical approaches are Options 18 and 20 per the trade results.

- Three activities are required beyond those conducted in support of Options 33, 1, 2, 3, and 5 to prove feasibility of Options 18 and 20.

***F-28.*** If failure of Options 3 and 5 is due to a need for biocide concentration active control, then Option 4 is the next logical step in development.

- Three additional activities are then required to implement Option 4.

***F-29.*** If failure of Option 3 and 5 is because the silver dosing technologies could not be made to adequately function or one criteria was significantly impacted (e.g., significant growth in mass/power/volume estimates that results in a change in trade outcome), then the trade suggests bromine biocide be explored for vehicle LSS per Options 27, 28, 30, and 31.

- It should be noted that in these options, xEMU hardware continues to use iodine as the biocide per the trade results.

***F-30.*** Bromine-based architectures are not warranted until Options 33, 1, 2, 3, and 5 have proven infeasible.

## 7.2 Observations

The following observations were identified:

***O-1.*** Under the circumstances on ISS, including operational controls, it is possible to maintain potable water quality with the biocide removed in the PWD.

***O-2.*** Materials compatibility studies largely focus on the depletion of silver in solution in contact with different materials, which focused on biocide efficiency with less focus on the impact of the silver on metallic and non-metallic materials. A knowledge gap exists regarding the effect of deposited silver on materials.

***O-3.*** None of the architecture options for Exploration have all the requirements and data necessary to fully understand the impacts in each area.

- Assumptions were made based on current understanding of the technology and engineering judgment on the likelihood of development activity success.

***O-4.*** A programmatic decision to require biocide in drinking water would eliminate iodine as a viable biocide option regardless of architecture.

## 7.3 NESC Recommendations

The following NESC recommendations are directed towards the AES LSS Project:

***R-1.*** Determine the necessity of biocide in the vehicle LSS architecture as soon as funding and personnel are available. *(O-1)*

***R-2.*** Analyze data to determine how silver plating forms on the internal components, what type and degree of degradation can be expected, and what system changes would be required to prevent or adequately mitigate LSS degradation as soon as funding and personnel are available. ***(O-2)***

***R-3.*** Pursue the following Tier 1 activities as soon as possible:
3a. Activities 1, 6, 7, 8, and 9 ***(F-19)***
3b. Activity 2 ***(F-20)***
3c. Activity 20 ***(F-22)***

***R-4.*** Pursue the following Tier 2 activities as soon as funding and personnel are available:
4a. Activities 3 and 4 ***(F-20)***
4b. Activity 5 ***(F-21)***
4c. Activity 12 ***(F-23)***, Activity 25 ***(F-24)***, Activity 23 ***(F-25)***
4d. Activity 11 at a relatively low level compared with other Tier 2 activities ***(F-28)***
4e. Activity 28 ***(F-5)***

***R-5.*** Pursue the following Tier 3 activities when Tier 1 and Tier 2 activities demonstrate the necessity:
5a. Activities 10, 16-19, 22, 26, and 27 ***(F-26)***
5b. Activities 50, 51, and 54 ***(F-27)***

***R-6.*** Pursue the following Tier 4 activities when Tier 1, Tier 2, and Tier 3 activities demonstrate the necessity:
6a. Activities 13 and 21 ***(F-28)***
6b. All bromine-related activities, including 29-41, 43, 45-49, 52, 53, 55 ***(F-31)***
6c. Activities 14, 15, 24, and 44 ***(F-31)***
6d. Activity 42 ***(F-31)***

***R-7.*** Prioritize bromine monitoring and pH monitoring development at Tier 4 and revisit them only if all other identified options fail to yield feasible solutions. ***(F-30)***

# 8.0 Alternative Viewpoint(s)

No alternative viewpoints were identified during the course of this assessment by the NESC team or the NRB quorum.

# 9.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

## 10.0 Lessons Learned

No lessons learned were identified as a result of this assessment.

## 11.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified.

## 12.0 Definition of Terms

| | |
|---|---|
| Finding | A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation. |
| Observation | A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided. |
| Recommendation | A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk. |

## 13.0 Acronyms and Nomenclature

| | |
|---|---|
| ACTEX | Activated Carbon/Ion Exchange |
| ACToR | Aggregated Computational Toxicology Resource |
| AER | All-Encompassing Rubric |
| AES | Advanced Exploration Systems |
| Ag+ | Silver Ion |
| AgCl | Silver Chloride |
| $AgNO_3$ | Concentrated Silver Salts |
| ATSDR | Agency for Toxic Substances and Disease Registry |
| BCDMH | 1-bromo-3-chloro-5,5-dimethylhydantoin |
| BFA | Biocide Filter Assembly |
| Br- | Bromine |
| $BrO^-$ | Hypobromous |
| CHXR | Condensing Heat Exchanger |
| Cl- | Chlorine ion |
| $ClO^-$ | hypochlorous |
| ConOps | Concept of Operations |
| CWC | Contingency Water Container |
| CWC-I | Contingency Water Container-Iodine |
| DBDMH | 1,3-dibromo-5,5-dimethylhydantoin |

| | |
|---|---|
| ECLSS | Environmental Control and Life Support System |
| ECM | Exploration Command Module |
| EDDA | EMU Don/Doff Assembly |
| EMU | Extravehicular Mobility Unit |
| EVA | Extravehicular Activity |
| FPU | Fluid Pumping Unit |
| FSA | Feedwater Supply Assemblies |
| FSH | Foundation Surface Habitat |
| HALO | Habitation and Logistics Outpost |
| HEOMD | Human Exploration and Operations Mission Directorate |
| HLS | Human Lander Systems |
| HPV | High Production Volume |
| $I_2$ | Iodine |
| ICWC | Iodine Compatible Water Containers |
| IEB | Ion Exchange Bed |
| ISS | International Space Station |
| IVA | Intravehicular Activity |
| JPL | Jet Propulsion Laboratory |
| JSC | Johnson Space Center |
| KSC | Kennedy Space Center |
| LCVG | Liquid Cooling and Ventilation Garment |
| lbm | pound mass |
| LS | Life Support |
| LSS | Life Support Systems |
| LTHE | Long-Term Health Effects |
| MCV | Microbial Check Valve |
| MSK | Microbial Shock Kit |
| NextSTEP | Next Space Technologies for Exploration Partnerships |
| OECD | Organization for Economic Cooperation and Development |
| OGA | Oxygen Generation Assembly |
| PLSS | Portable Life Support System |
| pph | pounds per hour |
| ppm | parts per million |
| PSA | Power Supply Assembly |
| PWD | Potable Water Dispenser |
| ROS | Reactive Oxygen Species |
| SBIR | Small Business Innovative Research |
| SOA | State-of-the-Art |

| | |
|---|---|
| SME | Subject Matter Expert |
| SPCE | Servicing, Performance, and Checkout Equipment |
| STMD | Space Technology Mission Directorate |
| SWEG | Spacecraft Water Exposure Guideline |
| SWME | Spacesuit Water Membrane Evaporator |
| TCL | Thermal Control Loop |
| THL | Toxicity Hazard Level |
| TIM | Technical Interchange Meeting |
| TOCA | Total Organic Carbon Analyzer |
| TRL | Technology Readiness Level |
| U.S. | United States |
| UIA | Umbilical Interface Assembly |
| UPA | Urine Processing Assembly |
| USEPA | U.S. Environmental Protection Agency |
| UWMS | Universal Waste Management System |
| WPA | Water Purification Assembly |
| xEMU | Exploration Extravehicular Mobility Unit |
| xEVA | Exploration Extravehicular Activity |

## 14.0 References


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## Appendices

A. Identification and Initial Review of Biocides
B. Toxicological Evaluation of Candidate Biocides for Water in Exploration Vehicles
C. Material Compatibility Data
D. xEMU Compatibility Results with Biocide Options
E. Biocide Impacts on Vehicle Life Support
F. Architecture Criteria Scoring, Normalization, and Raw Data
G. Data from Architecture Trade Study

# Appendix A: Identification and Initial Review of Biocides

## A.1 Raw Data

### A.1-1 Chlorine-based Biocides

| | Biocide | A.K.A. | Active Biocide | Toxic at High Concentration of Storage | Literature Search: Toxic at Biocidal Concentration | Physical State of Storage | Dosing Method |
|---|---|---|---|---|---|---|---|
| Collected By | (Chemical name) | (alternative names) | (when added to H2O) | (yes/no/ describe) | (yes/no/ describe) | (g/l/s) | (describe) |
| LD | **ClO-** | hypochlorite, Sodium Hypochlorite, hypochlorous acid, bleach | **ClO-** | yes | no | liquid | |
| | **Halazone** | 4-((Dichloroamino)sulfonyl)benzoic acid<br><br>Pantocide<br><br>p-Sulfondichloramidobenzoic acid<br><br>(HOOC)(C6H4)(SO2)(NCl2) | mainly HClO<br><br>(R1)(R2)NCl + H2O → HOCl + (R1)(R2)NH | no<br><br>LDLo (rat, oral) = 3500 mg/kg [29] | no | solid | dissolves in water |
| LD | **Succinchlorimide** | N-Chlorosuccinimide | HOCl/OCl-<br><br>$C_2H_4(CO)_2NCl$ + H2O -> $C_2H_4(CO)_2NH$ + HOCl | no<br><br>LD50(Rat oral) = 2000 mg/kg [29]<br><br>LDLo (rat, oral) = 2700 mg/kg [29] | no | solid | dissolves in water |
| AL | **Ca(OCl)2** | Calcium Hypochlorite | **ClO-** | TDLo (man, oral) = 143 mg/kg [PubChem]<br><br>LD50 (rat, oral) = 850 mg/kg [PubChem] | no<br><br>approved for use in emergencies | solid | dissolves in water |

| Biocide (Chemical name) | Maturity of Biocide Technology [33] (application in spaceflight rating 1-5) | Max Concentration of Storage (relavent unit) | Effective Biocidal Concentrations (relavent unit) | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else | |
|---|---|---|---|---|---|---|---|
| **ClO-** | | | | | | Corrosive.<br>Heat and light degrade it.<br>Forms toxic vapor if mixed with NH3 or acid.<br>Unknown effect from radiation. | Lower pH is more effective as biocide.<br><br>Fe and Mg will comsume, as well as sulfates, nitrites, and ferrous. |
| **Halazone** | 3 | | Typical dosage is 4 mg/L | | Tablets have been used to disinfect water for drinking | Shelf life while unopened = 5-6 months<br><br>The primary limitation of halazone tablets was the very short usable life of opened bottles, typically 3 days or less. [35] | |
| **Succinchlorimide** | 3 | | biocidal kill observed in the presence of B. coli at 5-10 mg/L [40] | | swimming pool disinfectant, bactericide, bleaching agent, used as a drinking water disinfectant in isolated areas | solubility in water: 0.14 g/L in water at 25 C [PubChem] | |
| **Ca(OCl)2** | 3 | | EPA limit in case of emergency disinfection: 5 mg/L [38] | | Surface purification, bleaching, odor removal, emergency potable water disinfection. | 3-5 year shelf life [39] | |

| Collected By | Biocide | A.K.A. | Active Biocide | Toxic at High Concentration of Storage | Literature Search: Toxic at Biocidal Concentration | Physical State of Storage | Dosing Method |
|---|---|---|---|---|---|---|---|
| | (Chemical name) | (alternative names) | (when added to H2O) | (yes/no/ describe) | (yes/no/ describe) | (g/l/s) | (describe) |
| AL | **Sodium chlorite** | NaClO2 | chlorine dioxide<br><br>ClO2- --> ClO2 --> ClO- | LD50 (rat, oral) = 165 mg/kg [PubChem] | no | solid | sodium chlorite + weak food grade acid solution --> short lived acidified sodium chlorite When mixing main active infredient, chlorous acid is produced in equilibrium with chlorite anion. Chlorous acid breaks down to chlorine dioxide which then breaks down to chlorite anion and ultimately chloride anion. |
| LD | **Sodium dichloroisocyanurate** | Sodium 3,5-dichloro-2,4,6-trioxo-1,3,5-triazinan-1-ide<br><br>Sodium dichloroisocyanurate<br><br>Sodium troclosene<br><br>Sodic troclosene<br><br>NaDCC | HOCl<br><br>Cl2C3N3NaO3 + 2 H2O ↔ 2 HOCl + H2C3N3NaO3 | no<br><br>LD50 (Rat oral) = 1670 mg/kg [PubChem]<br><br>LDLo (Man, oral) = 3570 mg/kg [Pubchem] | no | solid | Dissolves in water and slowly releases HClO/OCl- over time |
| LD | **ClO2** | Chlorine dioxide | **ClO-** | yes | no | gas | Dissolves in water |
| LD | **NaOCl** | Sodium Hypochlorite | **ClO-** | TDLo (woman, oral) = 1000 | approved for use in | liquid / gas | Supposition: Potential solid/liquid storage with liquid/gas injection? |

| Biocide (Chemical name) | Maturity of Biocide Technology [33] (application in spaceflight rating 1-5) | Max Concentration of Storage (relevant unit) | Effective Biocidal Concentrations (relevant unit) | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sodium chlorite** | 3 | | EPA max: 1 mg/L drinking water<br><br>WHO guideline value: 0.7 mg/L [41] | | Manufacturing paper, component in therapeutic rinses, mouthwashes, toothpastes and gels, mouth sprays, as preservative in eye drops, and in contact lens cleaning solution | Samples of sodium chlorite show no measurable loss in storage after 10 years at room temperature [37] | stable in pure form and does not explode on percussive impact, unless organic contaminants are present.<br>Easily ignites by friction if combined with reducing agent like powdered sugar, sulfur or red phosphorus. | | | |
| **Sodium dichloroisocyanurate** | 3 | | 1 mg/L [Aquatab] | aquatabs | Tablets have been used to disinfect water for drinking. Replaced Halazone. | possible issues with chlorine taste in water | Aquatabs will lead to a 6 log reduction in bacteria, a 4 log reduction in viruses and a 3 log reduction in Cysts (Giardia) within 30 minutes, when used in non-turbid water | | | |
| **ClO2** | 5 | 1% ClO2 (10g/L) | EPA limit is 800ppb for drinking water | | Used as antimicrobial.<br>Used to disinfect water.<br>Onsite production of ClO-<br>Removes odor from water.<br>Removes taste from water.<br>Widely used in food, beverage, paper, and medical.<br>Gas used to steralize tools. | red to yellow-green gas.<br>Reacts w/ water forms ClO-.<br>Safe and effective at appropriate concentrations.<br>Pure gas is hazardous.<br>Decomposes in air to form chlorine and oxygen. | OSHA PEL is 0.1ppm, or 0.3 mg/m3 for workers using ClO2. | produces less harmful byproducts than chlorine | not as reactive as chlorine and only reacts with sulphuric substances, amines and some other reactive organic substances. Less chlorine dioxide needed to obtain an active residual disinfectant compared to chlorine [20] | |
| **NaOCl** | 3 | | EPA limit in case of emergency disinfection: approx. 6-8 mg/L (2 drops of 6 or 8.25% bleach in 1 L) [38] | 10-15% solution from Sigma. | Surface purification, bleaching, odor removal, emergency potable water disinfection. | From Wikipedia Sodium Hypochlorite 3/30/20:<br><br>Anhydrous NaOCl is unstable and may decompose explosively.<br><br>NaOCl can be crystallized as a pentahydrate NaOCl·5H2O, which is not explosive and is stable if kept refrigerated. | clear, slightly yellowish solution relative density of 1.1 (5.5% watery solution)<br>unstable: chlorine evaporates at a rate of 0.75 g of active chlorine per day from solution | lowest published toxic dose (woman, oral) = 1000 mg/kg | LD50(mouse, oral) = 5800 mg/kg | pentahydrate is the stable solid form but shows rapid loss in 1 month at 20 C; longer stability at 7 C with 98.9% mass remaining after 1 year [34] |

| Collected By | Biocide (Chemical name) | A.K.A. (alternative names) | Active Biocide (when added to H2O) | Toxic at High Concentration of Storage (yes/no/ describe) | Literature Search: Toxic at Biocidal Concentration (yes/no/ describe) | Physical State of Storage (g/l/s) | Dosing Method (describe) |
|---|---|---|---|---|---|---|---|
| LD | **Chloramine-T** | N-Chloro 4-methylbenzenesulfonamide, sodium salt<br><br>Plus many more: see wiki | monochloramine | Yes, probable oral lethal dose of 0.5-5g/kg Chloramine-T for a 70 kg individual<br><br>LDLo (rat, oral) = 935 mg/kg [PubChem] | maybe<br><br>has been used for emergency sanitation of drinking water (Axcentive) | solid | Dissolves in water |
| LD & AL (dark green) | **Cl2** | chlorine gas, chlorine | hypochlorite, underchloric acid ⇌<br><br>Cl2 + H2O H+ + Cl− + HClO | yes | no | gas | bubble through water |
| AL | **NH2Cl** | monochloramine | monochloramine<br><br>NH3 + NaOCl → NH2Cl + NaOH<br><br>⇌ 2 NH3 + Cl2<br><br>NH2Cl + NH4Cl | yes | no | liquid | chlorine added to water first then add ammonia |
| | **Trichloroisocyanuric acid, (and dichloroisocyanuric acid)** | 1,3,5-Trichloro-1,3,5-triazinane-2,4,6-trione<br><br>Plus many more: see Wiki | Free chlorine (HOCl)<br><br>Water dissociation forms hypochorous acid and cyanuric acid<br><br>Cl3Cy + H2O → HOCl + HCl2Cy | Considered a less hazardous alternative to sodium hypochlorite and gas chlorine. [14]<br><br>NOT listed on the California Proposition 65 list of carcinogens, reproductive toxicants and candidate carcinogens. (So it must be safe! Ha Ha) [14]<br><br>LD50 (Rat, oral) = 406 mg/kg (Tri) [PubChem]<br><br>LD50 (Rat, oral) = 1420 | no<br><br>EPA registered, (registration number 69681-22), and NSF Standard 60 (Drinking Water Chemicals - Health Effects) certified. . [14] | solid or granule | Disolves slowly in water forming the byproduct cyanuric acid |

| Biocide (Chemical name) | Maturity of Biocide Technology [33] (application in spaceflight rating 1-5) | Max Concentration of Storage (relavent unit) | Effective Biocidal Concentrations (relavent unit) | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chloramine-T** | 3 | | 200-300ppm<br><br>WHO guideline value: 3 mg/L [41] | | Investigational animal drug used in aquaculture, odor control, disinfection in: saunas, solariums, gyms, sport centers, kitchens, sanitary facilities, and air conditioning units. [23] | Corrosive | p-Toluenesulfonamide is a major metabolite of chloramine-T, used as an intermediate for pesticides and drugs, and fingernail polishes and enamels | has been used for emergency sanitation of drinking water (Axcentive) | chloramine-T tablets have a shelf life of at least 3 years at 25 C [36] | in vitro studies: 5% solution of chloramine T causes severe cell and tissue reactions mode of action: oxidative process | | |
| **Cl2** | 5 | | EPA limit: 4 ppm 0.2-0.4 required for disinfection | | disinfectant, consituent of varius medicines, glue, paints, solvents, foam rubbers, car bumpers, food additives, pesticides, antifreeze, PVC | Chlorine kills pathogens by breaking chemical bonds in their molecules.<br>Underchloric acid (stronger disinfectant and can penetrate cellular membranes) and hypochlorite ions form | Producest trihalomethanes (carcinogen; max levels allowed in drinking water: 0.08 mg/L) [9] | optimal disinfection conditions: pH5.5-7.5 (level of underchloric acid will decrease as pH increases) | chlorine gas affects mucous membrane (dissolves them) and can enter bloodstream. When chlorine gas is breathed in, the lungs fill up with fluid | comparitive study done where copper tube drillings are submerged in initial pH 4-8 with varying concentrations of hypochlorous acid in drinking water are mixed intermittiently for 24 hours; pH 5 shows increase in dissolved copper concentration relative to free chlorine concentration while pH 8 shows little change in dissolved copper relative to free chlorine [42] | results of this comparitive study found that HOCl is more corrosive/oxidative that OCl- [42] | |
| **NH2Cl** | 5 | | EPA: up to 4 ppm for drinking water (measured as Cl2), normal range for disinfection: 1.0-4.0 ppm (10) | | Water disinfection (esp secondary disinfection because it persists as water travels through pipes)<br>remove odor from water<br>remove taste from water | stays in solution for long time but reaction rate is also slower compared to chlorine<br>Monochloramine reacts directly with amino acids in bacterial DNA and destroys the shell that protects a virus | Ideal pH for disinfection: 8<br>up to 5 chlorine : 1 ammonia ratio | can be removed by activated carbon filter | can cause hemolytic anemia if let into blood stream<br>nitrosamines can be byproducts and are suspected to be human carcinogens [9] | addition of free chlorine into natural organic matter solutions will form organic chloramines within 10 min. Organic chloramines have little or no bactericidal activity. Preformed monochloramine persists in solution longer and forms minimal organic chloramines. [19] | Dichloramine and trichloramine have good disinfecting capabilities but cause taste and odor. They are much less stable than monochloramine and are generally avoided for drinking water disinfection. [21] | not effective for disinfection of pathogenic microorganisms |
| **Trichloroisocyanuric acid, (and dichloroisocyanuric acid)** | 3 | | The NSF 60 certification lists a 30 mg/L maximum concentration with disinfection and oxidation as the product function. | Allchem, Clearon, GE, Medentech, Occidental and Shikoku appear to be listed as NSF certified drinking water chemicals under NSF/ANSI 60. [13] | Comet (cleaner)<br><br>Horizon® 90 PT | The actual free chlorine concentration cannot be measured accurately by typical methods in these systems. | Solid forms of chlorine.<br>Simpler handling than liquid and gas chlorine. Stabilities on the order of years.<br>Does not add calcium.<br>Trichlor is92% percent chlorine.<br>Dichlor is65% percent chlorine. | Not compatible with calcium hypochlorite | Wet trichlor tablets produce a strong chlorinous odor.<br><br>Solubility:<br>Trichlor is 1.4g/L<br>Dichlor is 24g/L | Cyanuric acid protects chlorine from UV | Tri- and Di-chlor are related through equilibrium chemistry. See Ref 12 Figure 14 | |

## A.1.2 Bromine-Based Biocides

| Person Modifying | Biocide | A.K.A. | Active Biocide | Toxic at High Concentration of Storage | Literature Search: Toxic at Biocidal Concentration | Physical State of Storage | Dosing Method |
|---|---|---|---|---|---|---|---|
| | (Chemical name) | (alternative names) | (when added to H2O) | (yes/no) | (yes/no) | (g/l/s) | (describe) |
| JA | bromine | Br2 | OBr-, HOBr<br><br>Br2 + H2O -><br>HOBr ⇌ H+ + Br-<br><br>HOBr H+ + BrO-<br><br>2HBrO + BrO- --><br>BrO3- + 2 H+ + 2 Br- (decomposition to bromate) [28]<br><br>3 BrO− (concentrated)(basic) →<br>BrO3- + 2 Br− [wiki] | yes | no [26] | l/g | dissolves in water |
| JA | 1-bromo- 3-chloro- 5,5-dimethylhydantoin | BCDMH, C5H6BrClN2O2 | OBr-, HOBr, OCl-, HOCl<br><br>BrClC5H6N2O2 + 2 H2O →<br>HOBr + HOCl + C5H6N2O2H2<br><br>OBr- + HOCl →<br>HOBr + OCl- | no<br><br>LD50 (rat, oral) = 1390 mg/kg [Pubchem] | no [NSF] | s | dissolves in water |
| JA | Poly-1-bromo-5-methyl-5(4' -vinylphenyl)hydantoin | HaloPure BR | exposed oxidative Br(I) sites on porous bead surface; similar killing mechanism to HOBr | no | no<br><br>can be made into a polymeric filter | s (bead filter) | flow-through |
| JA | bromine monochloride | BrCl | OBr-, HOBr<br><br>BrCl + H2O →<br>HOBr + HCl | yes | no | g | bubble through water |
| JA | 2,2-Dibromo-3-Nitrilopropionamide | DBNPA, C3H3ON2Br2, 2,2-Dibromo-2-cyanoacetamide | DBNPA; non-oxidizing biocide; kills bacteria on contact | yes | not approved for potable water<br><br>maybe (oral LD50 = 235 mg/kg, approved only for industrial water use) | s | dissolves in water |
| JA | 2-bromo- 2-nitropropane-1,3-diol | Bronopol, C3H6BrNO4 | Bronopol; non-oxidizing biocide; kills bacteria on contact | yes | not approved for potable water<br><br>maybe (oral LD50 = 180 mg/kg, approved only for industrial water use) | s | dissolves in water |
| JA | domiphen bromide | $C_{22}H_{40}BrNO$ | quaternary ammounium; unsure if this counts | | | | |
| JA | 1,3-Dibromo-5,5-Dimethylhydantoin | DBDMH, C5H6Br2N2O2 | OBr-, HOBr<br><br>Br2C5H6N2O2 + 2 H2O → 2HOBr + C5H6N2O2H2 | no<br><br>LD50 (rat, oral) = 250 mg/kg [Pubchem] | no [Wiki] | s | dissolves in water |
| JA | Halogen-binding resin (UMPQUA) | successful resins are quaternary ammonium tribromide resins (refered to as polyhalides)<br><br>monomer structure: polystrene-CH2-N+/Br3-<br><br>work in progress under SBIR 19-1-H3.03-4124 | gradual release of bromine to form HOBr/OBr-<br><br>Br3--N+-R <-> Br2 + Br--N+-R + H2O -><br>HBrO + Br--N+-R<br><br>R = resin monomer | no | no | s (bead filter) | flow-through with bound bromine released and reacted to form HOBr/OBr- |

| Biocide | Maturity of Biocide Technology [33] | Max Concentration of Storage | Effective Biocidal Concentrations | Ref | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (Chemical name) | (application in spaceflight rating 1-5) | (relavent unit) | (relavent unit) | | | | (use multiple cells to as needed) | | | | | |
| bromine | 5 | | EPA limit: 1 ppm | 1,2,26 | available as reagent grade at Sigma | preparation of organobromine compounds for flame retardants or water treatment | volatile, toxic, corrosive, vapors at room temperature (212 mm Hg vapor pressure @ 20 C). | solubility in water @ 20-25 C - 0.3-0.4 g/100 mL [PubChem] | $Br_2$ in water forms HBrO/$BrO^-$ which decomposes into $BrO_3^-$ (bromate), a B2 probable carcinogen with an MCL of 10 ppb | OSHA PEL is 0.1 ppm. | Titanium and 28% Cr/3% Mo stainless steel show higher corrosion resistance to 1000 ppm bromine @ 25C/60C under immersion and vapor conditions than 316L stainless steel<br><br>Ti and 28% Cr/3% Mo steel still shows pitting at 60 C under vapor conditions [30] | |
| 1-bromo- 3-chloro- 5,5-dimethylhydantoin | 3 | | EPA reference dose: 1 mg/kg/day(for dimethylhydantoin) [31] NSF/ANSI 60 max concentration for drinking water = 9 mg/L [32] | 3 | Halobrom/Halogene | used for disinfection of recreational water and drinking water | skin irritant, meets NSF standards for drinking water additives (NSF/ANSI 60), recorded issues with skin sensitization and allergies | solubility in water @ 25 C - 0.15 g/100 mL [PubChem] | 1,3-dichloro- 5,5-dimethylhydantoin: IDLH = 5 mg/m3 PEL =0.2 mg/m3 | | Potential issues as a sensitizers that causes contact dermatitis as noted in pools/spas that use BCDMH | |
| Poly-1-bromo-5-methyl-5(4' -vinylphenyl)hydantoin | 5 | | Br disinfection on contact with bacteria; 0.01-0.05 ppm residual bromine in solution | 4,5, 27 | HaloPure BR cartridges and resin beads available as-is or in custom-made filters by HaloSource<br><br>HaloSource acquired by Strix and restructured to HaloSource Water Purification Techonlogy in Shanghai | used for drinking water disinfection | 16% bromine by weight; low residual Br released (0.1-0.5 ppm) | lifetime:non-RO application 1/4" filter with 15 g dry weight(30 cm^3 volume) resin lasts 6 months or 1500 L<br><br>filter sealed with dessicant lasts 2 years | dormancy issue: high residual bromine with HaloSource contact stating a 1-5 ppm residual Br within weeks of dormancy, requiring a flush | registered under EPA No. 72083-5 | 2 year shelf life with dessicant | |
| bromine monochloride | 5 | | 10 ppm (EPA recommended for wastewater treatment) [25] | 6, 25 | | used in mercury analysis and industrial water treatment | toxic, decomposes into chlorine and bromine | highly reactive and soluble in water [PubChem] | | | | |
| 2,2-Dibromo-3-Nitrilopropionamide | 1 | | | 15, 16, 24 | DOW Aquacar | used in papermaking slurries, cooling water, and industrial water treatment applications; NOT approved for online use of potable water systems | LD50 (rat, oral) = 235 mg/kg [24] | hydrolyzes quickly in water in hours, but kills bacteria on contact before degradation | half-life of 9 hours in water, 2 log kill of P. aerignosa with 1 ppm DBNPA in 12 min in pH 7.4 PBS water [16] | solubility in water - 1.5 g/100 mL [PubChem] | | |
| 2-bromo- 2-nitropropane-1,3-diol | 1 | | | 17, 18 | Sigma | preservative in shampoos/cosmetics, used in industrial water treatment | LD50 (rat, oral) = 180 mg/kg | can cause contact dermatitis, 15th most prevalent allergen | half-life: pH 4 > 5yrs, pH 6 1.5 yrs, pH 8 2 months | solubility in water - 25 g/100 mL [PubChem] | | |

| Biocide | Maturity of Biocide Technology [33] | Max Concentration of Storage | Effective Biocidal Concentrations | Ref | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (Chemical name) | (application in spaceflight rating 1-5) | (relavent unit) | (relavent unit) | | | | (use multiple cells to as needed) | | | | | |
| domiphen bromide | 2 | | | | | | | | | | | |
| 1,3-Dibromo-5,5-Dimethylhydantoin | 3 | | based on BCDMH: EPA reference dose: 1 mg/kg/day(for dimethylhydantoin) [31] NSF/ANSI 60 max concentration for drinking water = 9 mg/L [32] | | Sigma | | solubility in water @ 20 C - 0.1 g/100 mL [Wiki] | | | | | |
| Halogen-binding resin (UMPQUA) | 4 | | 0.5 - 4 mg/mL residual Br released | UMPQUA Phase I final report | currently being developed by UMPQUA Research Company | SBIR research for potable water treatment | generated polyhalides, hydantoin, and dichloroisocyuranate(DCC) resins with chlorine and bromine, but only the polyhalides have been successful with a residual halogen released slowly hydantoins showed no chlorine resiudal released and DCC resins didn't release halogens slowly | highest halogen-releasing resin made with Merrifield resin maintains target residual Br concentation between 0.5-4 mg/mL for 47 L water per cm^3 resin, but has shown susceptibility to residual Br spikes with Cl- ion added. | 2nd highest halogen-releasing resin made with Dowex PSR-2 maintains bromine for 22 L per cm^3 resin, but shows lower susceptibilty to residual Br spikes with addition of Cl- and SO4- ions. | for phase I, 100-200 mesh resin used; 16-45 mesh resin beads planned | first phase SBIR research started as of 6/2019 and completed (literature search on corrosion/biocidal properties and early work on bromine-binding resin) | second phase SBIR approved (studies on chlorine-binding resin, improving bromine resin, and in-house biocidal testing) |

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| 33 | Meaning of #s: |
| | 5 - A commercial material (polymer or gas) which could be quickly developed into a space application. |
| | 4 - Polymer system in development. |
| | 3 - Commercial product that uses dissolving solids as the method of delivery. Much work needed for space application. |
| | 2 - Studies done for, but no approval for potable water application. |
| | 1 - Needs a lot of work, including approval for potable water applications. |
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## A.1.4 Silver-Based Biocides

| Person Modifying | Biocide | A.K.A. | Active Biocide | Toxic at High Concentration of Storage | Toxic at Potable Biocidal Concentration | Physical State of Storage | Dosing Method |
|---|---|---|---|---|---|---|---|
| | **Silver Nitrate** | $AgNO_3$ | | | | | |
| | **Nanosilver** | AgNP | | | | | |
| LE, EKH | **Ionic Silver** | ex: $AgNO_3$ | structural and metabolic disruption due to ionic silver combination with and alteration of microbial proteins | | | | |
| | **Copper/Silver combination** | | | | | | |
| | AgNP coated polyurethane foam | citrate-stabilized silver nanoparticles | | | | | |

| Biocide | Max Concentration of Storage | Effective Biocidal Concentrations | Ref | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else |
|---|---|---|---|---|---|---|
| **Silver Nitrate** | | | 26, 27 | | | Bacterial resistance in *Pseudomonas aeruginosa* |
| **Nanosilver** | | TBD; many studies show no negative impacts but toxicological effects following chronic oral administration in rates were seen at [AgNP] of 20ug/kg bw per day | 26, 27, 28 | | | gap in knowledge on bacterial AgNP resistance; 5 to 10 µg/mL shown to induce necrosis and apoptosis in mouse spermatogonial stem cells; needs further investigation potential hazard to human health - preferential accumulation within the liver<br><br>some studies suggest smaller AgNP are more toxic to mammalian cells than larger nanoparticles but the wide range of particle size and cell types make generalizations difficult to conclude<br><br>complete characterization of AgNP (size distribution, shape and other |
| **Ionic Silver** | | 10-9 to 10-6 mol/L<br><br>10 mg/L contact time 3 hours for batch disinfection test of groundwater with 106 cfu/mL E. coli 28 | 26, 27, 28 | | antimicrobial activity against planktonic and sessile bacteria | enhanced activity with combination with other antimicrobial agents, antibiotics (sulphonamide, silver suphadiazine), chlorhexidine, cerium nitrate<br><br>forms salts with low water solubility, ionic silver is easily sequestered by anions commonly found in water (chloride, bromide, carbonate and phosphate); at levels that do no induce precipitation, chloride and phosphate have been shown to hinder antibacterial activity of ionic silver |
| **Copper/Silver combination** | | for Legionella 0.2 to 0.8 mg/L copper and 0.01 to 0.08 mg/L silver28 | 28 pg 15-17 | | Used in hospital hot water distribution systems; the water in these systems is not considered | recolonization occurs between 4 to 12 weeks later after cessation of disinfection28<br><br>not effective at temperature of 50C<br><br>High pH has had detrimental effects on the activity of copper ions on Legionella |
| AgNP coated polyurethane foam | | | | prototype filter made from the treated foam effectively eliminated E. coli growth but no equilavent data for untreated foam for comparison | | |

| Person Modifying | Biocide | A.K.A. | Active Biocide | Toxic at High Concentration of Storage | Toxic at Potable Biocidal Concentration | Physical State of Storage | Dosing Method |
|---|---|---|---|---|---|---|---|
| | AgNP impregnated fiberglass | | | | | | |
| | AgNP coated porous ceramic tiles | | | | | | |
| | AgNP coated polypropylene filters | | | | | | |
| | AgNP coated materials: zeolite, sand, fiberglass anion resin and cation resin substrates | | | | | 28 pg 19 | |

| Biocide | Max Concentration of Storage | Effective Biocidal Concentrations | Ref | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AgNP impregnated fiberglass | Ag-impregnated mat (1% silver by weight) added to 100 mL E. coli suspension (10^6 cfu/mL) for 1 hour: E. coli was undetectable in the suspension<br><br>10^6 cfu/mL E. coli solution was pumped through filters (5% Ag by weight) at 20 | 28 pg 18 | | | | | | | | | |
| AgNP coated porous ceramic tiles | 10^4 - 10^5 cfu/mL *E.coli* solutions were exposed to treated ceramic and after 24 hours no bacteria could be grown from treated samples; experimental filter showed no bacteria detection during flow test | 28 pg 18 | | | | variability in effectiveness at removing bacteria | | | | | |
| AgNP coated polypropylene filters | 15L of 10^3 cfu/mL *E. coli* flow through the filters at 3L/hour after 7 hours bacteria level was zero; no silver detected in the filtered water | 28 pg 18 | | | | | | | | | |
| AgNP coated materials: zeolite, sand, fiberglass anion resin and cation resin substrates | | silver/cation resin filter performance was best | | | | | | | | | |

| Person Modifying | Biocide | A.K.A. | Active Biocide | Toxic at High Concentration of Storage | Toxic at Potable Biocidal Concentration | Physical State of Storage | Dosing Method |
|---|---|---|---|---|---|---|---|
| | Biogenic AgNP - bacteria used as reducing agents to produce nanosized elemental | | | | | | |
| | Silver Coated Ceramic Filters | | | | | | |
| DG | AgNP | | Unknown | TBD | TBD | | |
| DG | AgNP | | ionic silver | | | | |
| DG | AgNP capped with water soluble ligands | | ionic silver | | | | |
| EKH | AgNP | | ionic silver, silverNP | | | | Solid matrix |

| Biocide | Max Concentration of Storage | Effective Biocidal Concentrations | Ref | Availability | Applications | Chemical Properties, known limitations, lessons learnt, and anything else |
|---|---|---|---|---|---|---|
| Biogenic AgNP - bacteria used as reducing agents to produce nanosized elemental | | biogenic silver nanoparticles showed increased effectiveness against bacteriophages (10^6 pfu/mL) compared to | | | | |
| Silver Coated Ceramic Filters | | | 28 pg 24-25 | | devices in developing countries | extensive study where over 8000 L drinking water passed through ceramic filters with and without silver and samples were spiked with E. coli: initially no difference, after 5500 L silver filters out perform and after 8000 L both filters lose |
| AgNP | | 3-4 uM | 29 | | | NP effective against nitrifying bacteria, ionic Ag more effective against heterotrophic organisms. Evidence NPs degrade to form ionic Ag in presence of oxygen. Efficacy of NPs seems to decrease in solution. |
| AgNP | | | 30 | | | Demonstrates lack of biocidal acitvity for AgNPs under anaerobic conditions. Suggests ionic silver is primary disinfectant. Formed by oxidation of NPs in the presence of oxygen. Also indicates that exposure to sublethal concentrations can trigger resistance. |
| AgNP capped with water soluble ligands | | | 31 | | | Confirms ionic Ag as acive biocide. Suggests shape of NP play a role in release of ionic silver. Surface oxidation of NP may also be beneficial. |
| AgNP | | 5-20 mg/kg | 32 | | | |

| Description | Ref. | Ag concentration (mg/L) | Commercially available (Y/N, list source) | Target application | Maturity | Notes, known limitations, concerns, etc. |
|---|---|---|---|---|---|---|
| ELS Technology Ag MCV | | | | Water treatment | | |
| Agion silver zeolite - Ag ions entrapped within alumino-silicate structure. | AG8 | Mass percentage of coating not provided. | Y - Agion Tehcnologies, although most information is on sciessent.com | Surface treatement and water purification | 4 | Some organisms showed resistance, especially gram positives. Results may be biased due to lack of control between last contact and sampling. Relies on exchange with other environmental cations, may be problematic for high purity water system. Would need counter ion to balance charge. Some COTS filters and carbon sorbents appear to be avaiable. Can be integrated into polymer surfaces. |
| Silver loaded onto Zeolite X - 2% Ag (by w) loading withing framework, 5-8% (by w) onto zeolite. | AG10 | 1.6 g AgNO3 loaded on 20 g zeolite. | TBD - zeolite used in study was synthesized in house. | Disinfection, directly applicable to water systems as studies were conducted in growth media. | 1 | Tested against cultures of E. coli, S. aureaus, and P. aeruginosa at 10e5 CFU/mL. tested at levels from 0.15 - 1.0 g/L. No viable cells after 45 min - 1 hour. First order release, effective on multiple exposures. ~3% release per exposure. |

| Description | Ref. | Ag concentration (mg/L) | Commercially available (Y/N, list source) | Target application | Maturity | Notes, known limitations, concerns, etc. |
|---|---|---|---|---|---|---|
| Silver Nanoparticles </= 20 nm ("patent-pending recipe") | AG9 | 0.5 for <35% efficiency psychrophilic/cryophilic microorganisms (22C in this paper)<br>2.0 for ~55% efficiency mesophilic microorganisms (36C in this paper) | Unknown | Cooling tower | 1 | Publication did not describe the nanoparticle other than size and patent-pending<br>% efficiency = (1- [average # bacteria after disinfection/average # bacteria before disinfection])*100<br>Bacteria were unspecified<br>Water samples taken during different phases of the cooling tower cycle resulted in different starting levels of bacteria<br>1 hour contact time with biocide |
| Silver nanoparticle surface-impregnated on plasma-treated activated carbon (0.8 wt% Ag; 28 nm median nanoparticle size) | AG12 | 48-64 mg/L silver in cell suspension (cell suspension = 10^4 CFU/mL E. coli)<br>2 mg/mL (2000 mg/L of 0.8 wt% Ag) results in 0 cell count after 35 minutes of contact time<br>4 mg/mL results in 0 cell count after 25 minutes | N | Drinking water purification | 3 | Plasma treatment of activated carbon granules selectively keeps AgNP impregnated on the surface as opposed to inside the activated carbon pores -- reduces amount of AgNP needed<br>Plasma treatment also converts activated carbon from hydrophobic to hydrophilic, increasing contact-killing of E. coli<br>Silver nitrate and trisodium citrate used for AgNP synthesis<br>Activated carbon mesh size: 20x40 for final AgNP impregnated activated carbon granule size 420-840um<br>Silver concentration in water after batch treatment for 10 days (using mQ water, no E. coli): 0.6 mg/L using 2 mg/mL treatment and 0.84 mg/L using 8 mg/mL treatment (does not increase much and approaches saturation after 15 days)<br>Silver concentration in outlet water after continuous column treatment was 0.0298 mg/L<br>First 15 minutes of E. coli cell decrease = adsorption NOT E. coli cell killing<br>Chloride ion-induced release of Ag from the AgNP impregnated activated carbon was shown to be low |
| 29.6 nm Silver nanoparticle (no surface charge, irregular morphology) | AG14 | | N | Desalinated water disinfection | 2 | |

| Description | Ref. | Ag concentration (mg/L) | Commercially available (Y/N, list source) | Target application | Maturity | Notes, known limitations, concerns, etc. |
|---|---|---|---|---|---|---|
| Membraneless Silver Biocide Cell | AG11 | 25-2000 ppb | Not COTS, but SBIR, Reactive Innovations | Spaceflight | 2 | Under guidance of Niklas Adam at JSC, Tubular reactor, process water at 100 ml/min, Internal Ag rod electrode with outer Ag tube electrode. Silver deposition via tank and piping still an issue. Works in conjunction with a Silver Ion Removal Module using a dimensionally stable anode such a platinum to remove Ag+ prior to discharge. They have a prototype with a mgentically driven electrode polisher to remove oxide buildup and extend the lifetime of the internal rod. Change voltage to change Ag+. Run time - 90 min. |
| Hybrid Membrane Silver Ion Reactor | AG11 | 100 ppb | Reactive Innovations | Spaceflight | 1 | Limited lifetime due to silver deposition on the membrane that could short the cell. Would need extensive research for improved membrane. Not a good candidate. |
| Silver Biocide Dosing System (Developed by Reactive Innovations) | AG13 | 300 ppb | Dosing electrode from Reactive Innovations in ref AG11. | Spaceflight | 3 | Used a sub-scale water bus model to monitor dosing function over time. Incorporated Ion Selective Electrode to measure Ag+ and verified with ICP-MS, controller to drive the Reactive Innovations "dosing electrode" otherwise known as Membraneless Silver Biocide Cell. Run time - 2 months. The system maintained 300 ppb +/- 40ppb. In-line monitoring needs to improve. A suspension of elemental silver was found in the tank at the conclusion of the run. Could be due to the mechanical electrode cleaning system removing elemental silver. System needs to be tested with scrubber sturned off. |

## A.1.5 Silver-Based Biocides References

| # | Reference |
|---|---|
| AG1 | Callahan, M. R., et al. "Investigation of Silver Biocide as a Disinfection Technology for Spacecraft - An Early Literature Review" |
| AG2 | Maillard J and Hartemann P. "Silver as an antimicrobial: Facts and gaps in knowledge" (2012) |
| AG3 | Silver as a drinking water disinfectant WHO 2018 |
| AG4 | Okkyoung Choia, Kathy Kanjun Dengb, Nam-Jung Kimc, Louis Ross Jr.d, Rao Y. Surampallie,Zhiqiang Hu. The inhibitory effects of silver nanoparticles, silver ions, and silver chloride colloids on microbial growth. Water Research, 47 (2008). |
| AG5 | Zong-ming Xiu, Qing-bo Zhang, Hema L. Puppala, Vicki L. Colvin, and Pedro J. J. Alvarez. Negligible Particle-Specific Antibacterial Activity of Silver Nanoparticles. NANO Letters, 12 (2012). |
| AG6 | Alexander B. Smetana, Kenneth J. Klabunde, George R. Marchin, and Christopher M. Sorensen. Biocidal Activity of Nanocrystalline Silver Powders and Particles. Langmuir, 24 (2008). |
| AG7 | Khaydarov R.R., Khaydarov R.A., Gapurova O., Garipov I., Lutfi Firdaus M. (2019) Silver Nanoparticles as a Biocide for Water Treatment Applications. In: Prasad R., Karchiyappan T. (eds) Advanced Research in Nanosciences for Water Technology. Nanotechnology in the Life Sciences. |
| AG8 | Potter, et. all. A long-term study examining the antibacterial effectiveness of Agion silver zeolite technology on door handles within a college campus. Letters in Applied Microbiology, 60 (2014). |
| AG9 | Podgorni E, et al. The Impact of Nano-Silver Doses on Microorganism-Deactivation Effectiveness in Water Circulating in a Cooling Tower Cycle. |
| AG10 | Bright Kwakye-Awuak, C. Williams, M.A. Kenward, I Radecka. Antimicrobial action and efficiency of silver-loaded zeolite X. Journal of Applied Microbiology, 104 (2008). |
| AG11 | Slote BM, Salley E, Carr D, Kimble MC, Adam N. Silver Ion Biocide Delivery System for Water Disinfection. ICES (2016). |
| AG12 | Biswas, P, et al. Water disinfection using silver nanoparticle-impregnated activated carbon: Escherichia coli cell-killing in batch and continuous packed column operation over a long duration. |
| AG13 | Gossel CA, Callahan MR, Raskovic D. Development of an Electrolytic Silver Biocide Dosing System for Use in a Spacecraft Potable Water Bus. ICES (2017). |
| AG14 | Al-Issai L, et al. Use of Nanoparticles for the Disinfection of Desalinated Water. |

## A.2 Biocidal Precursor

The biocidally active species of chlorine and bromine are the hypochlorous and hypobromous ions, respectively. However, these species are often formed by the reaction of a precursor molecule with water. The identified biocidal precursors are listed in Table A.2-23. The table identifies specific characteristics of these precursors as: 1) particularly suited for this application; 2) may have issues which can be overcome with engineering controls; 3) not approved for use in potable water; 4) ammonium biocide, although it does contain a halide; 5) short storage lifetime; and 6) especially toxic.

***Table A.2-23. Complete List of Chlorine and Bromine Biocides***

- Numerous Cl/Br biocide precursors are available
- Most are toxic in their concentrated form with a few exceptions
- Green – indicates precursors which may be particularly suited for this application: on UMPQUA's list
  Yellow – indicates there may be issues which could be engineered around
- Blue – non-oxidizing biocides and not approved
- Light Red – ammonium biocide, Br is not biocidal
- Red – short lifetime
- Dark Red – indicates especially toxic

| Chlorine list | Bromine list |
|---|---|
| Chlorine dioxide (ClO2) | Bromine (Br2) |
| Chlorine (Cl2) | 1-bromo- 3-chloro- 5,5-dimethylhydantoin |
| Monochloramine (NH2Cl) | Poly-1-bromo-5-methyl-5(4' -vinylphenyl)hydantoin |
| Calcium hypochlorite (Ca(OCl)2) | bromine monochloride (BrCl) |
| Sodium hypochlorite (NaOCl) | 2,2-Dibromo-3-Nitrilopropionamide |
| Halazone | 2-bromo- 2-nitropropane-1,3-diol |
| Sodium dichloroisocyanurate | Domiphen bromide |
| Trichloroisocyanuric acid, (and dichloroisocyanuric acid) | 1,3-Dibromo-5,5-Dimethylhydantoin |
| Chloramine-T | Halogen-binding resin (UMPQUA) |
| Sodium chlorite | |
| Succinchlorimide | |

4

## A.3 Polymer Delivery System – Hydantoin and Isocyanurate

Biocidal precursors present in the form of a solid polymeric material generally pose a minimal health hazard, as that form is well constrained and not prone to spreading, even in microgravity. Poly-1-bromo-5-methyl-5(4'vinylphenyl)-dimethylhydantoin and the UMPQUA's halogen-binding resin are both polymeric materials. The other hydantoins and isocyanurates listed are present in powder or pellet form, but can be polymerized to form polymeric materials. This is effectively the approach UMPQUA took in the development of its resin. The biocidal precursors listed as acceptable, yet having issues to address, are present as pellets, powders, and liquids. They would fall between the extremes described (i.e., volume-filling gas and constrained polymer), and could be managed using engineering controls.

Hydantoins and isocyanurates are two classes of nitrogen-containing ring molecules (Figure A.3-1) used as biocidal delivery systems by the halogenation of their ring nitrogens. This can produce the mono- or di-bromo, mono- or di-chloro, or the mixed bromo-, chloro- variants to achieve the biocidal effect desired. Both the 1,3-dibromo- (Halobrom and Halogene) and the mixed 1-bromo, 3-chloro-5,5-dimethyl hydantoin (from Sigma) are commercially available. Additionally, the poly-chlorinated isocyanurates are available as sodium dichloroisocyanurate (aquatabs) and trichloroisocyanuric acid (and dichloroisocyanuric acid) (from Allchem, Clearon, GE, Medentech, Occidental and Shikoku).

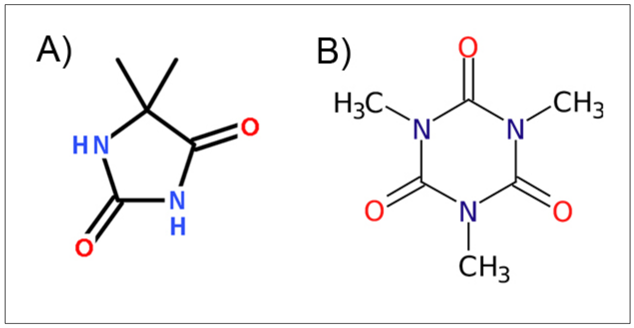



***Figure A.3-1. Two Classes of Molecules That Can Be Used as Biocidal Delivery Systems:***
***a) 5,5-dimethyl hydantoin and b) 2,4,6-trimethyl isocyanurate.***

Several biocidal polymers are commercially available. Some are based on isocyanurates and hydantoins. Hydantoins and isocyanurates can be immobilized to a polymer through one of their methyl groups (Figure A.3-2).

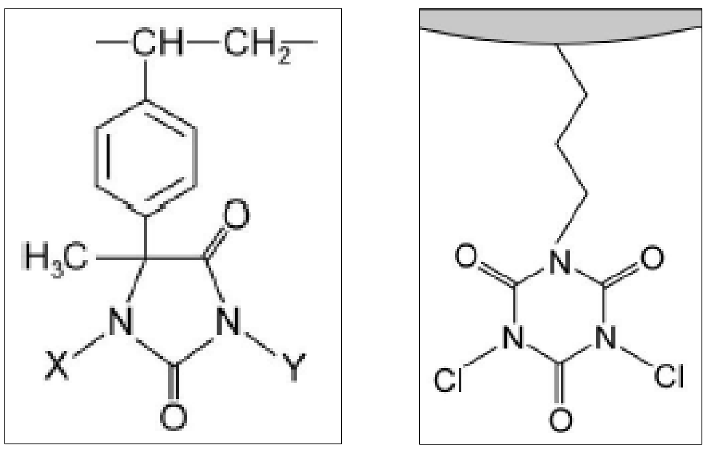


***Figure A.3-2. Examples of Hydantoin (left) and Cyanurate (right) Polymers***

The hydantoins are a class of biocides that contain the hydantoin ring. It is possible to chemically modify this structure through the methyl group and attach it to a polymer backbone, as shown in Figure A.3-2. It is also possible to replace the two hydrogens attached to the nitrogens with halides. Thus, it is possible to make a mono- or di-bromo, mono- or di-chloro, or the mixed bromo-, chloro- variants to achieve the biocidal effect desired.

Only one polymer variant was found commercially (poly-1-bromo-5-methyl-5(4'-vinylphenyl)hydantoin), sold as HaloPure BR. It is sold as a contact disinfectant with only a 0.01-0.05 ppm residual bromine in solution. It is also available as cartridges and resin beads, available as-is or in custom-made filters by HaloSource. It has a demonstrated lifetime of 2 years when stored sealed with a desiccant.

The isocyanurates are commercially available only as a chlorinated biocide. Theoretically, the brominated variant should be possible to produce, but as of yet, no evidence to this effect has been found. A major characteristic of the isocyanurates is that their hydrolysis to produce the biocide also produces free cyanuric acid. In addition to other issues, cyanuric acid interferes with the accurate measurement of biocide concentration. Thus, any system based upon isocyanurates would not have an accurate monitoring system.

An alternative delivery method using polymers is to imbed biocidal particles within a polymer matrix (Figure A.3-3). This has the potential of incorporating a wider variety of properties into the material as the polymer matrix and the biocide could be selected independently, although this method introduces a number of additional risks as well.

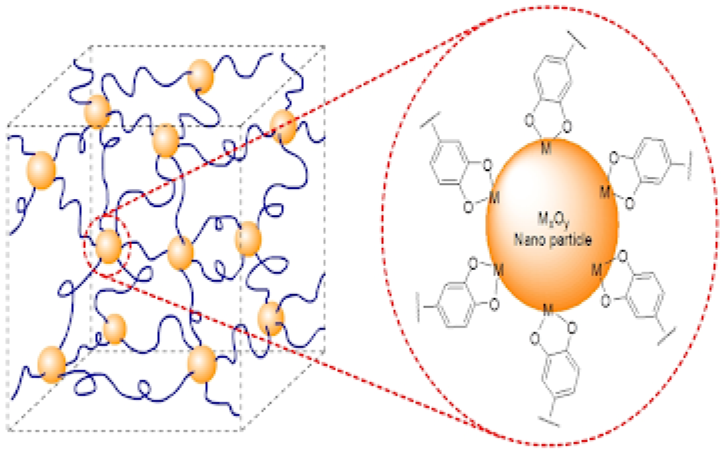



***Figure A.3-3. Nanoparticle Being Incorporated Into Polymer Matrix***

# Appendix B: Toxicological Evaluation of Candidate Biocides for Water in Exploration Vehicles

## B.1 Background and Methods

The scope of Task 2 is to determine the potential health impacts of each candidate biocide during flight and if used as drinking water. This task is composed of three subtasks: A) an evaluation of the Toxicity Hazard Level (THL) per standard NASA procedure for chemical substances flown to ISS, B) an assessment of potential short- and long-term health effects when water treated with the biocide is ingested, and C) a qualitative determination of the potential palatability of biocide-treated water. Upon completion of each subtask, a scoring schema was developed to assess the viability of each candidate biocide based on the findings.

To support these subtasks, information on the toxicological and chemical properties of each candidate biocide were gathered using standard resources employed by JSC Toxicology. These include, but are not limited to: the U.S. National Library of Medicine's Pubchem database and its underlying datasets, the U.S. Environmental Protection Agency's (USEPA) Integrated Risk Information System, the Agency for Toxic Substances and Disease Registry's Toxicological Profiles, the Aggregated Computational Toxicology Resource (ACToR), the High Production Volume (HPV) chemical assessment programs conducted by the USEPA and the Organization for Economic Cooperation and Development (OECD), publicly available safety data sheets and other product materials, and SWEG documents as available. Any other available safety and hazard assessments were also reviewed.

## B.2 Exploration Biocide Candidates

The candidates were based on disinfection using iodine, silver, chlorine, and bromine. Iodine was considered as the baseline option. The possible delivery forms for silver included electrolysis, introduction of concentrated silver salts, controlled release, and ion bed exchange. The possible delivery forms for chlorine included di- and tri-chloroisocyanuric acid, sodium chlorite, chloramine-T, calcium hypochlorite, and chlorosuccinimide. The possible delivery forms for bromine included 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH); 1,3-dibromo-5,5-dimethylhydantoin (DBDMH); and a brominated resin (such as HaloPure BR).

All the proposed disinfectants have been used in applications that include human contact, and in many cases, human consumption. Iodine and silver have been used in spaceflight.

**Task 2A: Determination of Candidate Biocide THL for Exploration Water**

The process for determining the THL is described in JSC 26895 (Table B-1). NASA toxicologists assimilate information on toxicological test data, physical properties, and application of a chemical substance to determine the THL of any chemical (e.g., liquid, solid, gas, particle, gel, particulates/powders) that will fly to the ISS. In many cases, data on the toxicological properties of a chemical substance are not available. At these times, the toxicologist may infer properties from similar substances, using expert judgment.

*Table B-1. Criteria for Designation of Chemical Substance for THL in Spaceflight*

| Toxicity Hazard Level (Hazard classification) (color code) Physical State | Irritancy | Systemic effects | Containability and Mitigation |
|---|---|---|---|
| 0 (Negligible) (Green) Gas, solid, liquid | Slight irritation that lasts <30 minutes and will not require therapy | None | May or may not be containable. No PPE required but may be donned at crew discretion |
| 1 (Critical) (Blue) Gas, solid, liquid | Slight to moderate irritation that lasts >30 minutes and will require therapy | Minimal effects, no potential for lasting internal tissue damage | May or may not be containable. Crew should don PPE according to applicable procedures/flight rules |
| 2 (Catastrophic) (Yellow) Solid or non-volatile liquid | Moderate to severe irritation that has the potential for long-term performance decrement and will require therapy. Eye hazards: May cause permanent eye damage | Minimal effects, no potential for lasting internal tissue damage | Can be disposed of and contained by a cleanup procedure. Crew should don PPE according to applicable procedures/flight rules |
| 3 (Catastrophic) (Orange) Solid or non-volatile liquid | Negligible to severe irritation may accompany systemic toxicity; however, irritancy alone does not constitute a level 3 hazard | Appreciable effects on coordination, perception, memory, etc., or has the potential for long-term serious injury (e.g., cancer), or may result in internal | Can be disposed of and contained by a cleanup procedure. Crew should don PPE according to applicable procedures/flight rules |
| 4 (Catastrophic) (Red) Gas, volatile liquid, or fumes that are **not containable** | Moderate to severe irritancy that has the potential for long-term crew performance decrement (for eye-only hazards, there may be a risk of permanent eye damage). Note: Will require therapy if crew is exposed | Appreciable effects on coordination, perception, memory, etc., or has the potential for long-term serious injury (e.g., cancer), or may result in internal tissue damage | Crew **cannot** contain the spill. The ECLSS may be used to decontaminate. Crew should done PPE according to applicable procedures/flight rules |

To be identified as THL 3, a substance must pose “appreciable effects on coordination, perception, memory, etc. or have the potential for long-term serious injury.” To be identified as THL 4, a substance must a) be either severely irritating or have systemic effects that have the potential for long-term injury and b) not be containable by the crew. In general, spills of gas or large quantities of powders/ particulates may be considered not containable and thus can rise to a THL 4. Biocides that are THL 3 or 4 will not be considered further.

### Task 2B: Assessment of Potential for Long-Term Health Effects From Consumption of Biocide-Treated Drinking Water

Two exposure scenarios were initially considered: 1) one-time exposure to 1L of water treated with the candidate biocide at its effective concentration (analogous to the off-nominal event in which ISS crew member Luca Parmitano ingested leaking water during an EVA in 2013), and 2) long-term consumption of water treated with the candidate biocide for drinking water. However, the second scenario became the driver for scoring of the biocide candidates under Task 2B, as a lack of health effects from long-term consumption would be expected to preclude health effects from a one-time exposure.

The effective concentration of each candidate biocide was used as the exposure concentration in this scenario, and a toxicological assessment was compiled for possible adverse effects of exposure to 2–3.5L of water per day at this concentration. This level of consumption is consistent with terrestrial exposure guidelines and the proposed intake level for crew members during long-term exploration missions (i.e., to lessen the risk of developing renal stones).

**Task 2C: Assessment of Palatability of Biocide-Treated Drinking Water**

Though this is not strictly a toxicological assessment, palatability of drinking water is an important concern for exploration spaceflight. Insufficient hydration is associated with a number of adverse health effects in terrestrial populations, and in spaceflight it increases the risk of the development of renal stones (which could lead, under worst-case scenarios, to loss of mission and/or loss of crew life.

The assessment of palatability of drinking water is fundamentally subjective. There is no physiological outcome to bad-tasting water per se, and so quantitative judgments cannot be rendered. However, information on taste and odor thresholds, where available, were gathered for each candidate biocide along with experiential information from prior studies.

## B.3 Assumptions and Limitations

Several assumptions were made regarding the application of these candidates. Iodine's effective concentration (4 mg/L) is well above the level at which NASA flight surgeons have determined crew members are at greater risk of thyroid dysfunction (Medical Operations Branch, 1998). Thus, it was assumed that iodine would be removed from water prior to crew consumption, but it could be present in system or xEMU water at its effective concentration. It was also assumed that biocide substances to be released from polymeric matrices would be flown to the exploration vehicles wetted, as has been frequently observed on ISS.

In terms of scope, this document does not consider suitability criteria for the biocides other than potential adverse health effects for crew. Potential concerns regarding long-term effectiveness of the biocides, engineering complications, or readiness will be addressed elsewhere. Further, the impact of potential disinfection byproducts has not been robustly considered, as the proposed exposure scenario is not compatible with current scientific understanding of the potential toxicological impacts of such substances. Most safety values for terrestrial populations are set based on lifetime exposures, as opposed to the likely maximum exposure window of three years during exploration missions to Mars (and/or the possible one-year Lunar mission).

## B.4 Review of Candidate Biocides

Data relevant to assessment of THL (Task 2A) and the potential for long-term health effects (Task 2B) will be summarized in the following sections.

### B.4.1 Iodine

Iodine is an essential dietary nutrient. In many countries, addition of iodine to salt has been used to address dietary deficiencies that increase the risk of thyroid cancer. Iodine is commonly used worldwide for disinfection of drinking water (WHO 2018), and iodine pills are commercially available to disinfect water in the field (e.g., while camping). Iodine's effective biocidal concentration has been regarded as between 2.5 and 7.5 mg/L (WHO document). Iodine also has a low vapor pressure and thus is unlikely to volatilize (Black et al., 1970).

Iodine is 100% absorbed in the gastrointestinal (GI) tract. Approximately 25% of any iodine dose is distributed to the thyroid, and as much as 60% is excreted in urine. In the body, most iodine is concentrated in the thyroid (70-90%) where it is incorporated into $T_3$ and $T_4$ hormones. Absorbed iodine is quickly converted to iodide ($I^-$).

Ingested iodine can be fatal at high concentrations (17-120 mg/kg or 1200-9500 mg). Acute iodine toxicity may include acidosis, GI disturbances (vomiting and diarrhea), and CNS effects (seizure, stupor). The critical effect for long-term, low-level iodine exposure is a change in thyroid function, often assessed via circulating levels of TSH, $T_3$, and $T_4$. Numerous studies ranging from 2 weeks to 6 months have determined that exposure levels on the order of 0.4-0.8 mg/day appear to have no discernable adverse health effects in healthy adults.

Numerous expert panels have reviewed the available data and set acceptable daily intake (ADI) or tolerable maximum daily intake (TMDI) values for iodine (reviewed in WHO 2018). For adults, these values generally range from 0.15–0.5 mg/day. As with all safety values, safe levels are determined by adding additional uncertainty factors to protect those who may be vulnerable.

A previous analysis of the potential health effects associated with iodine exposure (Medical Operations Branch, 1998) identified some slight increases in thyroid hormone levels. Generally, the medical community has determined that exposure to iodine in drinking water for short periods will cause transient, reversible effects, but that some sensitive individuals may develop more serious health conditions. As it is difficult to identify sensitive individuals, the medical community at NASA has recommended intake of <0.5 mg/day during long-exposure activities (missions, ground studies). By contrast, some individuals during prior missions were consuming 10-20 mg/day (2-4 L of 4 mg/L iodinated water). As crew experienced only slight effects after prolonged exposures to iodine in drinking water at levels of 10-20 mg/day, a one-time exposure to iodinated water at 4 mg/L in an off-nominal scenario (e.g., as Luca Parmitano experienced in 2013) is not expected to result in adverse health effects.

Given the healthy background of most members of the astronaut corps and the shortened window of exposure to lightly iodinated water, a value of 0.5 mg/day as previously recommended by the flight surgeon community is fully protective of crew health (Medical Operations Branch, 1998). Given the effective concentration of 2-4 mg/L, this would mean that only 125-250 mL of iodinated water could be consumed per day, compared with the approximate requirement for crew members of 2-3.5 L/day. Thus, it is assumed for the purposes of this exercise that iodine is removed from drinking water prior to consumption, as is the practice on the ISS. As a result, ***no long-term health effects would be expected from the application of iodine as an exploration biocide, assuming it is removed prior to consumption.***

The potential presence of iodinated disinfection byproducts (I-DBPs) has raised some concerns about its use. Little toxicological data exists to allow for a robust assessment of these substances, and their presence at relevant concentrations in the controlled environment of the ISS or other vehicle is unlikely. However, a few studies have suggested that I-DBPs may have genotoxic properties that could increase the risks of cancer (Richardson et al., 2007). These studies are based on in-vitro assays, and more robust in-vivo experiments have not been conducted to determine whether the findings translate to animal models. Given the nature of exposures in exploration spaceflight, carcinogenicity or genotoxicity are not relevant toxicological endpoints for assessment (this is generally true for spaceflight exposures, due to the length of missions).

Iodine has previously been delivered to ISS water via a MCV assembly, filled with iodinated Umpqua resin (styrene divinyl benzene). Assuming that the application of iodine to exploration water systems would follow this paradigm, the ***THL for iodine in this instance is THL 0***. The resin is shipped wet, and eye contact with released solution is likely not plausible, but would result in no worse than mild, transient eye irritation.

### B.4.2 Silver

Silver has been used previously in spaceflight applications, going back to the Apollo Program. NASA previously published a document setting a SWEG value for silver (NRC, 2004). This document noted that Russian and U.S. crew members consumed water containing up to 0.5 mg/L in early ISS missions. The target concentration for biocidal effectiveness is 100-400 μg/L (0.1-0.4 mg/L). Silver is in use as a biocide on the Russian segment of the ISS.

Absorption of ingested silver is low in humans, on the order of 4% (NRC 2004). Long-term exposure to silver is commonly associated with argyria (blue-gray discoloration of the neck and face). In laboratory animals, lethargy was noted as a potential sign of neurotoxicity after exposures at higher concentrations in drinking water.

The 1-day and 10-day limit for silver in water is 5 mg/L, based on decreased water consumption in laboratory animals (Table B-2). This response appears to be associated, at least initially, with taste aversion as opposed to an adverse health effect. The 100-day limit is based on an observation of lethargy in mice who received silver in their drinking water for 125 days. The 1000-day limit is 0.4 mg/L, based on human case reports of repeated exposures that resulted in argyria. The 1000-d SWEG is similar to the upper bound of the effective biocidal concentration. For the purposes of comparison, the EPA set a health advisory value of 0.2 mg/L for drinking water. This value is intended to protect all persons (including sensitive subpopulations) from adverse health effects over a lifetime of exposure. Given that the upper limit of biocidal effectiveness for silver is 0.4 mg/L and the 1000-day SWEG for silver is also 0.4 mg/L, ***no long-term health effects are expected from consumption of water treated with silver in this scenario.***

***Table B-2. Spaceflight Water Exposure Guideline Values for Silver (NRC, 2004)***

| SWEG Duration | SWEG Value | Critical Effect |
|---|---|---|
| 1-day | 5 | Decreased water consumption |
| 10-day | 5 | Decreased water consumption |
| 100-day | 0.6 | Neurotoxicity |
| 1000-day | 0.4 | Argyria |

Four delivery methods have been proposed for silver in exploration vehicles: a) introduction of concentrated silver salts (AgF/AgNO3), b) controlled release, c) electrolytic generation of silver, and d) ion bed exchange.

Concentrated silver nitrate (CASRN 7761-88-8) can cause severe eye damage that may lead to blindness (HSDB, Patty's). Silver nitrate at 5-50% causes permanent eye damage with dose-dependent effects that include marked edema and bloody discharge from the conjunctiva. Similar effects are seen whether the silver nitrate is in liquid or solid form. These effects are consistent with an assignment of a THL of 2, indicative of long-term effects and significant tissue damage. Much less toxicological information is available on silver fluoride (CASRN 7775-41-9). However, a report from the U.S. Coast Guard indicates that the substance is irritating to eyes and skin. This is consistent with a THL of 1 or 2.

Electrolytic generation of silver is produced from a solid silver electrode, and in that form, silver (e.g., silver plated on steel) would be judged as a THL of 0 (the electrolyte solution may require a separate toxicological assessment). Similarly, the use of silver embedded in a matrix (e.g., polymer or resin for controlled release or ion bed exchange), regardless of the silver compound used, would be expected to present a THL of 0 (assuming particulate matrices are flown wetted). If dry particulates impregnated with silver nitrate were to be flown, a worst case scenario would result in a THL 2. ***To summarize, the THLs for the delivery forms of silver to exploration water systems range from THL 0-2.***

### B.4.3 Chlorine and Bromine

Both chlorine and bromine have been used to disinfect drinking water and swimming pools. In such situations, the candidate biocides are engineered to release free halogen molecules. Thus, a consideration of the toxicological implications of these biocides requires examination of the properties of free chlorine and bromine, the chlorinated or brominated substances (e.g., sodium diisocyanurate), and the parent compounds—to the extent that this is possible. It is also important to distinguish between the physical forms of chlorine and bromine: Chlorine in its gaseous form is a highly hazardous substance, bromine less so. However, in water these substances are relatively non-toxic.

The active chemical form of these halogenated biocides is ClO or BrO, though there is evidence to support HOCl or HOBr (NRC, 2004). Many of the brominated or chlorinated substances used for disinfection of water are provided as solids, granules, or powders. It is possible that these disinfectants may be immobilized on a resin or polymer before being flown (e.g., the impregnated Umpqua resin being used on the ISS). Depending on the nature of the resin or polymer, it would be expected that these would be regarded as THL 0, as the native substance would not be available for exposure to the crew. However, considering a worst-case scenario in which dry particulates impregnated with the most acutely toxic substances to the eye were released on-orbit, these would not be expected to create a THL greater than 2.

The U.S. National Toxicology Program conducted a two-year study of chlorinated drinking water in rats and mice (NTP, 1992). Groups of 70 rats of both sexes were exposed to water containing chlorine at 0, 70, 140, or 275 ppm for up to two years. This study observed “no clinical findings attributable to the consumption of chlorinated water.”

The EPA has set a maximum contaminant limit (MCL) for drinking water of 4 mg/L for free chlorine (EPA 2018). WHO has promulgated a guideline value of 5 mg/L, based on NTP’s study (NTP, 1992). As previously discussed, these safety values are set for terrestrial populations that include sensitive groups (i.e., elderly persons, children, persons with existing disease) and thus are frequently considered conservative with respect to the crew population.

Given the widespread use of chlorinated drinking water, exposure to swimming-pool water (which is chlorinated at higher concentrations) and the availability of a robust chronic study in laboratory animals, ***it is reasonable to conclude that the use of chlorine at these levels in drinking water is unlikely to be associated with long-term health effects***. The chlorinated substances will be evaluated separately, though it is justified to extrapolate the conclusion above to sodium chlorite and calcium hypochlorite, which are inorganic chlorine salts.

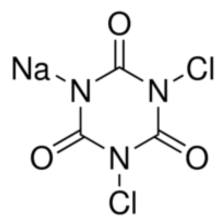
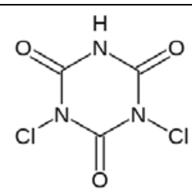
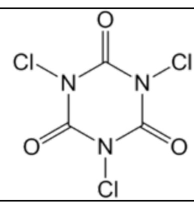
Bromine has predominantly been used in cooling towers and swimming pools, as opposed to drinking water disinfection. It has been used, however, to disinfect drinking water aboard ships and submarines. In some of these applications, reverse osmosis systems are used as a final step to remove much of the bromine prior to consumption.

The WHO has set an ADI for bromine of 0.4 mg/kg body weight, resulting in a safe consumption level of 0.5 mg/L. This value was based on minor changes detected in electroencephalograms (that were within normal limits) in women who ingested 9 mg sodium bromide/kg day (Sangster et al., 1986 as summarized by WHO, 2009). NSF International has proposed a safety level of 10 mg/L (NSF, 2011) based on the same study.

Given the available data, and noting its deficiencies, ***it is reasonable to conclude that the use of bromine at effective levels in drinking water is unlikely to cause adverse long-term health effects for exposure durations of three years or fewer***. The brominated hydantoins will be evaluated separately.

### B.4.4 Sodium Dichloroisocyanurate and Di- and Tri-Chloroisocyanuric Acid

***Table B-3. Chlorinated Isocyanurates***

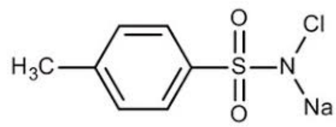
| | | |
|---|---|---|
| CAS: 2893-78-9 |  | MW: 286 g/mol |
| CAS: 2783-57-2 |  | MW: 198 g/mol |
| CAS: 87-90-1 |  | MW: 232 g/mol |

Chemically, the chlorinated isocyanurates are functionally equivalent and thus will be treated as a group in this section. Sodium dichloroisocyanurate (NaDCC) is recommended by the WHO for treatment of surface water in the field. Tablets are commercially available for this purpose. NaDCC is also used for disinfection of swimming pools and in sanitation in the food industry. The toxicological properties of this disinfectant were reviewed by Clasen and Edmonson (2006). As with most other chlorine-bearing disinfectants, NaDCC can cause significant eye damage as well as skin and eye irritation. An EPA review of ocular toxicity testing concluded that this substance is “no more than slightly toxic and corrosive.” This finding is consistent with a study in rabbits that suggested no treatment-related effects on eye irritation. As a worst case, the chlorinated isocyanurate conjugates are judged to be a ***THL 1***.

The Joint Food and Agriculture Organization/WHO Expert Committee on Food Additives (JEFCA) set a tolerable daily intake limit of 2 mg/kg/day for NaDCC in drinking water (WHO, 2004b). Under the proposed exposure scenario, the effective concentration is > 150-fold lower than the TDI. Sodium diisocyanurate and its parent compound have been observed to cause calculi in the urinary tract; this finding may be of concern given that crew members are thought to be at increased risk of developing renal stones during long-term missions (Tice, 1997; WHO, 2008). However, these observations occurred at high dose levels, far above the exposure concentrations expected in this scenario. ***With that caveat, the chlorinated isocyanurates are not believed to pose a risk of adverse long-term health effects for crew members on exploration missions.***

### B.4.5 Chloramine-T

***Table B-4. Chloramine-T***

| | | |
|---|---|---|
| CAS: 127-65-1 |  | MW: 228 g/mol |

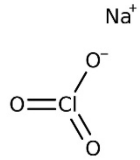
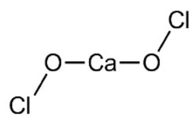
Simple chloramines are currently used to disinfect drinking water in major U.S. cities, including Philadelphia, San Francisco, Tampa Bay, and Washington, D.C. Chloramine concentrations up to 50 mg/L have been regarded as safe. The scheme at water treatment plants is to add chlorine and ammonia at a ratio that will maximize the formation of monochloramine and minimize the formation of di- and trichloramine. The chlorine is added using gas or hypochlorites, but in water it exists as the hypochlorite ion or hypochlorous acid. The use of pure chlorine gas and ammonia on exploration vehicles is obviously not a feasible alternative for engineering or health reasons. Thus, mono-, di-, and trichloramines were previously discarded as candidates for the exploration biocide.

The more complex substance Chloramine-T is not used for water disinfection except in emergency situations. It is primarily used as a disinfectant in hospitals and in agricultural applications, including direct use on cats, cattle, dogs, domestic birds, goats, horses, pigs, poultry, and sheep. It has also been used as a bactericidal mouthwash in dental practice and for disinfection of wounds (Haneke, 2002). Contact with eyes is irritating and causes conjunctivitis, but no serious injury; this is consistent with a ***THL 1***.

In two subchronic studies (5 and 17 weeks), high doses (up to 640 mg/kg) of intravenous chloramine-T produced adverse effects in dogs, including anemia and lung damage. The utility of this study is unclear in this context, as the doses expected in humans would be < 1 mg/kg. Also, dogs and rats ingesting chloramine-T in their food for 90 days experienced no treatment-related effects. Based on this relatively scanty data, ***it appears that chloramine-T is unlikely to produce adverse long-term health effects*** if used at levels designed to produce 4 mg/L free chlorine.

### B.4.6 Sodium Chlorite and Calcium Hypochlorite

***Table B-5. Sodium Chlorite and Calcium Hypochlorite***

| | | |
|---|---|---|
| CAS: 7758-19-2 |  | MW: 90 g/mol |
| CAS: 7778-54-3 |  | MW: 143 g/mol |

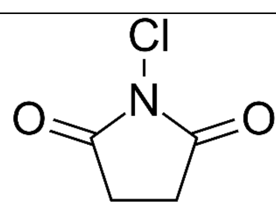
The safety of sodium chlorite for use in drinking water has been assessed by WHO and others. WHO has set a TDI of 0.03 mg/kg. Given its reactivity, it is not surprising that eye contact with sodium chlorite can cause severe irritation to eyes, consistent with a ***THL of 2***. Ten male volunteers consumed 500 mL solutions of 5 mg/L sodium chlorite daily for 12 weeks. No clinical or physiological changes were detected (Lubbers et al., 1984). Numerous studies have examined communities with chlorine dioxide (i.e., chlorite) disinfected water (reviewed in EPA 2000). No health effects were observed. ***Given this data, the use of sodium chlorite is not expected to cause adverse long-term health effects.***

Calcium hypochlorite is a common product used for chlorine-based disinfection. In particular, it is used as “pool shock.” Generally, it is purchased in powder or granular form that carries a chlorine odor. The pH of a concentrated calcium hypochlorite solution is 10.8, consistent with a ***THL of 2***. The powder or liquid form would be expected to cause eye irritation and possible injury. Inhalation is also associated with respiratory irritation including burning and sore throat, wheezing, labored breathing and shortness of breath (HSDB). As previously discussed, the presence of a large mass of particles of any kind in the open cabin might pose a physical hazard. Previous work on calcium hypochlorite has suggested that it might be flown as imbedded granules; depending on how this was achieved, it might be regarded as a THL 0 (i.e., the substance could not be liberated, so exposure is implausible).

With regard to long-term health effects, this substance should be considered in the context of the NTP study cited above (NTP, 1992). ***The use of calcium hypochlorite for water disinfection does not appear to pose long-term health risks for crew members on exploration missions up to three years.***

### B.4.7 Chlorosuccinimide

***Table B-6. N-chlorosuccinimide***

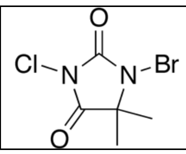
| | | |
|---|---|---|
| CAS: 128-09-6 |  | MW: 134 g/mol |

N-chlorosuccinimide is also used to sanitize swimming pools, and has been tested in prevention of membrane biofouling in reverse osmosis systems (Yu et al., 2015). It can be purchased mostly as a white solid, with the odor of chlorine. Little toxicological information is available; however, chlorosuccinimide does appear to carry a risk of corneal damage or blindness in the event of eye contact (***THL 2***). No information on the extent of eye contact was available. Similarly, this substance was reported to be a severe irritant to skin and the respiratory tract. Following 5 weeks of intermittent oral exposures at 5800 mg/kg BW, some changes in red blood cells were observed. As with the previous compounds, the remaining parent compound ***succinimide does not appear pose a risk to human health at the concentrations used in this application***.

Succinimide (123-56-8) is not irritating to skin (REACH dossier), but does cause reversible irritation to eyes at high concentrations (i.e., 1 g/mL). No information on ingestion is available beyond an LD50 of 11 and 14 g/kg BW in mice and rats, respectively. This generally indicates low toxicity.

### B.4.8 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH)

***Table B-7. BCDMH***

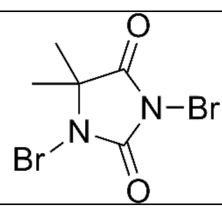
| | | |
|---|---|---|
| CAS: 16079-88-2 |   | MW: 242 g/mol |

According to the Hazardous Substances Data Bank (HSDB), this substance causes irreversible eye damage and skin burns on contact. This information was reported by one of the manufacturers of BCDMH in its EPA pesticide registration dossier. Based on this information, this substance is assigned a ***THL of 2***.

Relatively little data is available on the toxicity of BCDMH, but more is available on the parent compound (5,5-dimethylhydantoin). Administration of this compound at relatively high concentrations in the diets of rats and dogs over 78 to 104 weeks resulted in no adverse health effects (summarized in HSDB). This compound is expected to release bromine, and the parent compound will remain. It is reasonable to assess the toxicological effects as a potential combination of bromine and 5,5-dimethylhydantoin. Given the available information, ***it is reasonable to conclude that the use of this substance will pose no risk of adverse long-term health effects.***

### B.4.9 1,3-dibromo-5,5-dimethylhydantoin (DBDMH)

***Table B-8. DBDMH***

| | | | |
|---|---|---|---|
| CAS: 77-48-5 |   | MW: 286 g/mol | Effective concentration: |

The EPA has proposed a Preliminary Contaminant Candidate List value of 0.44 mg/kg/day for DBDMH. This value is based on a LOAEL from a 17-week animal study, which suggested decreased thyroid activity at that dose level. Under the current exposure scenario, a concentration of >3.6 g/L would be required to breach that screening level, orders of magnitude beyond the proposed concentration. This is relatively poor data, but given the large margin between the safe level assigned by EPA and the effective concentration, ***it is reasonable to conclude that***

***DBDMH represents no risk of adverse long-term health effects***. Data is lacking for ocular irritation effects of DBDMH, but it is also reasonable to conclude that it bears similar effects on eyes and skin as BCDMH, and thus a tentative worst-case ***THL of 2*** is assigned for this substance.

### B.4.10 Poly-1-bromo-5-methyl-5(4'-vinylphenyl) hydantoin (HaloPure BR)

According to the 2009 pesticide registration for HaloPure BR (HaloSource Inc., 2009), this substance is corrosive and can cause irreversible eye damage and is harmful if swallowed or inhaled. This is consistent with a worst-case ***THL of 2***. The THL may be adjudicated differently if this polymeric compound is flown in an assembly similar to the MCV, and wetted.

As with most specialty substances and polymers, detailed toxicological information is not available. Based on expert judgment, it is unlikely that the polymeric hydantoin will pose any risk to human health through ingestion. Polymers in general are favored in these applications because they are not bioavailable (i.e., they cannot be taken up by the body through the GI tract, and thus exposure does not functionally occur). The question of potential long-term health effects should be considered solely a function of the release of bromine, and therefore ***this candidate is not expected to pose a risk of adverse health effects to the crew***.

## B.5 Palatability

Palatability, with odor and taste as proxy measures, is an immensely important issue for terrestrial water treatment. Citizens who receive their water from a municipal water treatment facility are likely to be concerned about the safety of the water if an objectionable taste or odor is present.

The odor and taste thresholds for substances in drinking water are tremendously variable among demographics and individuals. For example, in a study conducted by Piriou et al. (2004), French participants had an odor threshold of chlorine of 0.2 mg/L compared with 1.1 mg/L for American panelists. Testing using a "Taste and Odor Wheel," as devised by the water resource community has demonstrated that bromine and chlorine produce a "chlorinous" odor, and that these odors are produced by chlorinated organic compounds more so than by the free chlorine and bromine equivalents (McDonald et al., 2009). Numerous studies have demonstrated that halogenated compounds found in drinking water can have odor thresholds in the pg/L range. The propensity of an exploration water system to form these compounds, in comparison to a more complex terrestrial municipal water treatment and delivery system, is a subject for further investigation.

### B.5.1 Iodine

The taste threshold for iodine is 0.15-0.2 mg/L in water (WHO 2003a). The biocidal concentration for iodine is 2.5-7.5 mg/L, but the recommended concentration for crew health is <0.5 mg/L. Analysis of drinking water on the ISS demonstrates that removal of iodine is effective (e.g., <0.05 mg/L). If removal is performed in exploration systems as it is performed on the ISS, then iodine-purified water would not be expected to have palatability issues from a taste perspective. However, if iodine were to be consumed near the recommended maximum level of 0.5 mg/L or the biocidal concentration, palatability issues may become a concern. Iodine has a low vapor pressure, so it is not plausible that it would reach the odor threshold of 0.9 $mg/m^3$.

### B.5.2 Silver

The effective biocidal concentration of silver is 0.1 – 0.4 mg/L. The upper limit coincides with the 1000-day SWEG level adopted by NASA (NRC). An explicit taste threshold could not be identified. Investigators theorized that body weight losses in laboratory animals consuming silver-treated water may be attributable to taste aversion. Previous ISS crew experience indicates that the silver-treated water from the Russian segment does have a noticeable metallic taste. Russian crews treat their drinking water with salts, and the justification for this treatment has been described alternatively as improving the taste of the water and maintaining proper electrolyte balance in crew members. The long-term use of this approach in spaceflight suggests two issues: that the taste threshold of silver is below the effective biocidal concentration, and that an existing approach is available to address this concern.

### B.5.3 Chlorine

The taste threshold for chlorine in water is as low as 0.3 mg/L, compared with the effective biocidal concentration of 4 mg/L. chlorinated water and the various alternatives for introducing chlorine into the system will also carry significant odor, as chlorine has a very low vapor pressure. According to the WHO, chlorinated water becomes increasingly unpalatable as concentrations of free chlorine increase above 1 mg/L (WHO, 2004). Per WHO, the taste threshold of chlorine is well below its biocidal concentration (as low as 0.3 mg/L). It is also clear that adaptation to chlorine in drinking water occurs, such that odor thresholds rise in those who obtain their drinking water from chlorinated systems (McDonald et al., 2009).

One group of disinfection byproducts, trihalomethanes, carry what is described as a medicinal, or sweet/flowery odor, similar to the odor of chloroform or bromoform.

Chlorine should be distinguished from chloride (a negatively charged chlorine ion). Chloride is generally assessed as sodium chloride, and its taste is likely to present as salty. The taste threshold for chloride is on the order of 200-300 mg/L (Dietrich et al., 2015).

### B.5.4 Bromine

As mentioned, brominated water carries a significant odor. The odor threshold ranges from 0.05 to 3.5 mg/L (McDonald et al., 2009; WHO 2018b), while the effective concentration for bromine is on the order of 4 mg/L. The taste threshold for bromophenols has been determined to be in the ng/L range (Piriou et al., 2007). Persons exposed to bromine odor often cannot distinguish it from chlorine odor, but some participants in taste/odor studies have described it as musty or earthy.

### B.5.5 Conclusion

Consumption of water treated with silver, chlorine, or bromine is expected to pose some issues of palatability for crew members. In particular, chlorine and bromine bear pungent odors that may be noisome, though there is evidence of adaptation for chlorinated water. Disinfection of drinking water through chlorination has a long history in the United States and elsewhere, and thus its palatability is better understood. Chlorine levels in treated drinking water fall as they approach the point of consumption, per municipal infrastructure design. Bromine may pose a larger palatability concern. Silver has been consumed on the Russian segment of the ISS for a number of years, and its palatability issues appear to be manageable. Iodinated water also has palatability issues at the effective concentration, but for the purposes of this exercise it was assumed that iodine would be removed prior to consumption.

The palatability of brominated water in particular constitutes a data gap, as there is no systematic data to support a robust judgment. Should this candidate score highly on other criteria in other tasks, a study would be needed to determine whether palatability concerns would affect crew consumption rates. The primary concern would be lowered consumption, leading to an increased risk of renal stones in crew members on long-term exploration missions (Lunar or Mars).

## B.6 Scoring

Each candidate biocide was evaluated against two separate rubrics. The goal, of course, is to examine the critical characteristics of the biocides, their toxicological properties, the palatability of each, and the data available to support robust decision-making. Thus, two custom rubrics were created in hopes of providing sufficient discrimination among the candidates and supporting understanding of the implications of each biocide in the trade space.

### B.6.2 Aggregate Rubric

The second, aggregate rubric included separate judgements on palatability, THL, the potential for long-term health effects, and data availability. The narrative descriptions for these criteria are summarized in the following tables. At times, it was difficult to fully separate the long-term health effects from data availability, as understanding those health effects is dependent on the availability of chronic toxicological studies conducted according to international regulatory standards. Alternative approaches to scoring for THL were also considered, including the use of a pass-fail criterion for THL, as the original scope had been to exclude any candidate assigned a THL of 3 or 4. It is fairly common to fly substances with THLs of 2.

***Table B-10. Narrative Descriptions for Scoring Criteria for Palatability***

| Numerical score | Criterion Narrative |
|---|---|
| 4 | No taste or palatability issues are expected at the effective concentration. |
| 3 | Minor taste or odor issues are expected at the effective concentration, but can be addressed. |
| 2 | Significant taste or odor issues are expected at the effective concentration, likely to lead to a reduction in crew consumption. |
| 1 | Taste or odor of water at biocidal concentrations is unacceptable to crew members. |

*Table B-11. Narrative descriptions for scoring of THL assignments*

| Numerical score | Criterion Narrative |
|---|---|
| 4 | THL 0 (marginal) |
| 3 | THL 1 (critical) |
| 2 | THL 2 (catastrophic) |
| 1 | THL 3 (catastrophic) |
| 0 | THL 4 (catastrophic) |

*Table B-12. Narrative Descriptions for Scoring Criteria for Long-Term Health Effects*

| Numerical score | Criterion Narrative |
|---|---|
| 4 | No effects expected. |
| 3 | Minor effects possible, which could be managed through treatments or other countermeasures. |
| 2 | Long-term health effects expected which would require treatment during or post flight, but will have only minor effects on crew performance during the mission. |
| 1 | Significant health effects expected that could cause adverse performance effects in crew, possibly leading to Loss of Mission Objectives, Loss of Mission, or Loss of Crew Life. |

*Table B-13. Narrative Descriptions for Scoring Criteria for Data Availability*

| Numerical score | Criterion Narrative |
|---|---|
| 3 | The available data is sufficient (including data from studies in humans), and existing assessments support robust decision-making. |
| 2 | The available data lacks one or more endpoints necessary for robust decision-making. |
| 1 | Insufficient or no data is available upon which to base an assessment. |

### B.6.1 All-Encompassing Rubric

The first rubric (Table B-9) attempts to incorporate broad considerations with regard to toxicological properties, data availability, palatability, and uncertainty. A scoring scale of 0-5 was established.

***Table B-9. Narrative Descriptions of Scoring Criteria for All-Encompassing Rubric***

| Numerical score | Criterion Narrative |
|---|---|
| 5 | The best option in this criteria. No short- or long-term toxicological concerns (marginal), no palatability concerns, sufficient data is available to make a robust judgment. |
| 4 | Excellent option in this criteria. Minimal toxicological (marginal) and palatability concerns, available data is adequate. |
| 3 | Very good option in this criteria. Few negative factors that are easily accommodated. Potential for minor toxicity (critical) or palatability issues, available data is adequate. |
| 2 | Good option in this criteria. Has negative factors that can be accommodated, but with impacts. Potential for minor toxicity (critical) or palatability issues, or available data is insufficient for robust assessment. |
| 1 | Option is minimally acceptable in this criteria, but may require countermeasures. Has a number of negative factors that can be accommodated but with significant impacts. Potential for serious, irreversible, or long-term toxicity (catastrophic), significant concerns with palatability, and/or little to no data availability. |
| 0 | Option is not acceptable in this criteria, one or more significant problems/impacts that cannot be accommodated within reason. One or more 'showstoppers'. High potential for serious, irreversible, or long-term toxicity (catastrophic), significant concerns with palatability, and/or little to no data availability |

### B.6.3 Scoring Outcomes

The candidate biocides that were assigned the highest scores were iodine (5/5, 15/15), and silver from electrolysis (5/5, 14/15) or controlled release/ion exchange (5/5, 14/15) (Tables B-14,1-3). Two of the chlorinated candidates scored highly (isocyanuric acid conjugates (4/5 and 12/15), though all of the chlorinated and brominated candidates received lower scores in the aggregate rubric for palatability. Brominated candidates scored lowest (3/5, 10-11/15) because of higher THLs, poor palatability, and data availability scores.

The ranges within each rubric and subcategory clustered relatively closely. For example, all candidates were judged to be 4 on long-term health effects, as no effects were expected from exposure to any of them at effective concentrations over the likely 3-year exposure window. Several were ranked lower on data availability, including chloramine-T, chlorosuccinimide, and the brominated hydantoin compounds. The brominated polymer (HaloPureBR) rated more highly because the delivery method should impart only bromine to the water.

As expected, scores were relatively similar within the candidate biocide groups (silver, bromine, and chlorine). All three bromine candidates were judged as a 3 in the all-encompassing rubric and 10-11 in the aggregate rubric. Several of the chlorinated candidates also fell into this lower tier, but the chlorinated isocyanurates were judged to be a 4 and 12.

The main discriminator separating the bromine and chlorine candidates from silver and iodine was palatability. As noted, prior experience with chlorinated and brominated water indicates that water at the effective concentration will bear noticeable odor and taste that may affect consumption rates. This is a significant data gap that may need to be addressed; terrestrially, the chlorine residual decreases in municipal water systems as distance from the treatment plant increases. This, coupled with in-home treatments (e.g., reverse osmosis, carbon filtration, Brita filters, filters on refrigerators) make it unlikely that most people will encounter chlorine in their drinking water at a level they would detect through odor or taste. It is expected that bromine will behave in a similar fashion, though it is not used for municipal water treatment. This paradigm is analogous to the removal of iodine from water on the ISS prior to consumption.

Given the difficult interplay between long-term health effects and data availability, the all-encompassing rubric might be the better paradigm for judging the candidates.

## *Table B-14.1. Scoring Outcomes for Iodine and Silver Candidates*

| Candidate | AER (0-5) | Overall | Palatability (1-4) | | Toxicity Hazard Level (0-4) | | Long-term Health Effects (1-4) | | Data Availability (1-3) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Iodine | 5 | 15 | 4 | Assuming that iodine will be removed from drinking water prior to consumption, the palatability is not an issue. However, the taste threshold for iodine is as low as 0.146 mg/L, well below the effective concentration. | 4 | THL 0: This material has previously been assessed by JSC Toxicology in spaceflight applications (ISS, Shuttle) | 4 | NASA has recommended that intake be limited to <0.5 mg/day during long duration activities (e.g., missions, ground studies). | 3 | Plentiful data is available, and an assessment of health effects is available for crew members. |
| Electrolytic silver | 5 | 14 | 3 | Silver treated water has no odor, but it does have a noticeable taste, per crew experience. Russian colleagues treat their water with salt solutions, and the reasons given for this include improvement of taste and management of electrolyte levels in crew. | 4 | THL 0: No exposure to silver would be expected from a solid silver electrode. | 4 | NASA has developed a 1000-d SWEG for silver (0.4 mg/L). This value is at the upper limit of biocidal effectiveness; during a potential 3 year exploration mission to Mars, the margin between average exposure and the safety value will be small. However, the critical effect is cosmetic and not expected to cause performance decrements. | 3 | Plentiful data is available, and a Spaceflight Water Exposure Guideline value is available. |
| Slow release silver | 5 | 14 | 3 | Silver treated water has no odor, but it does have a noticeable taste, per crew experience. Russian colleagues treat their water with salt solutions, and the reasons given for this include improvement of taste and management of electrolyte levels in crew. | 4 | THL 0: Exposure would not be expected, as microbial check valves are typically shipped with wet resin. | 4 | NASA has developed a 1000-d SWEG for silver (0.4 mg/L). This value is at the upper limit of biocidal effectiveness; during a potential 3 year exploration mission to Mars, the margin between average exposure and the safety value will be small. However, the critical effect is cosmetic and not expected to cause performance decrements. | 3 | Plentiful data is available, and a Spaceflight Water Exposure Guideline value is available. |
| AgF | 4 | 13 | 3 | Silver treated water has no odor, but it does have a noticeable taste, per crew experience. Russian colleagues treat their water with salt solutions, and the reasons given for this include improvement of taste and management of electrolyte levels in crew. | 3 | THL 1: The available information indicates that silver fluoride is irritating to eyes and skin. | 4 | NASA has developed a 1000-d SWEG for silver (0.4 mg/L). This value is at the upper limit of biocidal effectiveness; during a potential 3 year exploration mission to Mars, the margin between average exposure and the safety value will be small. However, the critical effect is cosmetic and not expected to cause performance decrements. | 3 | Plentiful data is available, and a Spaceflight Water Exposure Guideline value is available. |
| AgNO3 | 4 | 12 | 3 | Silver treated water has no odor, but it does have a noticeable taste, per crew experience. Russian colleagues treat their water with salt solutions, and the reasons given for this include improvement of taste and management of electrolyte levels in crew. | 2 | THL 2: Silver nitrate as a powder or concentrated solution can cause permanent eye damage. | 4 | NASA has developed a 1000-d SWEG for silver (0.4 mg/L). This value is at the upper limit of biocidal effectiveness; during a potential 3 year exploration mission to Mars, the margin between average exposure and the safety value will be small. However, the critical effect is cosmetic and not expected to cause performance decrements. | 3 | Plentiful data is available, and a Spaceflight Water Exposure Guideline value is available. |

# *Table B-14.2. Scoring Outcomes for Chlorine Candidates*

| Candidate | AER (0-5) | Overall | Palatability (1-4) | | Toxicity Hazard Level (0-4) | | Long-term Health Effects (1-4) | | Data Availability (1-3) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sodium diisocyanurat | 4 | 12 | 2 | All chlorinated waters and the products used to treat them will have a noticeable odor. The taste threshold is variable and can be as low as an order of magnitude below the effective concentration, so it must be expected that water purified using chlorine will have a noticeable taste. | 3 | THL 1: An EPA review determined that this substance is "no more than slightly toxic and not corrosive." A study in rabbits indicated relatively minor, reversible eye irritation. | 4 | WHO has established a guideline value of 50 mg/L based on chronic data from rats. This is well above the concentration required for biocidal effectiveness. | 3 | Numerious toxicological reviews are available, as NaDCC has broad use in emergency water purification. |
| Di- and tri-chloroisoc | 4 | 12 | 2 | All chlorinated waters and the products used to treat them will have a noticeable odor. The taste threshold is variable and can be as low as an order of magnitude below the effective concentration, so it must be expected that water purified using chlorine will have a noticeable taste. | 3 | THL 1: An EPA review determined that this substance is "no more than slightly toxic and not corrosive." A study in rabbits indicated relatively minor, reversible eye irritation. | 4 | WHO has established a guideline value of 50 mg/L based on chronic data from rats. This is well above the concentration required for biocidal effectiveness. | 3 | Numerious toxicological reviews are available, as NaDCC has broad use in emergency water purification. |
| Sodium chlorite | 3 | 11 | 2 | All chlorinated waters and the products used to treat them will have a noticeable odor. The taste threshold is variable and can be as low as an order of magnitude below the effective concentration, so it must be expected that water purified using chlorine will have a noticeable taste. | 2 | THL 2: Substance causes irritation and serious eye damage in rabbits. Safety data sheets describe the damage as irreversible. | 4 | A study in 10 male volunteers revealed no clinically significant changes when sodium chlorite was ingested at 5 mg/L in 500 mL for 12 weeks. No toxicological findings were observed in mice fed up to 100 mg/L sodium chlorite for up to 90 days. However, sodium chlorite may cause low levels of hemolytic anemia in susceptible individuals. | 3 | EPA has thoroughly reviewed this substance and generated an RfD. |
| Chloramine-T | 3 | 10 | 2 | All chlorinated waters and the products used to treat them will have a noticeable odor. The taste threshold is variable and can be as low as an order of magnitude below the effective concentration, so it must be expected that water purified using chlorine will have a noticeable taste. | 3 | THL 1: This substance is irritating to eyes, causing conjunctivitis, but the injury is not regarded as serious. | 3 | Robust assessment of potential for LTHE is not available, given the available data. | 2 | A toxicological review is avialable from NIEHS, but the dataset for this substance is not sufficient for assessment of LTHE. |
| Calcium hypochlorite | 3 | 11 | 2 | All chlorinated waters and the products used to treat them will have a noticeable odor. The taste threshold is variable and can be as low as an order of magnitude below the effective concentration, so it must be expected that water purified using chlorine will have a noticeable taste. | 2 | THL 2: This substance is regarded as causing severe, deep eye and skin irritation. | 4 | No LTHE would be expected. | 3 | This substance is very well understood given prior experience in water disinfection and use of a similar substance (sodium hypochlorite). |
| Chlorosuccinamide | 2 | 10 | 2 | All chlorinated waters and the products used to treat them will have a noticeable odor. The taste threshold is variable and can be as low as an order of magnitude below the effective concentration, so it must be expected that water purified using chlorine will have a noticeable taste. | 2 | THL 2: Exposure to this substance carries a risk of corneal damage or blindness in the event of eye contact. | 4 | The risk for LTHE is regarded as low, though no chronic toxicological test data is available. | 2 | Data availability is good for acute effects, but poor for subchronic or chronic effects (either for the substance or its non-chlorinated congener). |

## *Table B-14-3. Scoring Outcomes for Bromine Candidates*

| Candidate | AER (0-5) | Overall | Palatability (1-4) | | Toxicity Hazard Level (0-4) | | Long-term Health Effects (1-4) | | Data Availability (1-3) | |
|---|---|---|---|---|---|---|---|---|---|---|
| BCDMH | 3 | 10 | 2 | The taste threshold for bromine in water is as low as 0.168 mg/L, well below its biocidal concentration. Its odor concentration is lower than chlorine and the odor of bromine is described as very potent. | 2 | THL 2: According to HSDB, this substance causes irreversible eye damage and skin burns. | 4 | The WHO has set a drinking water guideline of 6 mg/L for adults, and NSF International has recommended an action level of 10 mg/L for bromine and bromide. A much lower safety value is available for bromate (10 ug/L), but formation of this species is usually associated with ozonation of drinking water. The potential long-term toxicity of the hydantoin compounds is likely to be low, but little specific information is available to assess them (as municipal water systems use other purification techniques such as UV/photodegradation or ozonation which degrade these complex molecules). | 2 | Data and safety values are available for bromine, bromide, and bromite in drinking water. However, long-term exposure data is somewhat lacking for the hydantoin compounds. |
| DBDMH | 3 | 10 | 2 | The taste threshold for bromine in water is as low as 0.168 mg/L, well below its biocidal concentration. Its odor concentration is lower than chlorine and the odor of bromine is described as very potent. | 2 | THL 2: Data is lacking, but this substance is expected to be strongly irritating to eyes and skin, as BCDMH is. | 4 | The WHO has set a drinking water guideline of 6 mg/L for adults, and NSF International has recommended an action level of 10 mg/L for bromine and bromide. A much lower safety value is available for bromate (10 ug/L), but formation of this species is usually associated with ozonation of drinking water. The potential long-term toxicity of the hydantoin compounds is likely to be low, but little specific information is available to assess them (as municipal water systems use other purification techniques such as UV/photodegradation or ozonation which degrade these complex molecules). | 2 | Data and safety values are available for bromine, bromide, and bromite in drinking water. However, long-term exposure data is somewhat lacking for the hydantoin compounds. |
| HaloPureBR | 3 | 11 | 2 | The taste threshold for bromine in water is as low as 0.168 mg/L, well below its biocidal concentration. Its odor concentration is lower than chlorine and the odor of bromine is described as very potent. | 2 | THL 2: Product literature indicates that this substance is corrosive and can cause irreversible eye damage. | 4 | The WHO has set a drinking water guideline of 6 mg/L for adults, and NSF International has recommended an action level of 10 mg/L for bromine and bromide. A much lower safety value is available for bromate (10 ug/L), but formation of this species is usually associated with ozonation of drinking water. The release of bromine from the polymeric hydantoin should not carry the uncertainty of the free hydantoins, so concerns about LTHE would be lower. | 3 | Data and safety values are available for bromine, bromide, and bromite in drinking water. |

## B.7 Uncertainty

As in all risk assessments, numerous sources of uncertainty should be considered when reviewing the conclusions of this exercise.

### B.7.1 Risk of Renal Stone Development

As previously mentioned, a primary factor in increased risk of renal stone development in crew members is insufficient hydration. In one assessment, sodium diisocyanurate is listed as causing renal stones in laboratory animals, at much higher dose levels than expected for crew (WHO, 2008). It is unlikely that these concentrations would increase crew risk of developing renal stones, but it represents a significant question that may need to be addressed.

### B.7.2 Water Treatment Technologies

In several cases, decision-making was impacted by experience from terrestrial drinking water treatment. Chlorine and bromine are used in those applications. However, the chemical behavior of chlorine, bromine, and the chemical substances employed to deliver them to water are well understood. Most municipal water treatment systems employ multiple levels of treatment using different technologies. Given that exploration water systems will not employ such sophisticated architectures, it is worth noting that there may be some gaps in understanding of chemical dynamics (e.g., biodegradation and taste management) as a result of these differences. In-home treatment technologies (e.g., reverse osmosis, carbon filtration) are often used to improve the taste and overall quality of drinking water. This obviously would not be available in an exploration vehicle.

### B.7.3 Disinfection Byproducts

Iodine, chlorine, and bromine are believed to produce disinfection byproducts (DBP). Halogenated DBPs are a subject of ongoing intensive research, as early studies have indicated they might carry some risk of developing cancer. In some cases, these indications arise from studies conducted on cells in vitro, compounding the uncertainty. Many toxicologists believe too little is understood about the dose response relationship to adequately assess the importance of these substances. However, some attempts at quantitative or semi-quantitative risk assessments have been performed (Krishnan et al, 1997; Wang et al., 2007). Such assessments are usually conducted in the context of lifetime exposure, whereas the current scenario is for no more than three years of continuous exposure. Historically, chemical risk assessments for crew members have not considered cancer as a critical toxicological endpoint as the exposure window has heretofore been one year or less.

It is worth mentioning that DBPs (e.g., chloroform, bromoform, chloromethane) often arise due to the presence of other organic substances in the water treatment system; these may not be present in exploration water systems, and so it is possible DBPs will not exist in this scenario.

## B.8 References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# Appendix C: Material Compatibility Data

## C.1 Methods to Estimate Biocide Reactivity with Materials

When determining the compatibility of a biocide with the materials in the xEMU and PWD components, the oxidation potential of the solution, electrochemical potential of the materials, and the corrosion kinetics of the materials in solution should be considered. The oxidation potential of the solutions are generally known and were compiled for comparison in **Error! Reference source not found.**. In general, a more noble potential value relates to a higher reactivity of species in solution and thus a greater likelihood for reactions to occur with a material surface. The pH value of an ionic solution indicates which species is more dominant and available for reaction.

***Table C-1. Oxidation Potential of General Reaction Species in Biocide Solutions***

| **Biocide Type** | **Chemical Formula** | **Oxidation Potential (V vs. SHE) 25 °C** |
|---|---|---|
| Fluorine | $F_2 + 2e^- \leftrightarrow 2F^-$ | + 2.87 |
| Ozone | $O_3$, as a hydroxyl radical | + 2.80 |
| Hypochlorous Acid | $Cl^2 + H_2O \leftrightarrow HOCl + H^+ + Cl^-$ | + 1.482 |
| Hypoiodous Acid (acidic pH) | $HIO \leftrightarrow H^+ + OI^-$ | + 1.43 |
| Chlorine | $Cl_2 + 2e^- \leftrightarrow 2Cl^-$ | + 1.358 |
| Hypobromous Acid | $HOBr \leftrightarrow H^+ + OBr^-$ | + 1.33 |
| Bromine | $Br_2 + 2e^- \leftrightarrow 2Br^-$ | + 1.08 |
| Hypoiodous Acid | $HIO \leftrightarrow H^+ + OI^-$ | + 0.99 |
| Hypochlorite | $OCl^- + H_2O + 2e^- \leftrightarrow Cl^- + 2OH^-$ | + 0.89 |
| Hypobromite | $OBr^- + H_2O + 2e^- \leftrightarrow Br^- + 2OH$ | + 0.766 |
| Ionic Silver | $Ag^+ + e^- \leftrightarrow Ag\ (s)$ | + 0.80 |
| Iodine | $I_2 + 2e^- \leftrightarrow 2I^-$ | + 0.54 |

For chlorine-based biocide delivery systems, for example, chlorine exists in a solution with a pH of 7.5 in a ratio of 1:1 for hypochlorite ions ($OCl^-$) and hypochlorous acid (HOCl). At a pH of 7.0, the ratio shifts to 1:3. At a pH of 8.5 or higher, the solution will be nearly all hypochlorite ions; at a pH of 5 or lower, the solution is nearly all hypochlorous acid. Hypochlorous acid is 80 to 100 times more effective as a biocide than hypochlorite, but hypochlorous acid is significantly more reactive. Chloride-based biocide solutions are often buffered to slow reactivity with materials and decrease corrosion, but buffering also decreases biocide effectivity because the more effective biocide is less prevalent in solution at higher pH values[1]. Similar relationships exist for hypobromous acid (HOBr) and iodine, though those two biocides tend to be less reactive overall due to their lower solution oxidation potentials. The relationship between pH and solution species is shown in Figure C-1 and Table C-2.

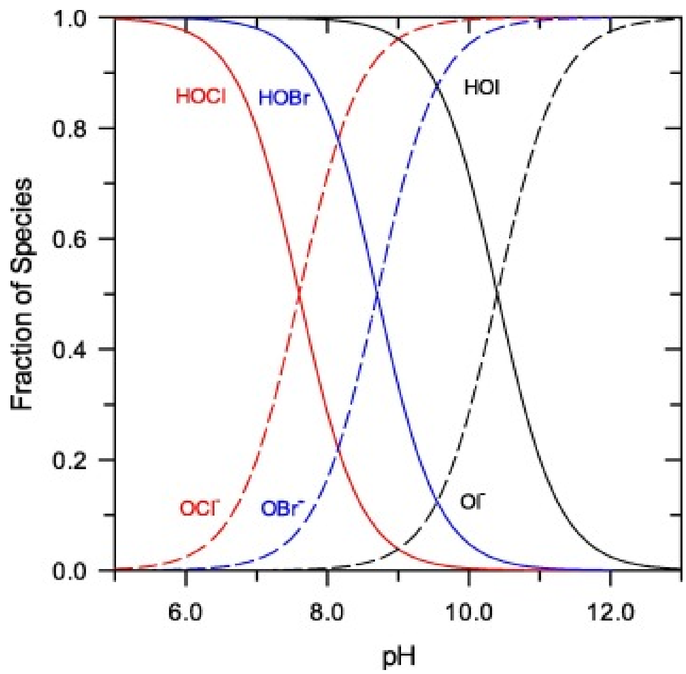


***Figure C-1. Relationship Between pH and Fraction of Species for Chlorine, Bromine, and Iodine-based Solutions Adapted from Sharma et al (2018).*** [2]

***Table C-2. pH-Dependent Speciation of Bromine, Chlorine, and Iodine in Water***

| pH | Bromine | | Chlorine | | Iodine | |
|---|---|---|---|---|---|---|
| | **% Br as HOBr** | **% Br as OBr-** | **% Cl as HOCl** | **% Cl as $OCl^-$** | **% I as HIO** | **% I as $OI^-$** |
| 5.0 | - | - | 99.5 | 0 | 1 | 0 |
| 6.0 | 100 | 0 | 90 | 10 | 10 | 0 |
| 6.5 | 99.4 | 0.6 | 80 | 20 | - | - |
| 7.0 | 98 | 2 | 70 | 30 | 48 | 0 |
| 7.5 | 94 | 6 | 37.5 | 62.5 | - | - |
| 8.0 | 83 | 17 | 25 | 75 | 88 | 0.005 |
| 8.5 | 57 | 43 | 12.5 | 87.5 | - | - |
| 9.0 | - | - | 1 | 99 | - | - |

*Adapted from "Alternative drinking-water disinfectants: bromine, iodine and silver." Geneva: World Health Organization; 2018.*[3]

The electrochemical potential, also known as corrosion potential, of a metal in solution should be considered for materials compatibility to determine the probability that a specific metal will react with a biocide solution within the use life of the component. Table C-3 shows the equilibrium electrochemical potentials of the metals and their main alloying components for alloys known to be used in the hardware in this study. A more noble, or positive, potential value directly relates to how easily a material is reduced. A corrosion potential value describes the expected reactivity, and corrosion kinetics (reported as corrosion rate or corrosion current) describes the rate of that expected reactivity[4]. Reactivity in this case is considered a redox reaction that causes unwanted corrosion or degradation of a material. Data can be gathered using potentiodynamic polarization methods, which purposely change the potential value as a function of time and measure the resulting current density, to determine the types of reactions that will occur. Figure C-2 is an example of potentiodynamic polarization results, where data is gathered for the values of corrosion potential ($E_{corr}$), pitting potential ($E_{pit}$), and the repassivation potential ($E_{rep}$). These potential values relate to the pitting or other forms of corrosion are most likely to occur and when the pitting is likely to be interrupted or stop. This data, gathered for solutions at varying pH ranges, can be used to create a Pourbaix diagram that will predict the expected reactions as a function of potential and pH values (Figure C-3).

***Table C-3. Electrochemical Potentials vs. Standard Hydrogen Electrode (SHE) at 25°C, 1 atm, and 1M Solution***

| Redox Reaction | Potential (V vs. SHE) |
|---|---|
| $Mg^{2+} + 2e^- \leftrightarrow Li(s)$ | - 2.36 |
| $Al^{3+} + 3e^- \leftrightarrow Al(s)$ | - 1.66 |
| $Ti^{2+} + 2e^- \leftrightarrow Ti(s)$ | - 1.63 |
| $Zn^{2+} + 2e^- \leftrightarrow Zn(s)$ | - 0.76 |
| $Fe^{2+} + 2e^- \leftrightarrow Fe(s)$ | - 0.41 |
| $Fe^{3+} + 3e^- \leftrightarrow Fe(s)$ | - 0.02 |
| $Ni^{2+} + 2e^- \leftrightarrow Ni(s)$ | - 0.25 |
| $H^+ + e^- \leftrightarrow 1/2H_2(s)$ | 0.00 |
| $Cu^{2+} + 2e^- \leftrightarrow Cu(s)$ | + 0.34 |
| $Fe^{3+} + e^- \leftrightarrow Fe^{2+}(s)$ | + 0.77 |
| $Ag^+ + e^- \leftrightarrow Ag(s)$ | + 0.80 |
| $1/2O_2(g) + 2H^+ + 2e^- \leftrightarrow H_2O(s)$ | + 1.23 |
| $1/2Cl_2(g) + e^- \leftrightarrow Cl^-$ | + 1.36 |
| $1/2F_2(g) + e^- \leftrightarrow F^-$ | + 2.87 |

*Adapted from Handbook of Chemistry and Physics (93rd ed.)*[5]

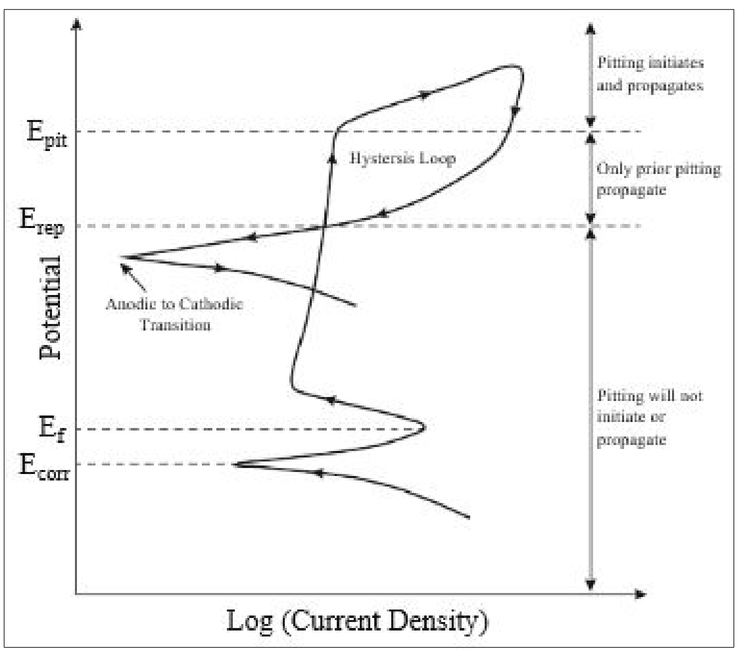


***Figure C-2. Illustration of Potential Curve and Corrosion Parameters***

***Note: Arrows indicate direction of polarization, showing potentials measured as metal undergoes reactions in solution. $E_{corr}$ is electrochemical or corrosion potential, considered the steady-state potential for the system.***[6]

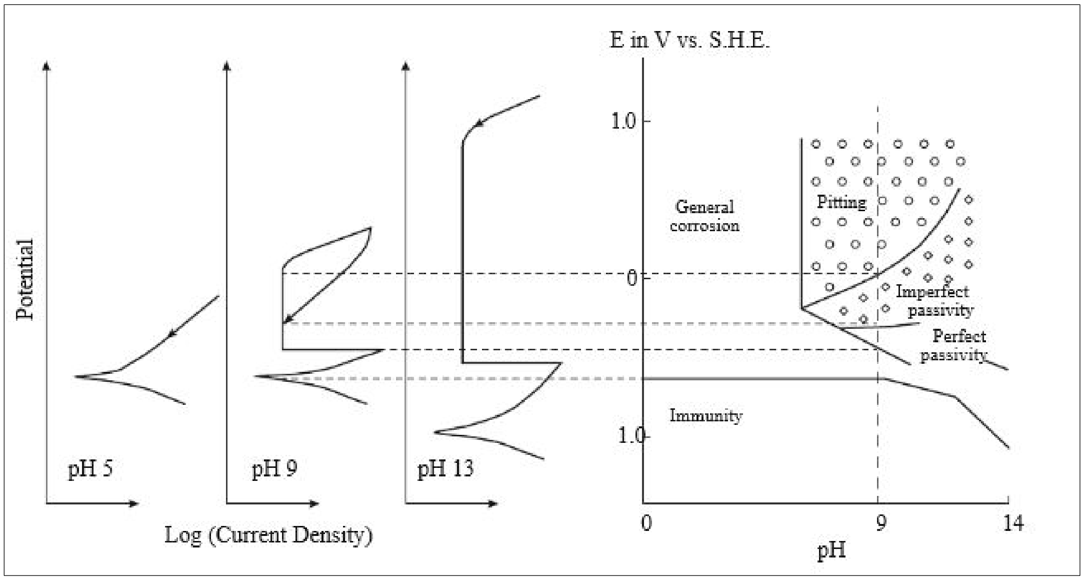


***Figure C-3. Illustration of Pourbaix Diagram for Iron in 0.01 M Cl− (right), Constructed from Experimental Anodic Polarization Curves (left), Which Shows Types of Reactivity Metal Can Have in Same Solution with Varying pH Values[6]***

To evaluate the compatibility of biocides with different materials, specifically metallic materials, current data and these generally known relationships between solutions, metal interfaces, and pH values can be used. If a chloride or bromine solution is slightly acidic, it will have a higher oxidation potential because there is a higher concentration of more active species in solution. The data show a lower pH value will increase corrosion kinetics and possibly pose a materials degradation risk with long-term use.

## C.2 Materials Compatibility Considerations

Problems arise from the fact that aqueous chemistry alone, even with specific additives, is not definitive. Storage and piping are always at risk from a variety of corrosion mechanisms under static and low-flow conditions. Notwithstanding the role of biocides and their influence on aqueous chemistry corrosion, the design, including galvanic effects, fabrication quality, operation and maintenance of potable water systems can profoundly affect the corrosion behavior of alloys. The precipitation of halide salts and deposition of silver complexes can lead to underdeposit corrosion unless minimum flow velocities are determined and maintained.

Materials compatibility was analyzed discretely for each material and biocide type, as well as the likelihood that they could degrade in common hardware configurations. For example, a titanium component is less likely to degrade in a crevice than a stainless-steel part due to their overall propensity to corrode. The reactions that a material may have with a biocide’s byproducts, such as the salt that the active biocide is attached to, as well as resulting corrosion products was also used to determine the suitability of each biocide. These compatibility considerations were used to create risk levels, defined in Table C-4, for evaluating overall materials compatibility with the data that is currently available for each biocide and materials type. Additional materials data are needed to increase the confidence level of the biocides with materials where there are limited data, and this is marked accordingly.

The configuration of materials within a component or system and their surface finish play a part in the reactivity of metal in a biocide solution. In areas where crevices or areas of oxygen depletion could occur, such as in a bellows tank, unexpected acidic conditions could be present in localized areas that will cause the breakdown of materials where pH is low. At these areas, a defect or corrosion nucleation point could develop locally, creating a potential difference between the point and the bulk metal that would drive a corrosion reaction until interrupted. Pitting corrosion is likely to initiate in areas with crevices or nucleation points due to localized lower pH pockets, regardless of alloy type[7].

Materials, especially metals, can react with a biocide's inactive reactants and corrosion products. Precipitates created by corrosion and reactivity products pose risks to fine metallic filters, delivery gear pumps, piston-style dose pumps, seats for 316SS solenoid valves that would cause leaking, 0.2μm filters in the potable dispenser, and tight tolerance journal bearings for external gear pumps, to name the known configurations of most concern. For example, the fluoride salt in silver fluoride is known to react with Inconel and result in preferentially depleting the nickel from the alloy, causing localized pitting reactions on the metal surface and unwanted nickel in the water. The nickel is then available to react with the silver in solution and increase the overall reactivity of the degradation mechanism.

The reactions occurring as a result of unwanted plating, in this case the plating of silver (the more cathodic metal) onto a more anodic substrate, leads to localized metal depletion. Because the cathodic region that is plated onto the surface is smaller than the anodic region, the corrosion reactions will generally progress slowly. Local corrosion at the dissimilar metal interface will occur, but general reactions are largely unknown. It is not known if pitting, intergranular corrosion, hydrogen embrittlement, or other forms of corrosion occur as a result of unplanned and uneven plating of silver onto the hardware components.

### C.2.1 Halogenated Compounds

In general, halogenated compounds (in this case, chlorine, bromine, and iodine) degrade a material via destabilization of protective oxide layers for metals and via embrittlement and oxidation for some non-metallics. The degree of risk ranges from relatively high for chlorine, then bromine, then to relatively low for iodine, but the risk is variable depending on solution pH and material type.

The materials analysis for the halogen compounds chlorine, bromine, and iodine assumes pH is ***not*** buffered and the halogens are being used within operating temperature not to exceed 150 °C. The ratings table key listed in Materials Compatibility was analyzed discretely for each material and biocide type, as well as the likelihood that they could degrade in common hardware configurations. For example, a titanium component is less likely to degrade in a crevice than a stainless-steel part, due to their overall propensity to corrode. The reactions that a material may have with a biocide's byproducts, such as the salt the active biocide is attached to and resulting corrosion products, was also used to determine the suitability of each biocide. These compatibility considerations were used to create risk levels, defined in Table C-4, for evaluating overall materials compatibility with available data for each biocide and materials type. Additional materials data are needed to increase the confidence level of the biocides with materials where there are limited data, and this is noted accordingly.

The configuration of materials within a component or system plays a part in the reactivity of metal in a biocide solution. In areas where crevices or areas of oxygen depletion could occur, such as in a bellows tank, unexpected acidic conditions could be present in localized areas that will cause the breakdown of materials where pH is low. In these areas, a defect or corrosion nucleation point could develop locally, creating a potential difference between the point and the bulk metal that would drive a corrosion reaction until interrupted. Pitting corrosion is likely to initiate in areas where there are crevices or nucleation points due to localized lower pH pockets, regardless of alloy type.

Materials, especially metals, can react with a biocide's inactive reactants and corrosion products. Precipitates created by corrosion and reactivity products pose risks to fine metallic filters, delivery gear pumps, piston style dose pumps, seats for 316SS solenoid valves that would cause leaking, 0.2µm filters in the potable dispenser, and tight tolerance journal bearings for external gear pumps, to name the known configurations of most concern. For example, the fluoride salt in silver fluoride is known to react with Inconel and result in preferentially depleting the nickel from the alloy, causing localized pitting reactions on the metal surface and unwanted nickel in the water. The nickel is then available to react with the silver in solution and increase the overall reactivity of the degradation mechanism.

The reactions occurring as a result of unwanted plating, in this case the plating of silver (the more cathodic metal) onto a more anodic substrate, leads to localized metal depletion. Because the cathodic region that is plated onto the surface is much smaller than the anodic region, the corrosion reactions will generally progress slowly. Local corrosion at the dissimilar metal interface will occur, but general reactions are largely unknown. It is not known if pitting, intergranular corrosion, hydrogen embrittlement, or other forms of corrosion occur as a result of unplanned and uneven plating of silver onto the hardware components.

If the solutions are buffered, then the ratings can be assumed to be classified to one risk rating better in most cases.

***Table C-4. Risk Ratings and Assumptions Used to Assess Materials Compatibility***

| Risk Rating | Assumptions |
|---|---|
| **None** | No degradation expected over time |
| **Low** | Minor and manageable amount of degradation expected |
| **Moderate** | Degradation may cause system issues but may be manageable if rate is slow |
| **High** | Degradation that will cause component failure expected |

### C.2.2 Chlorine-Based Biocide Materials Compatibility Summary

Chlorine-based biocides in general are effective, but they have well-known materials issues with metals and some non-metallics. Chlorine-based biocides are generally buffered to a neutral pH or higher to prevent long-term degradation or, in situations where buffering is not possible, replacement materials that are known to degrade are part of the operation plan[8]. During long-term storage, hypochlorite biocides are known to disproportionate and decompose, leading to the formation of chlorate and chloride. The most active metals for these decomposition reactions are nickel, cobalt, copper, iron, and magnesium. As is often the case, reactions will result in corrosion of metallic materials as well as depletion of the biocide by reaction with the metal ions in solution[3,9,10].

Studies have shown that hypochlorite and chloride-based biocides in general cause corrosion for Hastelloy C276, but not Titanium to a large extent[11]. Inconel types, both 625 and 718, have been found to degrade in some cases via pitting corrosion in long term immersion exposure to chlorides[7]. Stainless steels have been known to corrode via pitting when exposed to hypochloric acid-based solutions, as well as other halides besides fluorine[12]. Hypochloric acid-based compounds in solution are known to degrade polypropylene, Delrin, and to a lesser degree polyethylene components in immersion conditions[13]. In general, many risks to materials degradation exist in short- and long-term use of the candidate chloride-based biocides chosen in this study. A successful system would require constant monitoring and expectations of part replacement over time.

The materials analysis for chlorine-based biocides in this study, shown in Table C-5, assumes pH is ***not*** buffered and the biocides are being used within operating temperature not to exceed 150 °C. The ratings table key is listed in Table C-4. If the solutions are buffered, then the ratings can be assumed to be classified to one risk rating better in most cases.

***Table C-5. Materials Compatibility for Chlorine-Based Biocides Considered***

| Materials | Sodium dichloro-isocyanurate | Sodium chlorite ($NaClO_2$) | Chloramine-T | Calcium hypochlorite ($Ca(OCl)_2$) | Chlorosuccinimide |
|---|---|---|---|---|---|
| **Ti Grade 2 and Ti-6Al-4V tubing** | Low | Low | Low | Low | Low |
| **316L SS solenoid and internal bellows** | High | High | High | High | High |
| **Inconel 625 and 718 bellows and pressure transducer diaphragms** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **PTFE tubing and various components** | None | None | None | None | None |
| **PEEK tubing and various components** | None | None | None | None | None |
| **Polypropylene** | Low | Moderate | Low | Moderate | Low |
| **Polyethylene** | Low | Low | Low | Low | Low |
| **Delrin** | High | High | High | High | High |
| **Pump: Hastelloy C-276** | High | High | High | High | High |
| **Pump: E-234 epoxy varnish** | None | None | None | None | None |
| **Pump: MgO partially stabilized Zirconia** | None | None | None | None | None |
| **Pump: Stellite 6B** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **LCVG: Ethylene Vinyl Acetate tubing** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **LCVG: Viton** | None | None | None | None | None |
| **HX-440/HX-540 Evap: Henkel EA 9313 epoxy** | None | None | None | None | None |

### C.2.3 Bromine-Based Biocide Materials Compatibility Summary

The materials compatibility literature for bromine-based biocides is less-plentiful than for chlorine, but also well-known. Hypobromous acid (HOBr) is a highly effective biocide that is active in a wider range of pH values than chlorine and iodine. Bromine is known to be used by the U.S. Navy[14] for disinfection of its potable water supply system and in swimming pools. The Navy notes that use of halogen-based disinfectants for batch treatment "are less reliable, require greater time and effort, and are generally less effective."

Bromine in water produces varied pH-dependent species, as seen in Table C-6. Although the effective biocide hypobromous acid is present at lower pH, the molecular bromine ($Br_2$) exists in relatively high concentrations. Molecular bromine ($Br_2$) is not compatible with most stainless steel and some aluminum-based alloys due to its oxidizing characteristic[14–18]. The ratio of bromine and hypobromous acid is pH-dependent. At pH 6.5 through pH 9, bromine occurs almost entirely as hypobromous acid but beyond pH 9 the biocide is not present. The efficacy of bromine as a biocide and corresponding material compatibility testing at lower pH is being addressed. UMPQUA Research Company[2], under Proposal No: SBIR 2019-II – H3.03-4124, will perform antimicrobial and corrosivity testing to fill data gaps. Umpqua will evaluate the material compatibility and microbial efficacy of hypobromous acid at pH 5. In the case of this technology, approximately 85% of the bromine exists as hypobromous acid (HOBr) and approximately 15% as $Br_2$. The concentrations of $Br_3^-$ and hypobromite ($BrO^-$) are extremely low. The results from this upcoming SBIR Phase 2 research would provide a greater understanding of the corrosive behavior of the types of bromine in solution at the pH and conditions expected for unbuffered use.

Bromine is a reactive and corrosive halogen, stabilized using a halogen donor resin for use as a biocide. The resin creates an unknown effect on material compatibility, especially the initial release of bromine into the water supply. Additionally, bromine will react to any organic material in the water supply or in the component material to form brominated disinfection byproducts (DBPs). DBPs create micro-acidic environments that can potentially degrade components. Clear understanding of the species in solution at the lower pH levels is imperative because potential acidic species of bromines are corrosive to the materials listed in Table C-6. For example, the corrosion rate, defined as the depth of material loss over time in mils per year (mpy) is 50 mpy for stainless steel and 2 mpy for hastealloy[16] when exposed to hypobromic acid. Non-metals such as viton, PEEK, and low and high polyethylene[18] are also considered incompatible with hypobromic acid. The weak biocide hypobromous acid, however, could have a low risk to these materials.

The materials analysis for bromine-based biocides in this study, shown in Table C-6, assumes pH is NOT buffered and the biocides are being used within operating temperature not to exceed 150 °C. The ratings table key is listed in Table C-4. If the solutions are buffered, then the ratings can be assumed to be classified to one risk rating better in most cases.

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[2] Holtsnider, John T.,UMPQUA Research Company, P. N. S. 2019-I. – H. 0.-4124. Halogen Binding Resins for Potable Water Disinfection. (2019).

*Table C-6. Materials Compatibility for Iodine and Bromine-Based Biocides Considered*

| Materials | Iodine / Triiodide | Bromine ($Br_2$ and Br3-) | Poly-1-bromo-5-methyl;-5 (4'-vinylphenyl) hydantoin (HaloPure BR) | 1,3-Dibromo-5,5-dimethylhydantoin (DBDMH) | 1-bromo-3-chloro-5,5-dimethyl-hydantoin (BCDMH) |
|---|---|---|---|---|---|
| **Ti Grade 2 and Ti-6 Al-4V tubing** | None | Moderate | Low | Low | Low |
| **316L SS solenoid and internal bellows** | Moderate | Moderate | High | High | High |
| **Inconel 625 and 718 bellows and pressure transducer diaphragms** | Low | Moderate | Low | Low | Low |
| **PTFE tubing and various components** | None | None | None | None | None |
| **PEEK tubing and various components** | Low | Moderate | High | High | High |
| **Polypropylene** | Low | Low | Low | Low | Low |
| **Polyethylene** | None | High | High | High | High |
| **Delrin** | High | High | High | High | High |
| **Pump: Hastelloy C-276** | Low | Moderate | Moderate | Low | Moderate |
| **Pump: E-234 epoxy varnish** | None | None | None | None | None |
| **Pump: MgO partially stabilized Zirconia** | None | None | None | None | None |
| **Pump: Stellite 6B** | Low | Moderate | Low | Low | Moderate |
| **LCVG: Ethylene Vinyl Acetate tubing** | Moderate | Moderate | Moderate | No data | Moderate |
| **LCVG: Viton** | Moderate | Moderate | Moderate | Low | Low |
| **HX-440/HX-540 Evap: Henkel EA 9313 epoxy** | Moderate | Moderate | Moderate | Low | Low |

### C.2.4 Silver Biocide Materials Compatibility Summary

The literature and corresponding data for silver-based biocides in solution has been centered on effectivity in solution rather than materials compatibility, and while the biocide is a promising option, high quality materials-related data are needed to ensure viability. Materials compatibility for silver-based biocides is mainly based on issues with plating of the silver onto metals because of the high reactivity of silver, though some absorption onto non-metallics can occur. In all cases, the driving reaction is the supply of the silver. The potential differences between the silver biocide and the metallic substrates have been large enough to cause plating reactions to occur with no outside energy source, which is concerning in general. In areas with a high surface area to volume ratio, the depletion rate of silver in solution is enhanced, which is also likely to be related to the amount of silver that has deposited onto the surrounding material surfaces.

Once the silver plates onto a surface, localized potential differences will remain reactive in those areas. If unplanned silver plating occurs via many small nucleation points across the component, rather than in more consolidated areas, that will more likely result in overall embrittlement if a material is susceptible or cause intergranular corrosion issues where unwanted potential differences are present across a metal. These surface reactions would leave the alloy open to further failure or reactivity over time. If the surface is active enough to warrant plating in the first place due to oxidation and reduction electron transfer with the base material, unwanted hydrogen is produced for the reaction. For non-metallics, physical properties, such as embrittlement and flexibility, could be negatively affected. Limited research thus far has shown that silver biocide has acceptable materials compatibility with polymers.

If plating occurs via more consolidated islands and the silver builds up, it is unknown where that would happen, or whether the deposits could impair operation due to the physical buildup depending on where they agglomerate. In addition, because the plating is not a purposeful even layer, the silver is not inert on the surface and localized corrosion will eventually occur at the interface of the silver and bulk metal, such as the CRES or Inconel. The cathode in this case, the silver, is much smaller than the anode, but that does not preclude localized corrosion from occurring at the interface.

In studies with silver biocides, the amount of silver plating, or thickness and mechanism, whether it plates as islands or across the surface into grain boundaries, is not understood or investigated further. The studies largely focus on the depletion of silver in solution in contact with different materials, but materials analysis is noted and largely ignored. More data are needed to understand how the plating forms on the internal components and what type and degree of degradation can be expected. Enough research mentions silver issues with material surfaces to warrant some concern, especially because the silver in solution is depleted and deposited onto materials. In some studies, the silver appears to have caused some intergranular issues in CRES or nickel based alloys and/or plated on metallic surfaces as islands[19,20], but only general observations are made and no further materials analysis is available to aid in materials compatibility analysis. In some recent studies, silver chloride has been eliminated due to known materials compatibility concerns for corrosion[21]. Studies using silver ionization units to introduce silver into solution, although still focusing mainly on the depletion of silver in solution, did perform limited analysis of the biocide compatibility with Teflon, ethylene, propylene, rubber, stainless steel 316L with different surface treatments, stainless steel 15-5 pH, and Ti6Al4V[22]. Similar studies regarding further surface analysis showed that Ag metal is the silver form on 316L sample surfaces, while oxidized Ag was present on the Ti6Al4V surface, but corrosion mechanisms have not been determined[23–25].

In recent unpublished studies by NASA, data have pointed to concerns with Inconel components and silver fluoride biocide solutions. Silver fluoride was evaluated as a candidate biocide for the Orion Potable Water Tank, but rapid loss of silver biocide in the test and plating was noted. The results also showed that nickel in the wetted Inconel 718 tank material was depleted as a part of the redox reaction, and ionic nickel was found in solution, rendering the water non-potable. xEMU PLSS 2.0 Testing also found that silver fluoride biocide was rapidly lost in solution, along with similar corrosion, plating, and contaminant buildup in restricted-flow areas and on the SWME membrane. The proposed corrosion mechanism is that the ionic silver is reduced to metallic silver and the Si/Nb-rich areas of the Inconel-718 serve as cathodes because they are the most noble areas of the surface. These areas are where the reduced silver tends to deposit. The nickel is then oxidized; some of it was found to convert to nickel oxide ($Ni_2O$, $NiO_2$), nickel hydroxide ($Ni(OH)_2$), and nickel carbonate ($NiCO_3$) and remained bound to the surface nickel.

The following areas will remain a materials compatibility concern until further data are available:

- Ag+ deposition on metals, long-term stability of the deposition, and aqueous silver chemistry of the silver layer.
- Galvanic replacement reactions with unpassivated alloys.
- When deposited as elemental silver and as $Ag_2O$, the deposed provides a very conductive layer for electrons from oxygen vacancies and unpassivated substrate alloys.
- Anions of silver salts, such as fluoride and chloride, known to be corrosive to metals.
- Silver consumption by small concentrations of organic matter or other reduced compounds due to the low molar concentration of 400 ppb.
- Various metallic surface treatments, such as high-temperature surface oxidation, electropolishing, and coatings, which show promise, but are a challenge for complex hardware and wear surfaces.

The ratings in Table C-7 were made using the limited available data and a best guess based on known degradation mechanisms. These ratings could change as new data become available.

*Table C-7. Materials Compatibility for Silver-Based Biocides Considered*

| Materials | Ionic Silver | Electrolytic Silver | Controlled Release Salt Silver (Assumes AgCl) | Silver Nitrate | Silver Fluoride (salt solution) |
|---|---|---|---|---|---|
| **Ti Grade 2 and Ti-6Al-4V Tubing** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **316L SS Solenoid and Internal Bellows** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **Inconel 625 and 718 Bellows and Pressure Transducer Diaphragms** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **PTFE Tubing and Various Components** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **PEEK Tubing and Various Components** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **Polypropylene** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **Polyethylene** | No data | No data | No data | No data | No data |
| **Delrin** | Low | Low | Low | Low | Low |
| **Pump: Hastelloy C-276** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **Pump: E-234 Epoxy Varnish** | Low | Low | Low | Low | Low |
| **Pump: MgO Partially Stabilized Zirconia** | None | None | None | None | None |
| **Pump: Stellite 6B** | Moderate | Moderate | Moderate | Moderate | Moderate |
| **LCVG: Ethylene Vinyl Acetate Tubing** | Low | Low | Low | Low | Low |
| **LCVG: Viton** | Low | Low | Low | Low | Low |
| **HX-440/HX-540 Evap: Henkel EA 9313 epoxy** | Low | Low | Low | Low | Low |

## C.3 References


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# Appendix D: xEMU Compatibility Results with Biocide Options

The wetted materials in the xEMU TCL design were identified as a prelude to conducting this biocide assessment and are as follows:

- Backplate: Ti-6Al-4V annealed and autogenously welded, Inconel 625
- Pump: Ti-6Al-4V Additive Manufactured, MgO partially stabilized Zirconia, Inconel 718, Hastelloy C-276, E-234 epoxy varnish, Stellite 6B
- LCVG: Ethylene Vinyl Acetate (EVA) tubing, Ti-6Al-4V Ion Nitrided, Viton
- HX-440/HX-540 Evaporators: Polypropylene, Henkel EA 9313 epoxy, Ti-6Al-4V,
- HX-340 Vent Loop HX: Inconel 625

All of the candidate biocides considered in this assessment can be considered oxidants to some degree, potentially adversely impacting the wetted materials in the xEMU TCL. The halogenated biocide candidates (chlorine, bromine, iodine), preferentially attack metallic materials at defect sites in the surface oxide and also induce bond scission in the surface oxide away from defects. Additionally, silver-based biocides can attack metallic materials via oxidation/reduction electron transfer with elements in the bulk metal, where the redox reaction most commonly occurs at defects in the native oxide. Finally, non-metallic materials can be affected via adverse impact on physical characteristics (e.g., embrittlement, flexibility). Halogens and halogenated compounds tend to be a risk to metallic materials protected by oxide films, but the degree of risk ranges from relatively high for the chloride ion, then the bromine ion, then to relatively low for the iodine ion. The risk associated with the fluoride ion is variable and depends on solution pH and substrate material. Electrochemical potential (i.e, a quantitative measure of relative oxidative strength) was used as a discriminator when evaluating the relative risk of one biocide against another to choose a biocide for the xEMU water system application. Further details on these topics are presented in Appendix C.

## D.1 HX-440/HX-540 Evaporators – SWME Membrane Risk Assessment Results

Of particular concern when selecting an optimal biocide for the xEMU TCL application is compatibility with the SWME membranes used in the HX-440/HX-540 Evaporators (see Figure D-1). The polypropylene fibers included in the evaporators are particularly sensitive to oxidative damage (3M supplier input). The 3M supplier recommends limiting membrane exposure to oxidizing species, such as ozone, chlorine, hydrogen peroxide, or peracetic acid, to prevent membrane oxidation. Neutral or reductive biocides are recommended to minimize membrane oxidation and maximize membrane life. Per the SWME membrane supplier, less oxidative bromine-based biocides are advantageous compared with more oxidative chlorine-based biocides. Iodine-based biocides are hypothetically less oxidative than bromine-based biocides, but relevant experience or references to confirm this hypothesis were not available during this assessment. Neutral or reductive biocides are recommended over oxidizing biocides when considering compatibility with the SWME hollow-fiber membranes. Neutral and reductive biocides were identified, which include DBNPA (2,2-dibromo-3-nitrilopropionamide), glutaraldehyde, and isothiazolines. Membrane lifetime with oxidizing species depends primarily on cumulative exposure (concentration of oxidizer multiplied by total time of exposure. Life-time is also a strong function of parameters such as temperature and pH. Direct communication with the 3M supplier revealed that they have not tested silver-based biocides. While they expect the membrane will function nominally with silver biocides, there are no data to support this. 3M also indicated biocidal fluids with a surface tension less than 50 dynes/cm should not be used with the hollow-fiber membranes.

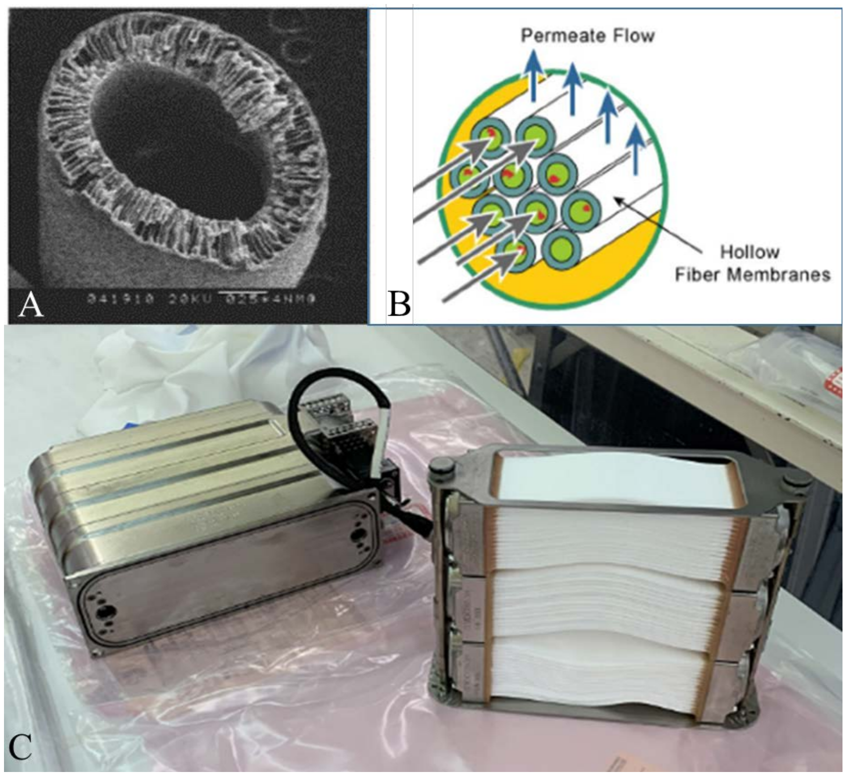


*Figure D-1. SWME Membrane Fiber (a), Fiber Bundle (b), and Sub-Assembly (c)*

## D.2 Candidate Biocide Solubility Evaluation

Precipitate formation is a risk to the xEMU TCL high-surface-area membranes, fine metallic filters, heat exchanger surfaces, and tight tolerance journal bearings in the external gear pumps. Therefore, candidate biocide solubility in water (g/L) was evaluated. Relevant solubility values were identified and are summarized in Table D-1.

*Table D-1. Candidate Biocides – Solubility in Water*

| Candidate | Biocide | Water Solubility Biocide Candidate (25C unless noted) |
|---|---|---|
| 1) Silver fluoride (AgF) salt solution | $Ag^+$ | 1791 g/L |
| 2) Silver nitrate ($AgNO_3$) salt solution | $Ag^+$ | 2370 g/L |
| 3) Controlled release salt solution | $Ag^+$ | Variable based on specific salt solution |
| 4) Ionic silver (electrolytic) | $Ag^+$ | unknown |
| 5) Ionic silver (flow-through IX bed) | $Ag^+$ | unknown |
| 6) Bromine/Tribromide | $Br_2/Br_3^-$ | 35.5 g/L |

| | | |
|---|---|---|
| 7) Poly-1-bromo-5-methyl-5 (4'-vinylphenyl) hydantoin (HaloPure BR) | $OBr^-$ | 35.5 g/L (at 20 °C) |
| 8) 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH) | $OBr^-$ | 1.5 g/L |
| 9) 1,3-Dibromo-5,5-dimethylhydantoin (DBDMH) | $OBr^-$ | 1.0 g/L |
| 10) Sodium dichloroisocyanurate | $OCl^-$ | 220 g/L |
| 11) Trichloroisocyanuric acid, and dichloroisocyanuric acid | $OCl^-$ | 227 g/L |
| 12) Sodium chlorite ($NaClO_2$) | $OCl^-$ | 785 g/L |
| 13) Chloramine-T | $OCl^-$ | > 100 g/L |
| 14) Calcium hypochlorite ($Ca(OCl)_2$) | $OCl^-$ | 210 g/L |
| 15) Chlorosuccinimide | $OCl^-$ | 12.7 g/L (at 20 °C) |
| 16) Iodine / Triiodide | $I_2/I_3^-$ | 0.29 g/L (at 20 °C) |

## D.3 Candidate Biocide Cabin Air Aesthetics

Volatile compounds will presumably evaporate through the SWME fibers and enter the crew cabin. Candidate biocide aesthetics, such as odor, were therefore evaluated. Candidate biocide aesthetic information is summarized in Table D-2.

***Table D-2. Candidate Biocide Vapor Pressure and Odor Information***

| Candidate | Vapor Pressure (mm Hg) (25 °C unless noted) | Literature / Vendor Comments Related to Odor |
|---|---|---|
| 1) Silver fluoride (AgF) salt solution | Negligible | No odor |
| 2) Silver nitrate ($AgNO_3$) salt solution | Negligible | No odor |
| 3) Controlled release salt solution (silver) | Variable based on salt solution | Variable based on salt solution |
| 4) Ionic silver (electrolytic) | Negligible | No odor |
| 5) Ionic silver (flow-through IX bed) | Negligible | No odor |
| 6) Bromine/Tribromide | Unknown | Unknown |
| 7) Poly-1-bromo-5-methyl-5 (4'-vinylphenyl) hydantoin (HaloPure BR) | Unknown | Odorless claim |

| | | |
|---|---|---|
| 8) 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH) | $2.9 \times 10^{-5}$ | "Faint" bromine odor |
| 9) 1,3-Dibromo-5,5-dimethylhydantoin (DBDMH) | $3.1 \times 10^{-7}$ | "Slight" bromine odor |
| 10) Sodium dichloroisocyanurate | $7.1 \times 10^{-5}$ | "Pungent" odor |
| 11) Trichloroisocyanuric acid (and dichloroisocyanuric acid) | $1.6 \times 10^{-8}$ | "Strong" chlorine odor |
| 12) Sodium chlorite ($NaClO_2$) | Negligible | "Chlorine" odor |
| 13) Chloramine-T | $4.7 \times 10^{-4}$ | "Weak" chlorine odor |
| 14) Calcium hypochlorite ($Ca(OCl)_2$) | Negligible | "Chlorine" odor |
| 15) Chlorosuccinimide | $7.8 \times 10^{-3}$ | "Slight" chlorine odor |
| 16) Iodine / Triiodide | $2.0 \times 10^{-1}$ | "Pungent" odor |

# Appendix E: Biocide Impacts on Vehicle Life Support

## E.1 Introduction

This appendix is a supplement to the NESC Biocide Assessment Study and is intended to provide a background and perspective on potential candidate biocide selections on spacecraft potable water systems from the LS perspective. As part of this assessment, the LS team assigned to this task, Task 4, was to evaluate the effect of each biocide on systems, subsystems, and components that are used in and/or interface with the water system.

## E.2 Background

From a LS perspective, the primary function of the potable water system is to provide clean water to crew for the purpose of drinking, food rehydration, and simple hygiene use, for urine flush water, to the Oxygen Generation Assembly for production of oxygen, and to the EVA system for cooling. As mission duration and complexity increases, requirements typically drive toward higher degrees of cross-system functionality, such as plant growth. For systems that will be implemented in partial gravity, it is also envisioned that potable water will play a role in activities such as shower and laundry.

The strategies for processing, storing, and distributing potable are also typically driven by mission duration, complexity and vehicle capabilities. The simplest form of water system design is the "fill and draw" system. In such a system, water is ground-supplied, typically to a system consisting of a pressurized storage tank(s), plumbing distribution system, and water dispenser. Over the course of the mission, water is consumed and not resupplied until the vehicle is returned post-mission and refurbished as part of the next mission cycle. Such systems are typically used for short-duration missions, especially where the vehicle does not generate water as part of its base operation. A second class of potable water systems are often resupplied throughout the mission by water generated as part of the vehicle's operation, e.g., water generated as a byproduct of fuel cell power production. Such systems are still typically ground serviced and supplied with potable water prior to launch, but water generated over the mission is available to be collected and stored for potable water use. Finally, for long-duration missions where vehicle resupply is logistically limited and/or costly, potable water is supplied by a water regeneration system. For these systems, makeup water is resupplied from Earth, but most is reclaimed from onboard wastewater sources generated over the mission, such as urine distillate and humidity condensate.

Regardless of the system, potable water must meet quality specifications prior to use. These specifications are set forth by the program and/or specific vehicle system and typically driven by health requirements for crew consumption, though certain parameters can be more stringent for EVA use (e.g., silicon). These standards include requirements for the chemical and microbial load. Typical microbial limits are provided in Table E-1.

***Table E-1. Typical Potable Water Microbial Limits Set for US Spacecraft***

| Characteristic | Maximum Allowable | Units |
|---|---|---|
| Bacterial Count | 50 | CFU/mL |
| Coliform Bacteria | Non-detectable per 100 mL | - |
| Fungal Count | Non-detectable per 100 mL | - |
| Parasitic Protozoa (e.g., *Giardia* and *Cryptosporidium*) | 0 | - |

***Rationale**: Microbially safe water is essential to prevent infection and mitigate risk to crew health and performance. These limits are consistent with those defined by the JSC Microbiology Laboratory and in the SSP 50260 (ISS MORD). On the ISS, maintenance of these specifications during operation has been accomplished using flow through a 0.2-micron filter and use of a residual biocide. Point of crew consumption or contact refers to the location from which potable water is dispensed for use in drinks, food rehydration, health (medical), hygiene, and any potential in-flight maintenance sites (example from MPCV 70024 – Orion Multi-Purpose Crew Vehicle Program Human-Systems Integration Requirements).*

To ensure compliance with the microbial requirement, NASA has historically employed a residual biocide added to the water at the completion of the treatment process as part of a set of multi-barrier technologies used to mitigate the risk of microbial growth in the spacecraft potable water system. A typical multi-barrier strategy on spacecraft is to (a) ensure proper cleaning and assembly of the water system components; (b) as required, provide sufficient treatment of the water added to the system, ground-supplied, or on-orbit generated, to remove most of the organic content—the food source for microbes; (c) perform a disinfection and/or sterilization step as part of water treatment (e.g., filtration or heat); (d) add a residual biocide to the system to carry through storage and distribution; and (e) perform a final disinfection and/or sterilization step at the point of use and prior to final delivery. In these systems, the specific role of the residual biocide is to help ensure the microbial population in the stored water and distribution system remains below the potable water limits set for a specific spacecraft vehicle and/or mission. In addition, the residual biocide can address off-nominal events that could introduce microbial contamination during operations (e.g., maintenance and/or introduction of contamination at a use point). Several biocides have been considered and used by NASA. Table E-2 shows a history of biocide uses on U.S. spacecraft to date, along with a description of mission type, crew size, duration, water system used, water source, and the biocide selected for the potable water system.

*Table E-2. U.S. Spacecraft and Biocide Selections*

| Spacecraft | Mission/Crew Size/ Duration | Water System | Water Source | Biocide |
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| Mercury | Orbit Earth/1 crew/up to 36 hours | Fill & draw | Municipal | N/A (relied on residual chlorine from municipal water source) |
| Gemini | Demo multiday manned missions, on-orbit docking/ 2 crew/up to 14 days | Fill & draw | Unknown | Chlorine addition supplied on ground |
| Apollo CM | Lunar Transport and orbit/ 3 crew/up to 12 days | On-orbit generation | Fuel cells | In-line chlorine addition (injected by crew) |
| Apollo LM | Lunar Landing/2 crew/ up to 45 hours | Fill & draw | Unknown | Iodine added on ground |
| Skylab | First US Space Station/ 3 crew/up to 84 days per mission | Fill & draw | Unknown | Iodine with added injection on orbit performed by crew |
| Shuttle | Space Transportation/ 5-7 crew/up to 7 days | On-orbit generation | Fuel cells | In-line iodine dosing, resin-based; iodine removed at PWD (cold water) |
| ISS | Science Ops/up to 6 crew/ continuous operation | Regen ECLSS | Urine distillate, humidity condensate, Sabatier | In-line iodine dosing, resin-based; iodine removed at PWD (hot & cold water) |
| Orion | Space Transport/ 4 to 7 crew/short duration | Fill & draw | Deionized | Silver fluoride salt, added on ground |

CM – Command Module; LM – Lunar Module

The biocides listed in Table E-2 have had varying success and several lessons learned over the course of their implementation. A full review of these systems can be found in Peterson et al., 2007; Steele et al., 2018; and references therein. Additional details related to the use of iodine on the ISS can be found in Peterson et al., 2006. Similarly, development of silver biocide for Orion and other spacecraft can be found in Petala et al., 2016; Li et al., 2018; and Wallace et al., 2016. A summary of these biocide use cases is presented in the following section.

The use of chlorine for the short-duration missions of Mercury and Gemini had no reported issues. Mercury had only a simple fill and draw system, a water pouch which allowed direct crew hydration upon squeezing. No biocide was added beyond the residual biocide provided by the municipal drinking water used to fill the pouch. The Gemini potable water system was part of the vehicle infrastructure. It contained storage tanks, plumbing, and a water-dispensing gun. The system was used for drinking water and as part of a secondary system, along with the humidity condensate collection system, for vehicle cooling during contingency periods and/or periods of high heat load. As such, the potable water system did interconnect to the humidity condensate collection system. With the humidity condensate system open to the cabin environment, biocide beyond that used by the municipal water source was now required. The disinfection step was presumably conducted on the ground during the fill procedure, but details of that process are not provided. The Gemini system did supply water by way of fuel cells, but issues with water quality in the early implementation prevented this water from being used for drinking.

For the Apollo missions, two water systems were employed. For the Apollo Command Module (CM), the potable water system supplied water for drinking, food and beverage reconstitution, and crew personal hygiene. The system also provided water for emergency vehicle cooling in the event of a malfunction of the primary water-glycol heat transfer loop. The water generated by CM fuel cells on-orbit was successfully used for drinking water. The water generated was clean, but as with Gemini, it was connected to the humidity condensate system and susceptible to microbial contamination. The use of chlorine continued for the Apollo CM. However, issues with this biocide were cited, including challenges with dosing, requiring crew to inject the biocide manually using syringes, and corrosion and decomposition of system materials resulting in poor water quality and taste. The addition of buffers and anticorrosion inhibitors was needed to mitigate the issues. However, it is not clear that the core issues surrounding component corrosion and poor taste were fully resolved before the end of the program.

The Apollo Lunar Excursion Module (LEM) was a fill and draw system. Here the potable water system served dual purposes: drinking water for the crew and water for evaporative cooling for the spacecraft via sublimators. The system consisted of pressurized storage tanks, plumbing to drinking water guns, and connection to the spacecraft sublimators. Iodine was specifically selected as the biocide due to issues of corrosion with chlorine. The iodine was added on the ground prior to launch. The major issue with iodine in this case was that the biocide was found to deplete over time due to interactions with metallic and non-metallic system components. Therefore, high concentrations of the biocide were added to ensure it was maintained over the course of the mission and that the biocide level was itself potable when consumed by the crew during the lunar landing operations.

The use of iodine was continued for Skylab and Space Shuttle. Skylab was the first U.S. space station, intended for longer-term habitation. Potable water for the Skylab missions was supplied for drinking, food and beverage reconstitution, crew personal hygiene, housekeeping, and flush water of the urine separators. Three Skylab missions were conducted, the longest lasting 84 days. Between missions the vehicle experienced quiescent periods, about 30 days between crewed missions. The water system design was a fill and draw system consisting of 10 pressurized tanks, a distribution system, and crew drinking guns. The tanks were filled on the ground and dosed with 12 ppm iodine. The water system was used without resupply over all three missions. Due to mission duration and despite the high initial load of iodine, on-orbit redosing to the stored water was necessary. Again, this was due to the depletion of iodine over time. Redosing was done by syringe injection performed periodically by the crew. A monitoring kit was also added for periodic system checks to ensure the biocide was being maintained within acceptable limits.

For Shuttle, water could again be generated by fuel cells used to power the orbiter. Water on this system was used to supply water for drinking, food and beverage reconstitution, crew personal hygiene, housekeeping, flush water of the urine separators, Extravehicular Mobility Unit (EMU) filling, and feed water for cooling via the primary and secondary evaporator units. The system consisted of four pressurized bellows tanks, plumbing from the fuel system to the tanks, plumbing to the galley PWD, plumbing to the primary and secondary cooling systems, and a water dump. Only one tank (Tank A) was designated for potable water. However, because the water was being generated on-orbit, a new technology was needed for in-line iodine dosing to the potable tank. The dosing system consisted of iodine loaded onto a resin IEB material. Clean water flowing over the loaded resin would exchange dissociated water ions for iodine. The rate of iodine released could be predicted as a function of pH, flow, and temperature and used with the dosing system design to meter a controlled dose at the required concentration. The resin was packed into a cartridge, referred to as a microbial check valve (MCV). The cartridge device could be placed between the fuel cell water line and storage tank to ensure the water was sufficiently iodinated in flight. The MCV was used successfully on Shuttle for many years. However, in 1990s ground testing of closed-loop ECLSS regeneration systems with human subjects raised concerns about excessive iodine consumption and potential problems with crew thyroid function over time. Subsequently, NASA determined a maximum safe iodine consumption level for astronauts, limiting it to no more than 0.5-mg/day from either food or water. This limit was above the 1 to 4 mg/L concentration used for microbial control and led to a requirement to remove much of the biocide prior to consumption. The design solution was the introduction of a new piece of biocide removal hardware referred to as the Activated Carbon/Ion Exchange (ACTEX) cartridge. The carbon and ion exchange media removed all forms of iodine. The ACTEX was implemented ahead of the potable water dispenser. However, because the ACTEX removal efficiency is temperature sensitive, it could be applied only to remove iodine from the cold water supply. The use of hot water had to be limited. Cold water was used for food rehydration and the reconstituted foods heated in a conduction-based food warmer as needed. To ensure microbial protection on the downstream side of the ACTEX, a 0.2-micron microbial filter was added near the PWD needle dispense point. For periods of sleep, it was possible to reconfigure the PWD to iodinate the chilled water line.

A similar iodine-based biocide architecture was carried forward to the ISS, where water is used for drinking, food and beverage reconstitution, crew personal hygiene, housekeeping, urinal flush water, and supply water for the Oxygen Generation Assembly (OGA). The water system consists of a bellows-style water storage tank, a pump, and plumbing to the PWD, flush water system, OGA, etc. Because the ISS was developed for long-term continuous operation as a microgravity and space environment research laboratory, it is the first vehicle to employ a water regeneration system. The system is used to recover potable water from spacecraft wastewater. For ISS, the wastewater includes urine and humidity condensate. Urine is initially distillated and delivered to the Water Processor Assembly (WPA), along with the humidity condensate. In the WPA, the urine distillate and humidity condensate are processed through a multifiltration bed containing adsorbent and ion exchange media to remove larger organic compounds and ionic contaminants. The process water is then treated with a high-temperature catalytic reactor to oxidize low molecular weight organics to carbon dioxide. Final polishing is done by an IEB to remove oxidation byproducts, including MCV resin, to impart a biocidal concentration of iodine prior to storage and distribution. As on Shuttle, the iodinated water is carried through the PWD system but removed with an ACTEX prior to crew consumption. Also similar in design to the Shuttle, the ISS PWD employs a 0.2-micron filter after the ACTEX to provide redundant microbial removal. The filter also protects against microbial introduction into the potable water system, which may occur due to the user interface touch point at or near the dispense needle.

For the ISS, potable water is also used to supply water to the OGA, EMU, and urinal flush water. Iodine is removed at the inlet to the OGA (since iodine would poison the cell stack used for electrolysis); the urinal (because iodine was never certified for use in the Russian urine collection system employed in the U.S. segment); and EMU (due to the inherent EMU treatment process, though iodine is subsequently added back to the water to ensure a biocide is present in the EMU water loop). The system has worked for ISS operations, in which water flows continuously through the system. However, it is highly undesirable to continue to use a biocide that cannot be used in the region of the potable bus that is most at risk for microbial growth (i.e., the PWD interface with the crew). There is some evidence on the ISS and concern for future spacecraft that periods of stagnation may facilitate microbial challenges in systems where periods of dormancy are expected (Maryatt, 2018).

### E.2.1 Need to Address PWD Issues Initially on ISS

Future water system development is expected to reflect designs similar to those discussed above. Early exploration vehicles and missions are expected to employ fill and draw water system designs, while systems employing water recovery are expected to implement architectures like the regeneration system used on ISS. Because of the limitation associated with iodine (i.e., it must be removed prior to the use point), the NASA Advanced Exploration System (AES) Program has been developing silver as the biocide for future water systems. The Orion spacecraft, a fill and draw system, has already selected silver biocide for near-term mission use. Similarly, the International Environmental Control and LSS Interoperability Standards (IECLSSIS) specifies silver, and/or compatibility with silver, as the baseline biocide for potable water systems. However, there is also rationale for maintaining iodine as the biocide for missions beyond ISS. The advantages of continuing to use iodine is that a) iodine has already been proven on ISS and thus no additional development work would be required, and b) iodine is the only biocide known to be compatible with the EMU loop. Any change to the biocide employed by the EMU loop is expected to require significant development costs, along with the associated schedule implications. In comparison, the primary advantages for silver are (a) it is a powerful board spectrum antimicrobial—i.e., effective against numerous microbial species; (b) it is an effective biocide at concentration acceptable to be consumed directly by crew—i.e., silver does not require removal prior to consumption, thus minimizing logistics and system complexity; and (c) silver is the current biocide used by the Russian Space Agency, offering system interoperability by way of a common biocide. Iodine and silver are incompatible, and the respective biocides must be removed and/or swapped prior to mixing water that may contain either of these biocides.

Despite the potential advantages of silver, development work remains to ensure its successful use for future exploration missions. The main challenges center on materials compatibility and the development of silver dosing and sensing technology. Of these, the major obstacle is the compatibility of silver with the wetted materials of construction used for spacecraft water systems. Silver will plate out on metallic surfaces readily, despite conventional processes to passivate those surfaces. Some absorption of silver onto non-metallic surfaces can also be observed, although this phenomenon occurs on far fewer materials and generally the observed losses are not of a significant issue. Finally, there remains concern about the application of silver biocides in other systems planned to make use of potable water. The EMU suit loop is a system where significant concern and risk currently exist for the implementation of a silver biocide.

Development work continues to address these challenges, and technical, cost and schedule debate continues within the ECLSS and EVA communities as to the preferred candidate biocide for exploration. The NESC is working with NASA personnel to evaluate four biocides for future water systems. These include various iodine-, chlorine-, bromine-, and silver-based alternatives. Ultimately, the full assessment of the candidate biocides will be handled by the overall NESC biocide assessment team, as outlined in the main body of this report.

## E.3 Preliminary Evaluation of Candidate Biocides

### E.3.1 Maintaining Concentration

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| **Iodine** | Iodine is the state of the art (SOA). Concentration range for the biocide has been established for microbial control at 1-4 ppm. At these concentrations, removal of the biocide is necessary prior to crew consumption due to health concerns. Removal is achieved through use of the ACTEX cartridge in the PWD. As a result, a biocidal concentration of iodine is not maintained across the entire system, leaving the end portion without a biocide. Residual biocide at the end of the system is considered a primary need to address potential back-contamination through the dispensing needle. In addition, iodine is known to be reactive on many of the wetted materials of construction, resulting in changes to the biocidal form and/or losses through absorption on to the wetted surfaces. Under nominal conditions of continuous operation, such as on the ISS, iodine has been shown to maintain a sufficient residual to the removal point and ultimately meets potable water microbial requirements. However, as discussed below, where periods of dormancy may be required, additional work may be required to verify that this biocide architecture will be appropriate. |
| **Silver** | Silver is used by the Russian Space Agency and is an emerging biocide technology being explored by NASA. A preliminary concentration range between 200 and 400 ppb has been recommended for microbial control. At this concentration, removal of the biocide prior to crew consumption is not required. As such, silver has the potential to provide full coverage across the potable water system up to and through the end use point. However, silver has material compatibility challenges with much of the traditional wetted materials of construction. The main issue is loss of the biocide from the bulk solution, in particular, by plating out on the metallic surfaces. Silver losses due to plating are strongly driven by the surface-to-volume ratio. More work is needed to determine the extent of the issue as related to maintaining biocide concentrations as a function of water system design and operational use. Ongoing research is exploring alternative material processing and materials that have exhibited promising results for strategies to improve and/or fully maintain silver concentrations in the water system (Colon et al., 2020; Muirhead et. al., 2020, and Vance & Delzeit, 2019, 2020). |
| **Chlorine & Bromine** | Chlorine and bromine are biocide options similar to iodine. Like iodine, these substances are halogens. Chlorine and bromine hold further promise in that both can presumably be consumed by crew at levels appropriate for microbial control. However, full toxicology assessments have not been completed for either biocide in spaceflight applications. In addition, bromine is cited as having an “undesirable” taste and odor that could impact crew consumption rates. Further studies are necessary to provide sufficient rationale for maintaining these biocides as candidates. In addition, like iodine, the biocidal forms of bromine and chlorine are expected to deplete over time according to a similar chemistry. In fact, chlorine and bromine are more reactive and more volatile than iodine, so ultimately these losses could be more extensive for biocides of these halogens. Like silver, their ability to maintain biocidal concentrations through the use point must be studied/verified. |

### E.3.2 Dosing Method

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| **Iodine** | Iodine, as the SOA, has well-established dosing technology. As discussed previously, the technology employs a MCV, which consists of a housing containing polyiodide anions bound to quaternary amine fixed charges of a polystyrene-divinylbenzene copolymer anion exchange resin. The iodinated loaded polymer releases a predictable concentration of iodine as water passes through the device according to flow rate, chemistry, and temperature. |
| **Silver** | Four methods are being developed for silver addition. Two are passive systems that would function similarly to the iodinated MCV (i.e., chemistry-based release, no power required). The first is a silver nanocomposite immobilized into a polystyrene foam matrix. The system is referred to as passive silver foam. This technology is being developed at KSC. Results to date are promising, with a nanocomposite silver compound and foam matrix developed and preliminary release testing between 200 to 400 ppm conducted for a one-crew, one-year equivalent (Irwin et al., 2019 & 2020). Additional development is required to refine the release performance and quantify long term performance and required mass of the system.<br><br>A second passive silver dosing technology is based on packed beds using various compounds of silver salt particles. This technology, referred to as solid phase reagent (SPR), is being developed under a Phase II SBIR by ELS Technology. The firm claims the development of several compounds, including sulfonated, ortho-phosphate, and silver metal, which can be used to target the desired silver concentration. Depending on the compound selected, additional work may be required to condition the influent water stream. Additional development is required to demonstrate that desired silver release characteristics can be met, to quantify long-term system performance, and to determine the overall required mass.<br><br>The third silver dosing technology in development is an active system based on electrolytic dosing. For this system, a low current is passed through plates of silver (electrodes) to generate silver ions in solution. The amount of silver released is directly proportional to the amount of current. The technology is commercially available, simple and straightforward, but does require power and a control system. Work to development the technology for spacecraft application is under way at JSC (Hicks and Nelson, 2020). Development work is focused on system design for release in low-conductivity water, as well as investigation into the potential for electrode fouling and particulate generation. A final area of investigation for this technology is whether electrolytic silver dosing would be appropriate for an MCV function on the recirculation line of a water regeneration system. The technology would provide microbial isolation between the clean and dirty portions of the water system that require hydraulic connection. If the electrolytic device cannot be used, alternative silver dosing technology may be needed as well. Here one dosing system would supply the main biocide addition to clean product water supplied to the potable water system, and a second silver dosing technology would serve the MCV function on the reject line to return unacceptable potable water to the head of the water reclamation system. Currently, the electrolytic technology development is being conducted at JSC.<br><br>Finally, early development has been funded in FY21 to begin an investigation of an active dosing system based on pumping a known concentration of liquid silver into the water processor prior to storage/delivery. Major components of this system are expected to be a liquid tank to hold the concentrate, a small microdosing pump for concentrate delivery, and a controller. No development work has been conducted to date, but some |

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| | micropump technology is available commercially. Concentrated liquid delivery systems are already used on the ISS for adding pretreat solution to stabilize urine during collection. Work will be needed to prove the liquid dosing concept and understand where in the trade space this dosing technology should be considered. Ames Research Center will initiate this work in FY21. |
| **Chlorine & Bromine** | Bromine and chlorine addition may be passively dosed via a halogenated resin system similar to the current MCV, or biocide solutions could potentially be dosed via a liquid concentrate dosing system. The resin technology is being developed by Umpqua under an SBIR effort. Promising results were achieved for bromine in Phase I, but no complementary resin was identified for chlorine. A Phase II effort was recently funded, and work is under way to prove the bromine resin dosing technology. In addition, preliminary microbial and material compatibility studies are planned. It is not known whether the system will have buffering requirements that may be driven by the need to improve the microbial efficacy and/or minimize corrosion. The system is being developed without buffering to see if performance can be met without this addition. Additional development work may be needed. It is not known whether additional work will be done under the SBIR Phase II to achieve a chlorine resin technology. Other forms of bromine and/or chlorine, if selected as a biocide, would likely require addition as liquid concentrate, similar to the silver liquid dosing system development effort described above. For this type of system, it is expected any potential buffering requirement would be addressed in such a liquid dosing design. |

### E.3.3 Operational Simplicity

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| **Iodine** | Addition of iodine via MCV resin is a proven approach for biocide addition. The technology does have a limited lifetime, and once spent the cartridge becomes an expendable mass. Under this configuration, multiple units may need to be supplied to cover the mission. In addition, as the iodine cannot be consumed by crew, removal of the biocide is required at the PWD. This creates the need for an ACTEX biocide removal hardware at this location, adding to the overall operational complexity. No monitoring is required for an iodine system, based on ground testing that verified the long-term performance of the MCV resin coupled with on-orbit sampling (after three years) to confirm acceptable iodine concentrations are being achieved. If for future missions a biocide monitoring should be required, development of an iodine monitor was initiated, but not completed, under the PCWQM program. Achieving monitoring capability, if required, is considered a moderate risk. |
| **Silver** | Implementation of a silver biocide technology is expected to be like iodine, i.e., single pass addition at the effluent of water processor assembly (WPA) IEB. Assuming silver is properly maintained throughout the bus, no additional silver dosing is anticipated. Since the silver can be directly consumed, no additional silver removal hardware is expected for the potable water system. This gives silver a slight advantage in overall operational simplicity vs. iodine. It is assumed that a similar technology will be developed for dosing and for the MCV reject line, so no additional complexity is anticipated to accomplish both functions. Finally, there is no current requirement for silver monitoring, although there is some effort to develop this technology should it be required in response to future systems development and/or analysis. |

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| **Chlorine & Bromine** | Addition of bromine and chlorine would also be like iodine, i.e., added at effluent of WPA IEB. Neither of these biocides would be expected to require removal at the PWD, and both are expected to have operational simplicity similar to iodine. However, materials testing and analysis is needed to confirm the need, if any, for pH buffering to mitigate corrosion effects. The literature indicates that the Navy also employs pH monitoring to ensure proper system function. If buffering is required, it is expected to increase system complexity, as buffering would need to be robust and the overall system would likely require additional monitoring (e.g., pH). It is also unknown if microbial efficiency may drive buffering requirements, which may increase system complexity and drive monitoring requirements. |

### E.3.4 Mass Required to Implement

All dosing methods are expected to require similar mass to implement. Iodine should be expected to have a slight disadvantage because the ACTEX hardware is needed for removal in the PWD. Some small mass savings might be realized for silver, as the mass of biocide needed is almost an order of magnitude less than iodine, bromine, and chlorine. Mass will also be driven slightly by the mass of the expendable material for each technology. However, it is expected that these masses will be comparable, with perhaps a slight advantage for a silver-based system. Outside the potable water system, all biocides are expected to need to be removed by OGA DI Bed (IX resin). Currently, technology should be available in the form of ACTEX variations to achieve this function for all the biocides. No biocides should require removal at the toilet, although additional studies should be conducted to confirm.

For the EMU water cooling loop, the biocides may or may not require removal depending on the ultimate configuration and operation selected for that system. Studies are under way to better understand these impacts for silver and iodine. Regardless, it is not expected that removal requirements will be a strong driver in system mass. Similarly, the overall difference in mass across these biocide candidates are not expected to be a deciding factor in the present trade studies. It is worth noting, however, that early Gateway missions are looking into the use of silver for potable water and iodine for EMU. The rationale for the split biocide architecture being (a) mass and volume savings with silver use the potable water system, and (b) insufficient time to develop a silver biocide for the EMU. Regardless, more studies will be required to understand the total masses required of these systems.

### E.3.5 Reliability

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| **Iodine** | Iodine biocide technology is well proven for potable water system applications. Therefore, the iodine biocide is considered a high reliability biocide system. However, the requirement to remove the biocide prior to crew consumption is a significant disadvantage and the long-term effects for exploration are still unproven, especially regarding periods of dormancy. |
| **Silver** | Risks remain associated with silver plating and its potential impact on function of components in the potable system. However, the dosing systems, if successful, are simple and expected to be highly reliable once proven. Similarly, silver can be consumed by the crew allowing the biocide to be provided through the use point, which, assuming a biocide is needed, should increase the overall reliability of the water system. Similarly, too, silver is considered to be a more broad-spectrum biocide relative to iodine, and if so, should also improve system reliability. |

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| **Chlorine & Bromine** | Chlorine and bromine are expected to be able to be consumed by the crew. Similarly, their concentrations should be maintainable throughout the potable bus. However, like silver, work is needed to ensure the higher reactivities of chlorine and bromine result in no significant loss of the biocide during nominal operations and/or dormancy. Development risk remains low for bromine, but high for chlorine. If the resin-based technologies are successful, the reliability of these systems is expected to be high. Navy experience suggests bromine may be consumed by the crew, and that its concentration can be maintained throughout the potable bus. However, if a buffer should be needed for corrosion control and/or microbial efficacy, the overall reliability would be expected to be lower than systems not requiring this additional complexity. |

### E.3.6 Storage

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| **Iodine** | MCV resin for iodine addition has an expected five-year shelf life. |
| **Silver** | Insufficient data are available to determine the storage life for silver dosing methods. However, the electrolytic approach would be expected to exceed three-year shelf life. Additionally, there are no significant hazard concerns regarding the storage of concentrated silver biocides. |
| **Chlorine & Bromine** | Insufficient data are available to define storage life for bromine and chlorine biocides. Resin-based systems are expected to have similar storage life and safety concerns as the current iodine system. For liquid concentrate systems, additional research would be required. Also, chlorine has a credible storage risk—no dosing technology is known, and as such, the storage stability is unknown. |

### E.3.7 Materials Compatibility

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| **Iodine** | Iodinated water is known to be a corrosive solution if not used with compatible materials. Niflor coating used on Parker QDs is no longer applied to QDs exposed to iodinated water due to corrosion issues. Other than Niflor coating, no other corrosion issues have been identified on ISS under the use conditions for that mission/vehicle system. Iodine is also considered compatible with the EMU cooling loop and is the SOA for that system. However, currently, the EMU loop must be periodically scrubbed to remove contaminants, which also removes the biocide. Therefore, biocide addition for EMU operations is required presently. It is hoped the xEMU system in development will eliminate this scrubbing requirement, allowing potable water with iodine to be used directly in the suit loop. Studies are in work to prove this operational concept. Another advantage to iodine use in the suit application is that it is volatile and therefore does not build up in the water loop over time as water evaporates to cool the suit. However, as the biocide is lost in the evaporative process, the concentration in the loop is reduced over time. Similarly, in the EMU and the potable water system, iodine is known to absorb onto certain polymer surfaces as well as to be reduced to non-biocidal forms when in contact with certain metal surfaces. These cumulative effects result in the loss of the biocide, and it is not clear that the true requirements for maintaining biocidal control in these systems are fully understood, especially regarding new exploration requirements for proposed operational uses (e.g., no loop scrubbing and long periods of dormancy). Regarding the OGA, it is expected iodine will need to be removed as the biocide will negatively impact the performance of the catalyst used in that system. Currently, iodine is also removed from the toilet flush water. However, studies could confirm whether such removal is a hard requirement. If removal is needed for any or all of these systems, ACTEX technology is developed and available. |

| | |
|---|---|
| **Silver** | The primary compatibility issue with silver is plating on metal surfaces. This effect has a strong dependency on surface-to-area ratios, and work is ongoing to understand these effects as they pertain to application of silver biocide technology within spacecraft potable water systems. Significant work is also being done in the area of material and material processing to mitigate and/or eliminate these effects. Promising related work involves the use of Teflon-lined non-permeable flex lines, as well as alternate tank technology and coatings. There is hope that these material improvements could be applied to future xEMU water loop designs to mitigate silver interactions. Collaborative work is being done to understand the impacts of silver biocides in the xEMU loop. Like iodine, silver is expected to need removal from the OGA supply water. Similarly, studies of requirements for toilet flush water will be needed, but no known issues are anticipated. Technology similar to that of the ACTEX is available and flight-tested. |
| **Chlorine & Bromine** | Material compatibility risks for chlorine and bromine are expected to be like iodine. Both would be expected to be more reactive than iodine, and issues of biocide loss and/or corrosion will deserve additional consideration. If proven to be no issue for the potable water system, then bromine, at least, should be suitable for EMU use. However, reactivity and volatility, expected to be more significant for iodine, may be an issue for maintaining microbial control in the EMU water loop. As for chlorine, the EMU group has already expressed concern and is strongly considering omitting this biocide from the candidate list. The potable water system team, including those helping with material compatibility, has expressed a similar reluctance to use the biocide. Like iodine, bromine and chlorine would be expected to be removed from the OGA supply. Removal may not be needed for flush water, but studies should confirm. Removal technology, if needed, is expected to resemble that already used for iodine. |

### E.3.8 Dormancy

Per the philosophical approach intended for dormancy, maintaining a biocide during dormancy is not required. Microbial control will be maintained by ensuring the water and hardware provides limited nutrients to support microbial growth. This assessment will focus on the perspective of maintaining effective microbial control entering dormancy, such that biofilm growth can be appropriately limited for the duration.

| | |
|---|---|
| **Iodine** | Iodine has no proven track record through periods of dormancy. The primary concern is that its use is inherent to the absence of biocide in the final leg of the water system. |
| **Silver** | Silver may have some advantage for taking a system into dormancy, as the biocide residual would be available through the use point. However, confirmation is needed that silver would provide adequate microbial control if lost due to plating over long periods of dormancy. |
| **Chlorine & Bromine** | Bromine and chlorine would be expected to behave like iodine during dormancy. Further, because these biocides would not be removed in the final leg of the water system, they could provide some additional benefit when taking the system into dormancy. Like iodine, the biocides would need to be tested to verify their performance during long-term dormancy. This may include maintaining microbial control, corrosion, and long-term changes in water quality. |

### E.3.9 Technology Readiness

| | |
|---|---|
| **Iodine** | Iodine is a proven concept based on 12 years of operation on ISS. |
| **Silver** | Significant effort remains to complete development of silver as a viable biocide technology. Based on findings at the Silver TIM in late 2019, confidence remains high that issues can be resolved. Multiple dosing methods have shown promising results to date. The issue of silver plating is expected to be resolved with primary use of non-metallic tubing. Studies involving surface area-to-volume ratios, materials processing, coatings, and preconditioning surfaces with silver "aging" are also yielding promising results (Colon et al., 2020; Muirhead et al., 2020 & Vance and Delzeit, 2019 & 2020). Confirmation that silver plating will not impact the long-term performance of the system and/or the function of components in the potable bus is also needed. |
| **Chlorine & Bromine** | Experience with bromine and chlorine as a biocide are limited. NASA used chlorine in early spaceflight programs (Mercury, Gemini and Apollo). Challenges were noted due to corrosion and the dosing technology was rudimentary (syringe injection by crew). Bromine is cited as having use by the Navy, especially on submarines. The operational experience is considered significant, but also with challenges regarding the need for buffering and continuous monitoring of the biocide to ensure proper maintenance. Both biocides still have development issues surrounding dosing, the challenge being greater for chlorine as no known dosing technology is currently available. Material compatibility is also expected to be an area of needed research, again more challenging for chlorine, which is known to have significant reactivity with metallic and non-metallic surfaces. This includes impacts to the biocide, losses, and impact to the materials themselves. |

## E.4 Technology Review

In the following section, the advantages and concerns around the candidate biocides are reviewed. Except for iodine, these considerations could be assessed only with the commensurate level of uncertainly around the technologies, as they are still in development. Although iodine biocide technology is the SOA and therefore best known, uncertainty remains around the application of the technology to requirements expected for future exploration missions. For all biocides, the ultimate objective is to conduct further prioritized studies in the relative biocide gap areas to develop a full set of data upon which these biocides can be more fully compared.

### E.4.1 Iodine

| | |
|---|---|
| **Advantages** | • Iodine is the SOA biocide technology with more than 12 years of flight experience on the ISS and other past vehicle platforms. |
| **Concerns & Development Needs** | • Requires removal prior to the use point, leaving the most vulnerable portion of the water system without a biocide.<br>• Unknown performance against new mission requirements, e.g., dormancy, long-term material compatibility, biocide losses. |

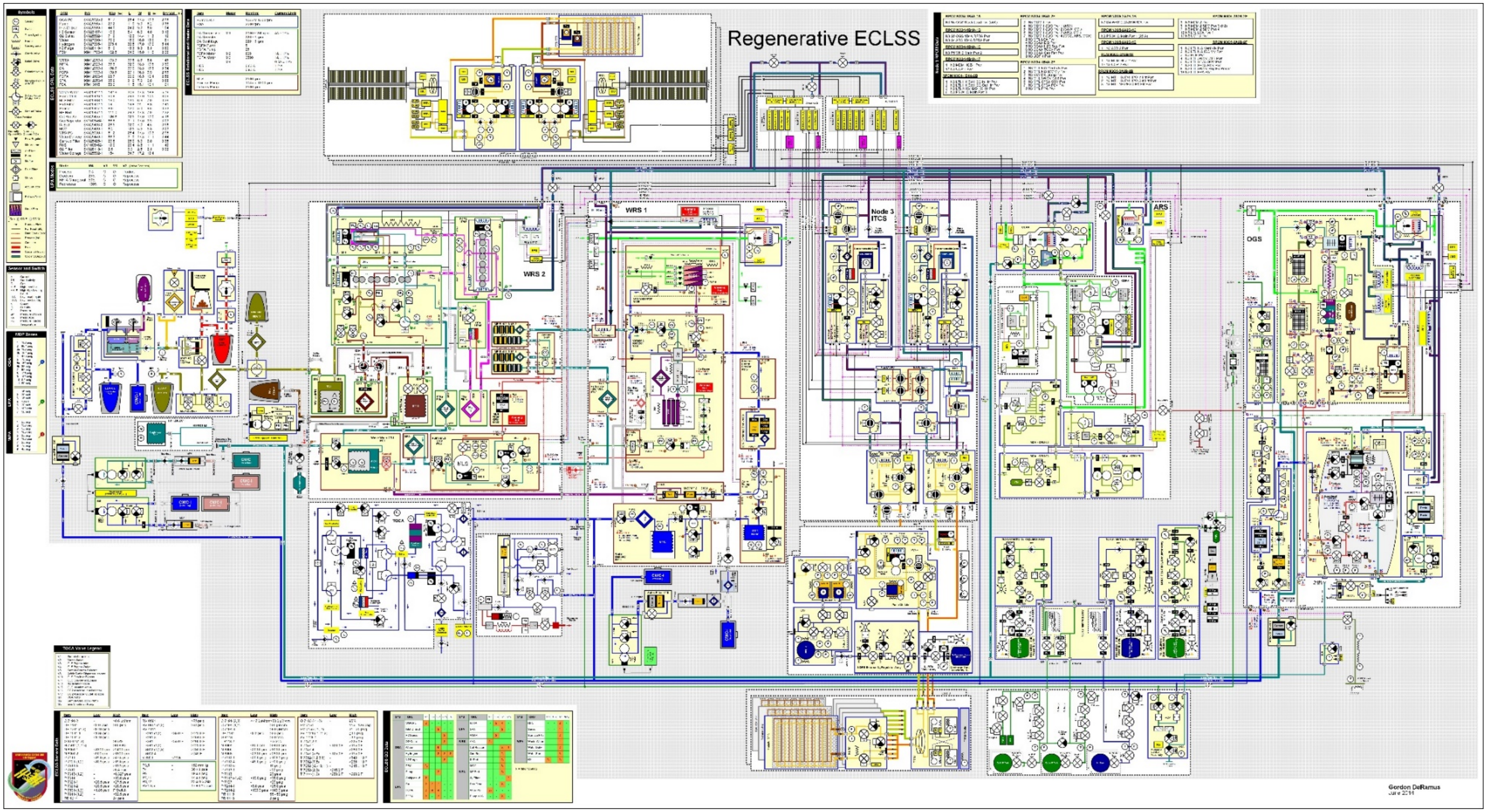
### E.4.2 Silver

| | |
|---|---|
| **Advantages** | • Strong biocidal properties, good broad-spectrum antimicrobial at acceptable potable water levels, i.e., no removal requirement. Stable if maintained in solution, e.g., no change in Ag+ speciation within potable pH range.<br>• Provides disinfection residual throughout entire water system.<br>• Accepted and established biocide for spacecraft application. Used by Russian Space Agency. Some NASA experience with ISS and Orion provides insight into knowledge gaps, biocidal effectiveness, and other areas of concern.<br>• Several simple, well-understood delivery options, including soluble salts, electrolytic generation, and liquid injection.<br>• Good materials compatibility with polymers. Coatings are promising (Parylene and Alumina).<br>• Ionic silver's reduced oxidation state of elemental silver is not corrosive. |
| **Concerns & Development Needs** | • Rapid loss of biocide as Ag+ deposits as elemental silver and ionic silver oxides on passivated metal surfaces.<br>• May display reactivity with other materials, e.g., polymers and organics.<br>• Corrosion effects of silver and/or silver salt counter ions unknown, i.e., may undergo galvanic replacement reactions with unpassivated alloys.<br>• Dosing technology still in development. |

### E.4.3 Chlorine & Bromine

| | |
|---|---|
| **Advantages** | • Effective oxidant and provides residual level of disinfection of water at potable drinking water levels. Can maintain biocidal concentration throughout entire water system.<br>• Promising disinfection technology for bromine, similar to iodine SOA. |
| **Concerns & Development Needs** | • Low photostability and thermostability. May be issues of taste and odor, especially for bromine.<br>• Oxidizing capacity of free chlorine or bromine species varies with pH. If solution is not buffered, slightly acid solutions will increase corrosion kinetics and pose a materials degradation risk with long-term use.<br>• Reactivity and volatility may lead to significant losses in biocide with time, of particular concern for long-term use and dormancy.<br>• Chlorine dosing and storage unknown/unproven.<br>• Precipitants created by corrosion and reaction products pose significant risk to downstream components and systems (critical that corrosion risk be addressed with proper materials selection and buffering pH). |

## E.5 ISS Regenerative ECLSS Schematic



# Appendix F: Architecture Criteria Scoring, Normalization, and Raw Data

## F.1 Baseline Scoring

Baseline scoring for each architecture was accomplished by evaluating each subsystem: xEMU, LSS, and Integration, against each criteria and subcriteria. Rationale was captured for each item in the evaluation. For every subcriteria, the impact on that subsystem was assessed and designated a color based on the definitions shown in Table F-1.

*Table F-1. Impact Levels of Subcriteria on Individual Subsystems*

| |
|---|
| **Positive impact** |
| **No impact** |
| **Small/minimal negative impact** |
| **Moderate negative impact** |
| **Significant negative impact** |

Once the impact of each subcriteria was determined, the overall subsystem was assigned a score based on the metrics specific to the criteria. Scoring criteria and raw data are provided below.

### F.1.1 Criteria 1: Minimal Mass, Power, and Volume

Table F-2 shows the scoring definitions for Criteria 1. Any of the subsystems with positive or no impact scored a 5. Those with mostly positive/no impact, but some minimal impacts, scored a 4. Those subsystems with a single significant impact combined with a few minimal or moderate impacts, or those with a few moderate impacts, scored a 3. Subsystems with multiple significant and moderate impacts scored a 2, and those with numerous significant impacts scored a 1. No solution scored 0 for Criteria 1. The core team reviewed every subcriteria for all options. In cases where a score did not directly follow the described practical application, rationale was captured.

*Table F-2. Scoring Definitions for Criteria 1: Minimal Mass, Volume, and Power*

| Score | Criteria 1: Minimal M/V/P Scoring Definitions |
|---|---|
| **5** | Near-ideal design solution. No additional mass, volume, and/or power required beyond ISS baseline to implement. |
| **4** | Excellent option. Very little additional mass, volume, and/or power required beyond ISS baseline to implement. |
| **3** | Very good option. Additional mass and/or volume required, but limited to slight modifications to hardware mass/volume and/or infrequent resupply; small impact on power. |
| **2** | Good option. Additional mass, volume, and/or power required with significant impact to initial mass and/or resupply; moderate impact on power. |
| **1** | Option is acceptable. Significant impact on initial mass/volume and/or resupply; significant impact on power. |
| **0** | Option is not acceptable. One or more significant problems/impacts that cannot be accommodated within reason. One or more “showstoppers.” |

The raw data for Criteria 1 is provided in Tables F-3 through F-13.

*Table F-3. Criteria 1 Subsystem Scoring for Options 1, 2, and 33*

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **xEMU** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable - may be as simple as tubing swap rather than extensive hardware | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| New Hardware Added to xEMU | None | None | None |
| Hardware Eliminated from xEMU | Eliminates biocide removal and re-iodination in UIA | Eliminates biocide removal and re-iodination in UIA | Eliminates biocide removal and re-iodination in UIA |
| Hardware Modified - Material Change | None | None | None |
| Hardware Modified - Physical Design Change | None | None | None |
| Hardware Modified - Approach Change | None | None | None |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of | Something, but assume same regardless of | Something, but assume same regardless of |
| Dormancy - Other consumables | None expected | None expected | None expected |
| Additional Power | None expected | None expected | None expected |
| Resupply - Consumables for Dosing hardware | None above baseline | None above baseline | None above baseline |
| Resupply - "Fresh" Biocide | None above baseline | None above baseline | None above baseline |
| **SCORE** | 4 | 4 | 4 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **Integration** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | a consumable - may be as simple as tubing swap rather than extensive hardware replacement. | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| New Hardware for Integration | None | None | None |
| New power for integration | None | None | None |
| **SCORE** | 5 | 5 | 5 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **LSS** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | as a consumable - may be as simple as tubing swap rather than extensive hardware replacement. | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| New Hardware Added to LSS | None | None | None |
| Hardware Eliminated from LSS | None | None | Eliminate some length of lines and "dead legs". |
| Hardware Modified - Material Change | None | None | None |
| Hardware Modified - Physical Design Change | Option 1: design change to PWD to achieve iodine removal @ or closer to nozzle. Already redesigning to eliminate "dead legs". Iodine removal possible at higher temperatures? (ND) Anticipate minimal impact in overall M/V. Do not anticipate any additional power. | Option 2: significant due to need for design for removal. Entirely new mechanical design + human factors. More volume likely required for sufficient access. Replacement parts. | Design Change to PWD to eliminate those volumes. |
| Hardware Modified - Approach Change | None | Option 2: Consumable "end leg" of PWD - replaced when microbes detected or after dormant period. | None |
| Resupply - Replacement Parts/Consumables for LSS | Possible replacement of nozzle after dormancy | Option 2: Consumable "end leg" of PWD - replaced when microbes detected or after dormant period. | None |
| Dormancy - Hardware change-out | None | Option 2: Consumable "end leg" of PWD - replaced when microbes detected or after dormant period. | Consumable PWD with every mission change-out. |
| Dormancy - Other consumables | None above baseline. | None above baseline. | None above baseline. |
| Resupply - Consumables for Dosing hardware | None above baseline. | None above baseline. | None above baseline. |
| Resupply - "Fresh" Biocide | None | None | None |
| Additional Power | None | None | None |
| **SCORE** | 4 | 3 | 2 |

*Table F-4. Criteria 1 Subsystem Scoring for Options 3-5*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **xEMU** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver |
| New Hardware Added to xEMU | None. | None. | None. |
| Hardware Eliminated from xEMU | Eliminates biocide removal and re-iodination in VISE | Eliminates biocide removal and re-iodination in VISE | Eliminates biocide removal and re-iodination in VISE |
| Hardware Modified - Material Change | Modification of materials for backplate, pump, LCVG, Evaporators (Ti) and HX (Inconel). Does not add mass. Anticipate a near-net-zero. | Modification of materials for backplate, pump, LCVG, Evaporators (Ti) and HX (Inconel). Does not add mass. Anticipate a near-net-zero. | Modification of materials for backplate, pump, LCVG, Evaporators (Ti) and HX (Inconel). Does not add mass. Anticipate a near-net-zero. |
| Hardware Modified - Physical Design Change | None. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | None. |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None above current baseline | None above current baseline | None above current baseline |
| Additional Power | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | None. | None. |
| Resupply - "Fresh" Biocide | None. | None. | None. |
| **SCORE** | 4 | 4 | 4 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **Integration** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver |
| New Hardware for Integration | None | None | None |
| New power for integration | None | None | None |
| **SCORE** | 5 | 5 | 5 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **LSS** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver |
| New Hardware Added to LSS | Electrolysis unit, controller | Electrolysis unit, controller, silver monitor | ELS/Foam in-line dosing |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated |
| Hardware Modified - Material Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - material change for all tubing, no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing, - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. |
| Hardware Modified - Physical Design Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. |
| Hardware Modified - Approach Change | None besides core technology | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. | None. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V |
| Dormancy - Hardware change-out | None. | Sensor replacement possible after dormancy | None. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | Consumables expected for recalibrating the silver monitor. | None above baseline approach. |
| Resupply - "Fresh" Biocide | None expected - potentially reduces resupply mass with no fresh biocide required for primary dosing. | None expected. | None above baseline approach. |
| Additional Power | Negligible - <1mA @ <1V = <1W | Negligible - <1mA @ <1V = <1W for dosing, Minimal impact for monitor. | None |
| **SCORE** | 3 | 2 | 4 |

*Table F-5. Criteria 1 Subsystem Scoring for Options 6-8*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **xEMU** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| New Hardware Added to xEMU | None. | None. | None. |
| Hardware Eliminated from xEMU | Eliminates biocide removal and re-iodination in VISE | Eliminates biocide removal and re-iodination in VISE | Eliminates biocide removal and re-iodination in VISE |
| Hardware Modified - Material Change | Modification of materials for backplate, pump, LCVG, Evaporators (Ti) and HX (Inconel). Does not add mass. Anticipate a near-net-zero. | Modification of materials for backplate, pump, LCVG, Evaporators (Ti) and HX (Inconel). Does not add mass. Anticipate a near-net-zero. | Modification of materials for backplate, pump, LCVG, Evaporators (Ti) and HX (Inconel). Does not add mass. Anticipate a near-net-zero. |
| Hardware Modified - Physical Design Change | None. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | None. |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None above current baseline | None above current baseline | None above current baseline |
| Additional Power | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | None. | None. |
| Resupply - "Fresh" Biocide | None. | None. | None. |
| **SCORE** | 4 | 4 | 4 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **Integration** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| New Hardware for Integration | Significant impact on implementing secondary dosing approach for control of Ag concentration in the system. Added M/V/P for secondary dosing method. | None | None |
| New power for integration | Dependent on secondary dosing approach. Power may be required if automated dosing is implemented. | None | None |
| **SCORE** | 1 | 5 | 5 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **LSS** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| New Hardware Added to LSS | ELS/Foam in-line dosing, monitor | Salt solution dosing system required to implement. Anticipated to include pump and reservoir at a minimum. | Salt solution dosing system required to implement. Anticipated to include pump and reservoir at a minimum, silver monitor |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated |
| Hardware Modified - Material Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing. No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Possible additional M/V to mitigate counterion. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing. No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Possible additional M/V to mitigate counterion. |
| Hardware Modified - Physical Design Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag). No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change to add new dosing system for salt. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag). No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change to add new dosing system for salt (M/V), moderate additional power for pump. |
| Hardware Modified - Approach Change | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of the Ag sensor. | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). Unknown lifetime of the sensors. |
| Dormancy - Hardware change-out | Sensor replacement possible after dormancy | None. | Sensor replacement possible after dormancy |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Consumables expected for recalibrating the silver monitor. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Consumables expected for recalibrating the silver monitor. |
| Resupply - "Fresh" Biocide | Secondary dosing method will require additional fresh biocide in a TBD form. | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution vs MCV's. |
| Additional Power | Minimal additional power for Ag monitor. Possible power requirement for secondary dosing method. | Low additioinal power (micropump) required for pump to inject salt solution. Still TBD. | Minimal additional power for Ag monitor. Unknown additional power required for pump to inject salt solution. |
| **SCORE** | 1 | 2 | 1 |

*Table F-6. Criteria 1 Subsystem Scoring for Options 9-11*

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **xEMU** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| New Hardware Added to xEMU | None. | None. | None. |
| Hardware Eliminated from xEMU | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. |
| Hardware Modified - Material Change | Modification of materials in sensors for thermal loop (pressure sensors, RTDs) not expected to make significant changes to overall mass or volume. | None. | None. |
| Hardware Modified - Physical Design Change | Elimination of Hastelloy would require a similar type material (NI-based). No anticipated changes in M/V for these changes. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | None. |
| Resupply - Replacement Parts/Consumables for xEMU | Possible solution to Hastelloy sensors is more frequent replacement. Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None above current baseline | None above current baseline | None above current baseline |
| Additional Power | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | None. | None. |
| Resupply - "Fresh" Biocide | None. | None. | None. |
| **SCORE** | 3 | 3 | 3 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **Integration** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| New Hardware for Integration | None. | None. | None. |
| New power for integration | None. | None. | None. |
| **SCORE** | 5 | 5 | 5 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **LSS** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| New Hardware Added to LSS | Dosing system required to implement. Anticipated to include pump and reservoir at a minimum. | Biocide solution + buffer dosing system required to implement. Anticipated to include pump and reservoir at a minimum. | Biocide solution + buffer dosing system required to implement. Anticipated to include pump and reservoir at a minimum, Br & pH sensors. |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated |
| Hardware Modified - Material Change | Need to add carbon for the salt solution due to organic counterion to DI Bed (ion exchange bed) Media changed for OGA - no change in M/P/V, MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution vs cartridge dosing. | Need to add carbon for the salt solution due to organic counterion to DI Bed (ion exchange bed) Media changed for OGA - no change in M/P/V. MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution+ buffer vs cartridge dosing. | Need to add carbon for the salt solution due to organic counterion to DI Bed (ion exchange bed) Media changed for OGA - no change in M/P/V. MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution+ buffer vs cartridge dosing. |
| Hardware Modified - Physical Design Change | ACTEX Media changed for OGA, MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change and added mass/volume to add new dosing system for salt. Also need to consider double/triple containment. | ACTEX Media changed for OGA, MCV approach changed - minimal added M/V for MCV-Br (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution + Buffer vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change and added mass/volume to add new dosing system for salt. | ACTEX Media changed for OGA, MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution + Buffer vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change and added mass/volume to add new dosing system for salt. |
| Hardware Modified - Approach Change | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. Active monitoring and control software/logic of biocide/buffer concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). Significant replacement and calibration of pH sensor required. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump.Consumables expected for recalibrating the Br monitor and pH monitor. |
| Resupply - "Fresh" Biocide | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. |
| Additional Power | Unknown additional power required for pump to inject salt solution. | Unknown additional power required for pump to inject salt/buffer solution. | Unknown additional power for Br monitor and pH monitor. Unknown additional power required for pump to inject salt/buffer solution. |
| **SCORE** | 2 | 2 | 1 |

## *Table F-7. Criteria 1 Subsystem Scoring for Options 12-14*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **xEMU** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| New Hardware Added to xEMU | None. | None. | None. |
| Hardware Eliminated from xEMU | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. |
| Hardware Modified - Material Change | Modification of materials in sensors for thermal loop (pressure sensors, RTDs) not expected to make significant changes to overall mass or volume. | None. | None. |
| Hardware Modified - Physical Design Change | Elimination of Hastelloy would require a similar type material (NI-based). No anticipated changes in M/V for these changes. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | None. |
| Resupply - Replacement Parts/Consumables for xEMU | Possible solution to Hastelloy sensors is more frequent replacement. Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None above current baseline | None above current baseline | None above current baseline |
| Additional Power | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | None. | None. |
| Resupply - "Fresh" Biocide | None. | None. | None. |
| **SCORE** | 3 | 3 | 3 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **Integration** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| New Hardware for Integration | None. | None. | Significant impact on implementing secondary dosing approach for control of Br concentration in the system. Added M/V/P for secondary dosing method. |
| New power for integration | None. | None. | Dependent on secondary dosing approach. Power may be required if automated dosing is implemented. |
| **SCORE** | 5 | 5 | 1 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **LSS** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + |
| New Hardware Added to LSS | No impact - would be direct replacement for existing MCV and resin. | No impact - would be direct replacement for existing MCV and resin. | Adds Bromine monitor and pH moniter. |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated | ACTEX in PWD eliminated | ACTEX in PWD eliminated |
| Hardware Modified - Material Change | MCV material changed, No change in mass/volume of new media. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. |
| Hardware Modified - Physical Design Change | None. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule unkown, but expected to be similar to I2. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| Additional Power | None | None | Minimal additional power for Br and pH monitors. Possible power requirement for secondary dosing method. |
| **SCORE** | 5 | 4 | 1 |

*Table F-8. Criteria 1 Subsystem Scoring for Options 15-17*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **xEMU** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| New Hardware Added to xEMU | None. | None. | None. |
| Hardware Eliminated from xEMU | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. | Eliminates biocide removal and re-iodination in VISE. May need to scrub salts out of the thermal loop. Would require hardware currently available in ISS, but not baselined for use in Exploration xEMU architecture. |
| Hardware Modified - Material Change | Modification of materials in sensors for thermal loop (pressure sensors, RTDs) not expected to make significant changes to overall mass or volume. | None. | None. |
| Hardware Modified - Physical Design Change | Elimination of Hastelloy would require a similar type material (NI-based). No anticipated changes in M/V for these changes. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | None. |
| Resupply - Replacement Parts/Consumables for xEMU | Possible solution to Hastelloy sensors is more frequent replacement. Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None above current baseline | None above current baseline | None above current baseline |
| Additional Power | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | None. | None. |
| Resupply - "Fresh" Biocide | None. | None. | None. |
| **SCORE** | 3 | 3 | 3 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **Integration** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| New Hardware for Integration | None. | None. | Significant impact on implementing secondary dosing approach for control of Br concentration in the system. Added M/V/P for secondary dosing method. |
| New power for integration | None. | None. | Dependent on secondary dosing approach. Power may be required if automated dosing is implemented. |
| **SCORE** | 5 | 5 | 1 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **LSS** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + |
| New Hardware Added to LSS | No impact - would be direct replacement for existing MCV and resin. | No impact - would be direct replacement for existing MCV and resin. | Adds Bromine monitor and pH moniter. |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated | ACTEX in PWD eliminated | ACTEX in PWD eliminated |
| Hardware Modified - Material Change | MCV material changed, No change in mass/volume of new media. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. |
| Hardware Modified - Physical Design Change | None. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | Replacement schedule unknown, but expected to be similar to I2, or slightly higher. | To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| Additional Power | None | None | Minimal additional power for Br and pH monitors. Possible power requirement for secondary dosing method. |
| **SCORE** | 4 | 4 | 1 |

*Table F-9. Criteria 1 Subsystem Scoring for Options 18-20*

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **xEMU** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| New Hardware Added to xEMU | None | None | None |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| Hardware Modified - Material Change | None | None | None |
| Hardware Modified - Physical Design Change | None | None | None |
| Hardware Modified - Approach Change | None | None | None |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None expected | None expected | None expected |
| Additional Power | None expected | None expected | None expected |
| Resupply - Consumables for Dosing hardware | None above baseline | None above baseline | None above baseline |
| Resupply - "Fresh" Biocide | None above baseline | None above baseline | None above baseline |
| **SCORE** | 4 | 4 | 4 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **Integration** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| New Hardware for Integration | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of silver capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Safety margin is likely to be required to ensure no Ag breakthrough. Would need to have extremely high confidence in silver capture media. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of silver capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Safety margin is likely to be required to ensure no Ag breakthrough. Would need to have extremely high confidence in silver capture media. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of silver capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Safety margin is likely to be required to ensure no Ag breakthrough. Would need to have extremely high confidence in silver capture media. |
| New power for integration | None | None | None |
| **SCORE** | 2 | 2 | 2 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **LSS** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| New Hardware Added to LSS | Electrolysis unit, controller | Electrolysis unit, controller, silver monitor | ELS/Foam in-line dosing |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated |
| Hardware Modified - Material Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - material change for all tubing, no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing, - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. |
| Hardware Modified - Physical Design Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. |
| Hardware Modified - Approach Change | None besides core technology | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. | None. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V |
| Dormancy - Hardware change-out | None. | Sensor replacement possible after dormancy | None. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | Consumables expected for recalibrating the silver monitor. | None above baseline approach. |
| Resupply - "Fresh" Biocide | None expected - potentially reduces resupply mass with no fresh biocide required for primary dosing. | None expected. | None above baseline approach. |
| Additional Power | Negligible - <1mA @ <1V = <1W | Negligible - <1mA @ <1V = <1W for dosing, Minimal impact for monitor. | None |
| **SCORE** | 3 | 2 | 4 |

## *Table F-10. Criteria 1 Subsystem Scoring for Options 21-23*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **xEMU** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| New Hardware Added to xEMU | None | None | None |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| Hardware Modified - Material Change | None | None | None |
| Hardware Modified - Physical Design Change | None | None | None |
| Hardware Modified - Approach Change | None | None | None |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None expected | None expected | None expected |
| Additional Power | None expected | None expected | None expected |
| Resupply - Consumables for Dosing hardware | None above baseline | None above baseline | None above baseline |
| Resupply - "Fresh" Biocide | None above baseline | None above baseline | None above baseline |
| **SCORE** | 4 | 4 | 4 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **Integration** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| New Hardware for Integration | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of silver capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Safety margin is likely to be required to ensure no Ag breakthrough. Would need to have extremely high confidence in silver capture media. Significant impact on implementing secondary dosing approach for control of Ag concentration in the system. Added M/V/P for secondary dosing method. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of silver capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Safety margin is likely to be required to ensure no Ag breakthrough. Would need to have extremely high confidence in silver capture media. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of silver capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Safety margin is likely to be required to ensure no Ag breakthrough. Would need to have extremely high confidence in silver capture media. |
| New power for integration | Dependent on secondary dosing approach. Power may be required if automated dosing is implemented. | None | None |
| **SCORE** | 1 | 2 | 2 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **LSS** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| New Hardware Added to LSS | ELS/Foam in-line dosing, monitor | Salt solution dosing system required to implement. Anticipated to include pump and reservoir at a minimum. | Salt solution dosing system required to implement. Anticipated to include pump and reservoir at a minimum, silver monitor |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated |
| Hardware Modified - Material Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing. No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Possible additional M/V to mitigate counterion. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag), material change for all tubing. No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Possible additional M/V to mitigate counterion. |
| Hardware Modified - Physical Design Change | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag) - no impact expected on power. No data on change in mass/volume of new media. However, should be minimal compared to mass/volume of entire system. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag). No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change to add new dosing system for salt. | ACTEX Media changed for OGA, MCV approach changed (new design, MCV-Ag). No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change to add new dosing system for salt (M/V), moderate additional power for pump. |
| Hardware Modified - Approach Change | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of the Ag sensor. | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). Unknown lifetime of the sensors. |
| Dormancy - Hardware change-out | Sensor replacement possible after dormancy | None. | Sensor replacement possible after dormancy |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Consumables expected for recalibrating the silver monitor. | Pump replacement anticipated after some duration. Assume infrequent replacement for | Consumables expected for recalibrating the silver monitor. |
| Resupply - "Fresh" Biocide | Secondary dosing method will require additional fresh biocide in a TBD form. | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution vs MCV's. |
| Additional Power | Minimal additional power for Ag monitor. Possible power requirement for secondary dosing method. | Low additioinal power (micropump) required for pump to inject salt solution. Still TBD. | Minimal additional power for Ag monitor. Unknown additional power required for pump to inject salt solution. |
| **SCORE** | 1 | 2 | 1 |

*Table F-11. Criteria 1 Subsystem Scoring for Options 24-26*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **xEMU** | 5,5,dimethylhydantoin (DBDMH) Salt Solution for Vehicle LS | 5,5,dimethylhydantoin (DBDMH) Salt Solution + Buffer for Vehicle LS | 5,5,dimethylhydantoin (DBDMH) Salt Solution + Buffer + Monitoring (OBr- & pH) |
| New Hardware Added to xEMU | None | None | None |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| Hardware Modified - Material Change | None | None | None |
| Hardware Modified - Physical Design Change | None | None | None |
| Hardware Modified - Approach Change | None | None | None |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None expected | None expected | None expected |
| Additional Power | None expected | None expected | None expected |
| Resupply - Consumables for Dosing hardware | None above baseline | None above baseline | None above baseline |
| Resupply - "Fresh" Biocide | None above baseline | None above baseline | None above baseline |
| **SCORE** | 4 | 4 | 4 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **Integration** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware for Integration | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. |
| New power for integration | None | None | None |
| **SCORE** | 4 | 4 | 4 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **LSS** | I2 for xEMU & 1,3-Dibromo-5,5,dimethylhydantoin (DBDMH) Salt Solution for Vehicle LS | I2 for xEMU & 1,3-Dibromo-5,5,dimethylhydantoin (DBDMH) Salt Solution + Buffer for Vehicle LS | (DBDMH) Salt Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware Added to LSS | Salt solution dosing system required to implement. Anticipated to include pump and reservoir at a minimum. | Salt solution + buffer dosing system required to implement. Anticipated to include pump and reservoir at a minimum. | Salt solution + buffer dosing system required to implement. Anticipated to include pump and reservoir at a minimum, Br & pH sensors. |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated | ACTEX in PWD eliminated, Iodine dosing eliminated |
| Hardware Modified - Material Change | Need to add carbon for the salt solution due to organic counterion to DI Bed (ion exchange bed) Media changed for OGA - no change in M/P/V, MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution vs cartridge dosing. | Need to add carbon for the salt solution due to organic counterion to DI Bed (ion exchange bed) Media changed for OGA - no change in M/P/V. MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution+ buffer vs cartridge dosing. | Need to add carbon for the salt solution due to organic counterion to DI Bed (ion exchange bed) Media changed for OGA - no change in M/P/V. MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution+ buffer vs cartridge dosing. |
| Hardware Modified - Physical Design Change | ACTEX Media changed for OGA, MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change and added mass/volume to add new dosing system for salt. Also need to consider double/triple containment. | ACTEX Media changed for OGA, MCV approach changed - minimal added M/V for MCV-Br (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution + Buffer vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change and added mass/volume to add new dosing system for salt. | ACTEX Media changed for OGA, MCV approach changed (new design, Umpqua MCV-Br). No data on change in mass/volume of salt solution + Buffer vs cartridge dosing. However, should be minimal compared to mass/volume of entire system. Significant design change and added mass/volume to add new dosing system for salt. |
| Hardware Modified - Approach Change | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. | Eliminates flow-through dosing and adds "injection" dosing. Requires new hardware that has mass and volume - significantly larger than SOA, plus a controller and power to operate. Active monitoring and control software/logic of biocide/buffer concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). Significant replacement and calibration of pH sensor required. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump.Consumables expected for recalibrating the Br monitor and pH monitor. |
| Resupply - "Fresh" Biocide | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. |
| Additional Power | Unknown additional power required for pump to inject salt solution. | Unknown additional power required for pump to inject salt/buffer solution. | Unknown additional power for Br monitor and pH monitor. Unknown additional power required for pump to inject salt/buffer solution. |
| **SCORE** | 2 | 2 | 1 |

## *Table F-12. Criteria 1 Subsystem Scoring for Options 27-29*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **xEMU** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware Added to xEMU | None | None | None |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| Hardware Modified - Material Change | None | None | None |
| Hardware Modified - Physical Design Change | None | None | None |
| Hardware Modified - Approach Change | None | None | None |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None expected | None expected | None expected |
| Additional Power | None expected | None expected | None expected |
| Resupply - Consumables for Dosing hardware | None above baseline | None above baseline | None above baseline |
| Resupply - "Fresh" Biocide | None above baseline | None above baseline | None above baseline |
| **SCORE** | 4 | 4 | 4 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **Integration** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware for Integration | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. | Significant impact on implementing secondary dosing approach for control of Br concentration in the system. Added M/V/P for secondary dosing method. Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. |
| New power for integration | None | None | Dependent on secondary dosing approach. Power may be required if automated dosing is implemented. |
| **SCORE** | 4 | 4 | 1 |

| Critieria 1: Minimal Mass/Power/Volume Increase | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **LSS** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware Added to LSS | No impact - would be direct replacement for existing MCV and resin. | No impact - would be direct replacement for existing MCV and resin. | Adds Bromine monitor and pH moniter. |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated | ACTEX in PWD eliminated | ACTEX in PWD eliminated |
| Hardware Modified - Material Change | MCV material changed, No change in mass/volume of new media. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. |
| Hardware Modified - Physical Design Change | None. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule unkown, but expected to be similar to I2. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| Additional Power | None | None | Minimal additional power for Br and pH monitors. Possible power requirement for secondary dosing method. |
| **SCORE** | 5 | 4 | 1 |

## *Table F-13. Criteria 1 Subsystem Scoring for Options 30-32*

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **xEMU** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware Added to xEMU | None | None | None |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| Hardware Modified - Material Change | None | None | None |
| Hardware Modified - Physical Design Change | None | None | None |
| Hardware Modified - Approach Change | None | None | None |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. | Possibly extra SWME membranes due to breakdown over time. Have run SWME over 1200 hours with I2 with no degradation. |
| Dormancy - Hardware change-out | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. | Something, but assume same regardless of biocide. Net zero across options. |
| Dormancy - Other consumables | None expected | None expected | None expected |
| Additional Power | None expected | None expected | None expected |
| Resupply - Consumables for Dosing hardware | None above baseline | None above baseline | None above baseline |
| Resupply - "Fresh" Biocide | None above baseline | None above baseline | None above baseline |
| **SCORE** | 4 | 4 | 4 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **Integration** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware for Integration | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. | Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. | Significant impact on implementing secondary dosing approach for control of Br concentration in the system. Added M/V/P for secondary dosing method. Impacted hardware for vehicle: SOA Umbilical Interface Assembly (UIA) includes two filters which filter and iodinate the water coming into the EMU thermal loop and wastewater leaving the EMU thermal loop. Development of bromine capture media would be required but is not expected to be significantly more mass/volume/power for implementation in these filters. Existing activated charcoal may be sufficient with no additional M/V/P. Safety margin is likely to be required to ensure no Br breakthrough. |
| New power for integration | None | None | Dependent on secondary dosing approach. Power may be required if automated dosing is implemented. |
| **SCORE** | 4 | 4 | 1 |

| **Critieria 1: Minimal Mass/Power/Volume Increase** | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **LSS** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| New Hardware Added to LSS | No impact - would be direct replacement for existing MCV and resin. | No impact - would be direct replacement for existing MCV and resin. | Adds Bromine monitor and pH moniter. |
| Hardware Eliminated from LSS | ACTEX in PWD eliminated | ACTEX in PWD eliminated | ACTEX in PWD eliminated |
| Hardware Modified - Material Change | MCV material changed, No change in mass/volume of new media. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. | MCV material changed, No change in mass/volume of Bromine media, but added mass/volume for buffer. |
| Hardware Modified - Physical Design Change | None. | None. | None. |
| Hardware Modified - Approach Change | None. | None. | Active monitoring and control software/logic of biocide concentration in system. Adds mass/volume/power of the monitor and associated avionics. |
| Resupply - Replacement Parts/Consumables for LSS | Replacement schedule unknown, but expected to be similar to I2, or slightly higher. | To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| Additional Power | None | None | Minimal additional power for Br and pH monitors. Possible power requirement for secondary dosing method. |
| **SCORE** | 4 | 4 | 1 |

### F.1.2 Criteria 2: Minimal Schedule Increase

Two mission scenarios and a timeline-independent option were chosen for this assessment. The first mission scenario was the ECM mission due to fly in 2027. The team assumed an on-dock date for hardware no later than 2026. Based on this, schedule ranges were scored as shown in Table F-14. The second mission scenario was the FSH mission due to fly in 2029 with an assumed on-dock date of 2028. This resulted in the scoring ranges shown in Table F-15. For the timeline-independent mission, no scoring was required.

***Table F-14. Scoring Definitions for Criteria 2: Schedule for ECM Mission***

| Schedule Range (years) | | Score |
|---|---|---|
| 0.0 | 2 | 5 |
| 2.0 | 3.5 | 4 |
| 3.5 | 4.5 | 3 |
| 4.5 | 5.5 | 2 |
| 5.5 | 6 | 1 |
| 6.0 | up | 0 |

***Table F-15. Scoring Definitions for Criteria 2: Schedule for FSH Mission***

| Schedule Range (years) | | Score |
|---|---|---|
| 0 | 2 | 5 |
| 2 | 3 | 4 |
| 3 | 5 | 3 |
| 5 | 7 | 2 |
| 7 | 8 | 1 |
| 8 | up | 0 |

To determine the schedule for each option and subsystem, the team met with project managers for the specific subsystem development efforts. Schedule estimates were made based on known technical challenges and historical experience with development and flight hardware qualification. The critical path for each option was determined by the longest development time to flight. This value was used as the final score for each option per the specific mission scoring. Impacts, as defined in Table F-1, were not applied to the subcriteria due to the quantitative nature of the schedule. The raw data for Criteria 2 is provided in Tables F-16 through F-26. A summary of subsystem schedules and the critical path schedule is shown in Table F-27.

*Table F-16. Criteria 2 Subsystem Scoring for Options 1, 2, and 33*

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **xEMU** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Added Schedule for Research (to get technology to TRL 4) | None | None | None |
| Added Schedule for Design of TRL 5 Hardware | None | None | None |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | None |
| Added Schedule for Testing of TRL 5 Hardware | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr |
| Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | None |
| Total Timeline | 1 | 1 | 1 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **Integration** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Added Schedule for Research (to get | None | None | None |
| Added Schedule for Design of TRL 5 | None | None | None |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | None |
| Added Schedule for Testing of TRL 5 Hardware | None | None | None |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | None |
| Total Timeline (years) | 0 | 0 | 0 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **LSS** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Added Schedule for Research (to get technology to TRL 4) | 1 year - To identify alternate iodine removal materials and prove safety, | 6 months - Development to determine exactly what portions of PWD need to be replaced. What REALLY has to be addressed. | |
| Added Schedule for Design of TRL 5 Hardware | 6 months | 1 year - chedule for new mechanical design + human factors. | |
| Added Schedule for Fabrication of TRL 5 Hardware | 3 months | 6 months | |
| Added Schedule for Testing of TRL 5 Hardware | 6 months | 6 months | |
| Added Schedule for Iteration of TRL 5 Hardware | 0 | 0 | |
| Added Schedule for Flight Qualification | 2.5 years | 2.5 years | 2 years - currently contracted for flight delivery |
| Total Timeline (years) | 4.75 | 5 | 2 |

*Table F-17. Criteria 2 Subsystem Scoring for Options 3-5*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **xEMU** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Schedule for Research (to get technology to TRL 4) | 18 months - Timeline = assumes 6 months to have electrolysis unit so can begin testing. 12 months for actual testing with the hardware. Assumes we get good understanding of deposition rate. | 18 months - Timeline = assumes 6 months to have electrolysis unit so can begin testing. 12 months for actual testing with the hardware. Assumes we get good understanding of deposition rate. | 24 months - Timeline = assumes 1 year to have passive release unit in hand so can begin testing + 12 months for actual testing with the hardware. Assumes we get good understanding of deposition rate. |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Actual design time estimated to be 9 months, but assume 3 month overlap with R&D. | 6 months - Actual design time estimated to be 9 months, but assume 3 month overlap with R&D. | 6 months - Actual design time estimated to be 9 months, but assume 3 month overlap with R&D. |
| Added Schedule for Fabrication of TRL 5 Hardware | 9 months - Based on timeline to fab current pump. | 9 months - Based on timeline to fab current pump. | 9 months - Based on timeline to fab current pump. |
| Added Schedule for Testing of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Iteration of TRL 5 Hardware | Assume no iteration. | Assume no iteration. | Assume no iteration. |
| Added Schedule for Flight Qualification | 2 years - Assumes overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing of TRL 5 hardware | 2 years - Assumes overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing of TRL 5 hardware | 2 years - Assumes overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing of TRL 5 hardware |
| Total Timeline (years) | 5.75 | 5.75 | 6.25 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **Integration** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Added Schedule for Research (to get technology to TRL 4) | 12 months - Time to research MCV-Ag materials | 12 months - Time to research MCV-Ag materials | 12 months - Time to research MCV-Ag materials |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Time to design new MCV-Ag with new material. | 6 months - Time to design new MCV-Ag with new material. | 6 months - Time to design new MCV-Ag with new material. |
| Hardware | 4 months | 4 months | 4 months |
| Added Schedule for Testing of TRL 5 Hardware | 6 months | 6 months | 6 months |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | 2.5 years | 2.5 years | 2.5 years |
| Total Timeline (years) | 4.83 | 4.83 | 4.83 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **LSS** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Added Schedule for Research (to get technology to TRL 4) | 12 months - Based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 | 12 months for electrolysis hardware based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 & 2 years for silver monitor research based on mini-TOCA development timeline. | 1 year - Based on anticipated SBIR completion at end of CY21. |
| Added Schedule for Design of TRL 5 Hardware | 1 year - Based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 | 1 year Based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 & 1 yr silver monitor design based on TRL 5 development timeline of mini-TOCA. | 6 months - Based on comparative similicity to electrolysis approach |
| Added Schedule for Fabrication of TRL 5 Hardware | 9 months - low fidelity estimate based on assuming a design is ready to go at end of FY21 and this time will be used to get a contract in place and have a newly designed unit fabricated and delivered. | 9 months low fidelity estimate based on assuming a design is ready to go at end of FY21 and this time will be used to get a contract in place and have a newly designed unit fabricated and delivered & 9 months silver monitor fab based on similarity with TOCA fabrication timeline. | 4 months - low fidelity estimate based on assuming a design is ready to go at end of FY21 and this time will be used to get a contract in place and have a newly designed unit fabricated and delivered and relative complexity with respect to electrolytic silver. |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months Assumes full suite of benchtop testing and partially integrated testing & simultaneous 6 months silver monitor testing | 6 months - Assumes full suite of benchtop testing and partially integrated testing. |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitor - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Timeline (years) | 5.75 | 6.75 | 4.83 |

*Table F-18. Criteria 2 Subsystem Scoring for Options 6-8*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **xEMU** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Schedule for Research (to get technology to TRL 4) | 24 months - Timeline = assumes 1 year to have passive release unit in hand so can begin testing + 12 months for actual testing with the hardware. Assumes we get good understanding of deposition rate. | 12 months - Timeline = assumes salt testing can begin immediately. 12 months for actual testing with the hardware. Assumes we get good understanding of deposition rate. | 12 months - Timeline = assumes salt testing can begin immediately. 12 months for actual testing with the hardware. Assumes we get good understanding of deposition rate. |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Actual design time estimated to be 9 months, but assume 3 month overlap with R&D. | 6 months - Actual design time estimated to be 9 months, but assume 3 month overlap with R&D. | 6 months - Actual design time estimated to be 9 months, but assume 3 month overlap with R&D. |
| Added Schedule for Fabrication of TRL 5 Hardware | 9 months - Based on timeline to fab current pump. | 9 months - Based on timeline to fab current pump. | 9 months - Based on timeline to fab current pump. |
| Added Schedule for Testing of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Iteration of TRL 5 Hardware | Assume no iteration. | Assume no iteration. | Assume no iteration. |
| Added Schedule for Flight Qualification | 2 years - Assumes overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing of TRL 5 hardware | 2 years - Assumes overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing of TRL 5 hardware | 2 years - Assumes overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing of TRL 5 hardware |
| Total Timeline (years) | 6.25 | 5.25 | 5.25 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **Integration** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Added Schedule for Research (to get technology to TRL 4) | 12 months - Time to research MCV-Ag materials | 12 months - Time to research MCV-Ag materials | 12 months - Time to research MCV-Ag materials |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Time to design new MCV-Ag with new material. | 6 months - Time to design new MCV-Ag with new material. | 6 months - Time to design new MCV-Ag with new material. |
| Hardware | 4 months | 4 months | 4 months |
| Added Schedule for Testing of TRL 5 Hardware | 6 months | 6 months | 6 months |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | 2.5 years | 2.5 years | 2.5 years |
| Total Timeline (years) | 4.83 | 4.83 | 4.83 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **LSS** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Added Schedule for Research (to get technology to TRL 4) | 1 year passive Ag release - based on anticipates SBIR Phase II completion at end of CY21 & 2 yrs silver monitor research based on mini-TOCA development timeline. | 2 years -Assumes research into counterion alternatives and mitigations. Assumes time to research dosing approaches. | 2 years - Assumes research into counterion alternatives and mitigations. Assumes time to research dosing approaches & 2 yrs silver monitor research based on mini-TOCA development timeline. |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Based on comparative similicity to electrolysis approach & 1 yr silver monitor design based on TRL 5 development timeline of mini-TOCA. | 1 year - Design schedule for dosing design per ARC schedule in FY21 and similar complexity as electrolytic silver approach | 1 year - Design schedule for dosing design per ARC schedule in FY21 and similar complexity as electrolytic silver approach & 1 yr silver monitor design based on TRL development timeline of mini-TOCA. |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months - low fidelity estimate based on assuming a design is ready to go at end of FY21 and this time will be used to get a contract in place and have a newly designed unit fabricated and delivered nad relative complexity relative to electrolytic silver. 9 months silver monitor fab based on similarity with mini-TOCA fabrication timeline. | 9 months - Combines design with fabrication in FY21 for ARC effort. | 9 months Combines design with fabrication in FY21 for ARC effort. 9 months silver monitor fab based on similarity with mini-TOCA fabrication timeline. |
| Added Schedule for Testing of TRL 5 Hardware | 6 months Assumes full suite of benchtop testing and partially integrated testing & simultaneous 6 months silver monitor testing | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months Assumes full suite of benchtop testing and partially integrated testing & simultaneous 6 months silver monitor testing |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years for technology and monitor - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitor - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Timeline (years) | 6.75 | 5.75 | 6.75 |

*Table F-19. Criteria 2 Subsystem Scoring for Options 9-11*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **xEMU** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Added Schedule for Research (to get technology to TRL 4) | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months |
| Added Schedule for Design of TRL 5 Hardware | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. |
| Added Schedule for Fabrication of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Testing of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Iteration of TRL 5 Hardware | None. | None. | None. |
| Added Schedule for Flight Qualification | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing |
| Total Timeline (years) | 6 | 6 | 6 |

| Critieria 2: Minimal Schedule Increase | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative) |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **Integration** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Added Schedule for Research (to get technology to TRL 4) | 2 year passive OBr-/buffer release - based on completion of ongoing SBIR Phase II at end of CY21 and added timeline for buffer development and demonstration. | 2 year passive OBr-/buffer release - based on completion of ongoing SBIR Phase II at end of CY21 and added timeline for buffer development and demonstration. | 2 year passive OBr-/buffer release - based on completion of ongoing SBIR Phase II at end of CY21 and added timeline for buffer development and demonstration. |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Based on comparative complexity with passive silver approach | 6 months - Based on comparative complexity with passive silver approach | 6 months - Based on comparative complexity with passive silver approach |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months | 4 months | 4 months |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months - Assumes full suite of benchtop testing and partially integrated testing. |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Timeline (years) | 5.83 | 5.83 | 5.83 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **LSS** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring |
| Added Schedule for Research (to get technology to TRL 4) | 2 years - Assumes research into salt biproducts and mitigations. Assumes time to research dosing approaches. | 2 years - Assumes research into salt biproducts and mitigations. Assumes parallel effort to identify and incorporate buffer. Assumes time to research dosing approaches. | 2 years & 3 yrs bromine monitor research & 1 year pH monitor research (all three in parallel) - Assumes research into biproducts and mitigations. Assumes parallel effort to research buffer. Assumes time to research dosing approaches. Assumes new research into OBr- detection and pH monitor development. |
| Added Schedule for Design of TRL 5 Hardware | 1 year - Assumes schedule for dosing design per ARC schedule in FY21 and similar complexity as silver salt approach. | 1 year - Assumes schedule for dosing design per ARC schedule in FY21 and similar complexity as silver salt approach. | 1 year - Assumes schedule for dosing design per ARC schedule in FY21 and similar complexity as silver salt approach. & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. |
| Added Schedule for Fabrication of TRL 5 Hardware | 9 months - combines design and fabrication effort in FY21 for ARC effort. | 9 months - combines design and fabrication effort in FY21 for ARC effort. | 9 months - combines design and fabrication effort in FY21 for ARC effort & 9 months OBr- monitor fab & 9 months pH monitor fab |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | testing & 6 months pH monitor testing - Assumes full suite of benchtop testing |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitors (in parallel) - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Timeline (years) | 6.75 | 6.75 | 7.75 |

*Table F-20. Criteria 2 Subsystem Scoring for Options 12-14*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **xEMU** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Schedule for Research (to get technology to TRL 4) | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months |
| Added Schedule for Design of TRL 5 Hardware | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. |
| Added Schedule for Fabrication of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Testing of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Iteration of TRL 5 Hardware | None. | None. | None. |
| Added Schedule for Flight Qualification | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing |
| Total Timeline (years) | 6 | 6 | 6 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **Integration** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Schedule for Research (to get technology to TRL 4) | None | None | 2 years secondary dosing |
| Added Schedule for Design of TRL 5 Hardware | None | None | 6 months secondary dosing |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | 4 months secondary dosing |
| Added Schedule for Testing of TRL 5 Hardware | None | None | 6 months secondary dosing |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | 2.5 years for technology |
| Total Timeline (years) | 0 | 0 | 5.83 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **LSS** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + |
| Added Schedule for Research (to get technology to TRL 4) | 1 year - based on completion of ongoing SBIR Phase II at end of CY21. | 2 year passive OBr-/buffer release - based on completion of ongoing SBIR Phase II at end of CY21 and added timeline for buffer development and demonstration. | 2 year passive OBr-/buffer release based on completion of ongoing SBIR Phase II at end of CY21 and added timeline for buffer development and demonstration. & 3 yrs OBr- monitor research & 1 year pH monitor research |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Based on comparative complexity with passive silver approach | 6 months - Based on comparative complexity with passive silver approach | 6 months - based on comparative complexity with passive silver approach & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months | 4 months | 4 months & 9 months OBr- monitor fab & 9 months pH monitor fab |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months & 6 months OBr- monitor testing & 6 months pH monitor testing - Assumes full suite of benchtop testing and partially integrated testing. |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitors (in parallel) - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Timeline (years) | 4.83 | 5.83 | 7.75 |

*Table F-21. Criteria 2 Subsystem Scoring for Options 15-17*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **xEMU** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Schedule for Research (to get technology to TRL 4) | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months | 18 months - Assume that non-buffered Br will corrode Hastelloy. Assume only replacing Hastelloy metal - 1 yr. If membrane is degraded - non-starter - membrane testing = 1.5 yrs. LCVG testing to determine what the Br does to the polymer tubing. (is it catastrophic risk where you get permeability/failure of the tubing from the thermal loop to the crew member, or just swelling of the membrane/depletion of biocide, etc) - testing = 6 months |
| Added Schedule for Design of TRL 5 Hardware | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. | 6 months - If Br kills the LCVG, then we would need to have very high confidence on the rates with margin to be able to accept. Non-starter for replacing the material of construction. For Hastelloy sensors, schedule 6 months. |
| Added Schedule for Fabrication of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Testing of TRL 5 Hardware | 12 months | 12 months | 12 months |
| Added Schedule for Iteration of TRL 5 Hardware | None. | None. | None. |
| Added Schedule for Flight Qualification | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing | 2 yrs - overlap with DVT and accept risk. So total of 2.5 years, but only 2 years beyond Testing |
| Total Timeline (years) | 6 | 6 | 6 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **Integration** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Schedule for Research (to get technology to TRL 4) | None | None | 2 year passive OBr-/buffer release & 2 years secondary dosing |
| Added Schedule for Design of TRL 5 Hardware | None | None | 6 months & 6 months secondary dosing |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | 4 months & 4 months secondary dosing |
| Added Schedule for Testing of TRL 5 Hardware | None | None | 6 months & 6 months secondary dosing |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None for now. |
| Added Schedule for Flight Qualification | None | None | 2.5 years for technology |
| Total Timeline (years) | 0 | 0 | 5.83 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **LSS** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + |
| Added Schedule for Research (to get technology to TRL 4) | 2 year - Based on no previous history with NASA, but assuming TRL 3 for NASA application. | 2 year passive OBr-/buffer release - Based on no previous history with NASA, but assuming TRL 3 for NASA application. | 2 year passive OBr-/buffer release Based on no previous history with NASA, but assuming TRL 3 for NASA application & 3 yrs OBr- monitor research & 1 year pH monitor research |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Based on comparative complexity with passive silver approach | 6 months - Based on comparative complexity with passive silver approach | 6 months - based on comparative complexity with passive silver approach & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months - low fidelity estimate assuming a design is ready to go at end of in-house testing at NASA. This time will be used to get a contract in place and have a newly designed unit fabricated and delivered. | 4 months - low fidelity estimate assuming a design is ready to go at end of in-house testing at NASA. This time will be used to get a contract in place and have a newly designed unit fabricated and delivered. | 4 months - low fidelity estimate assuming a design is ready to go at end of in-house testing at NASA. This time will be used to get a contract in place and have a newly designed unit fabricated and delivered. & 9 months OBr- monitor fab & 9 months pH monitor fab |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months & 6 months OBr- monitor testing & 6 months pH monitor testing - Assumes full suite of benchtop testing and partially integrated testing. |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitors (in parallel) - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Timeline (years) | 5.83 | 5.83 | 7.75 |

*Table F-22. Criteria 2 Subsystem Scoring for Options 18-20*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **xEMU** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | None | None | None |
| Added Schedule for Design of TRL 5 Hardware | None | None | None |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | None |
| Added Schedule for Testing of TRL 5 Hardware | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | None |
| Total Timeline (years) | 1 | 1 | 1 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **Integration** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 12 months for MCV-Ag & 12 months Ag removal materials research | 12 months for MCV-Ag & 12 months Ag removal materials research | 12 months for MCV-Ag & 12 months Ag removal materials research |
| Added Schedule for Design of TRL 5 Hardware | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months MCV-Ag & 4 months Ag removal | 4 months MCV-Ag & 4 months Ag removal | 4 months MCV-Ag & 4 months Ag removal |
| Added Schedule for Testing of TRL 5 Hardware | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | 2.5 years | 2.5 years | 2.5 years |
| Total Schedule (years) | 4.83 | 4.83 | 4.83 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **LSS** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 12 months - Based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 | 12 months for electrolysis hardware based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 & 2 years for silver monitor research based on mini-TOCA development timeline. | 2 years - Assumes research into salt biproducts and mitigations. Assumes time to research dosing approaches. |
| Added Schedule for Design of TRL 5 Hardware | 1 year - Based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 | 1 year Based on anticipated SBIR completion at end of CY20 and anticipate initial testing at JSC to be completed by end of FY21 & 1 yr silver monitor design based on TRL 5 development timeline of mini-TOCA. | 1 year - Assumes schedule for dosing design per ARC schedule in FY21 and similar complexity as silver salt approach. |
| Added Schedule for Fabrication of TRL 5 Hardware | 9 months - low fidelity estimate based on assuming a design is ready to go at end of FY21 and this time will be used to get a contract in place and have a newly designed unit fabricated and delivered. | 9 months low fidelity estimate based on assuming a design is ready to go at end of FY21 and this time will be used to get a contract in place and have a newly designed unit fabricated and delivered & 9 months silver monitor fab based on similarity with TOCA fabrication timeline. | 9 months - combines design and fabrication effort in FY21 for ARC effort. |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months Assumes full suite of benchtop testing and partially integrated testing & simultaneous 6 months silver monitor testing | 6 months - Assumes full suite of benchtop testing and partially integrated testing. |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitor - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Schedule (years) | 5.75 | 6.75 | 6.75 |

*Table F-23. Criteria 2 Subsystem Scoring for Options 21-23*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **xEMU** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | None | None | None |
| Added Schedule for Design of TRL 5 Hardware | None | None | None |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | None |
| Added Schedule for Testing of TRL 5 Hardware | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | None |
| Total Timeline (years) | 1 | 1 | 1 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **Integration** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 12 months for MCV-Ag & 12 months Ag removal materials research | 12 months for MCV-Ag & 12 months Ag removal materials research | 12 months for MCV-Ag & 12 months Ag removal materials research |
| Added Schedule for Design of TRL 5 Hardware | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months MCV-Ag & 4 months Ag removal | 4 months MCV-Ag & 4 months Ag removal | 4 months MCV-Ag & 4 months Ag removal |
| Added Schedule for Testing of TRL 5 Hardware | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal | 6 months MCV-Ag & 6 months Ag removal |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | 2.5 years | 2.5 years | 2.5 years |
| Total Schedule (years) | 4.83 | 4.83 | 4.83 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **LSS** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 2 years - Assumes research into salt biproducts and mitigations. Assumes parallel effort to identify and incorporate buffer. Assumes time to research dosing approaches. | 2 years & 3 yrs bromine monitor research & 1 year pH monitor research (all three in parallel) - Assumes research into biproducts and mitigations. Assumes parallel effort to research buffer. Assumes time to research dosing approaches. Assumes new research into OBr- detection and pH monitor development. | 1 year - based on completion of ongoing SBIR Phase II at end of CY21. |
| Added Schedule for Design of TRL 5 Hardware | 1 year - Assumes schedule for dosing design per ARC schedule in FY21 and similar complexity as silver salt approach. | 1 year - Assumes schedule for dosing design per ARC schedule in FY21 and similar complexity as silver salt approach. & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. | 6 months - Based on comparative complexity with passive silver approach |
| Added Schedule for Fabrication of TRL 5 Hardware | 9 months - combines design and fabrication effort in FY21 for ARC effort. | 9 months - combines design and fabrication effort in FY21 for ARC effort & 9 months OBr- monitor fab & 9 months pH monitor fab | 4 months |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months & 6 months OBr- monitor testing & 6 months pH monitor testing - Assumes full suite of benchtop testing and partially integrated testing. | 6 months - Assumes full suite of benchtop testing and partially integrated testing. |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitors (in parallel) - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Schedule (years) | 6.75 | 7.75 | 4.83 |

*Table F-24. Criteria 2 Subsystem Scoring for Options 24-26*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **xEMU** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | None | None | None |
| Added Schedule for Design of TRL 5 Hardware | None | None | None |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | None |
| Added Schedule for Testing of TRL 5 Hardware | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule.Soak testing timeline 1yr |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | None |
| Total Timeline (years) | 1 | 1 | 1 |

| **Critieria 2: Minimal Schedule Increase** | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative) |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **Integration** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 2 year passive OBr-/buffer release & 6 months Br removal | 2 year passive OBr-/buffer release & 6 months Br removal | 2 year passive OBr-/buffer release & 6 months Br removal |
| Added Schedule for Design of TRL 5 Hardware | 6 months & 6 months Br removal | 6 months & 6 months Br removal | 6 months & 6 months Br removal |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months & 4 months Br removal | 4 months & 4 months Br removal | 4 months & 4 months Br removal |
| Added Schedule for Testing of TRL 5 Hardware | 6 months & 6 months Br removal | 6 months & 6 months Br removal | 6 months & 6 months Br removal |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years for technology | 2.5 years for technology | 2.5 years for technology |
| Total Schedule (years) | 5.83 | 5.83 | 5.83 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **LSS** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 2 year passive OBr-/buffer release - based on completion of ongoing SBIR Phase II at end of CY21 and added timeline for buffer development and demonstration. | 2 year passive OBr-/buffer release based on completion of ongoing SBIR Phase II at end of CY21 and added timeline for buffer development and demonstration. & 3 yrs OBr- monitor research & 1 year pH monitor research | 2 year - Based on no previous history with NASA, but assuming TRL 3 for NASA application. |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Based on comparative complexity with passive silver approach | 6 months - based on comparative complexity with passive silver approach & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. | 6 months - Based on comparative complexity with passive silver approach |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months | 4 months & 9 months OBr- monitor fab & 9 months pH monitor fab | 4 months - low fidelity estimate assuming a design is ready to go at end of in-house testing at NASA. This time will be used to get a contract in place and have a newly designed unit fabricated and delivered. |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months & 6 months OBr- monitor testing & 6 months pH monitor testing - Assumes full suite of benchtop testing and partially integrated testing. | 6 months - Assumes full suite of benchtop testing and partially integrated testing. |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitors (in parallel) - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) |
| Total Schedule (years) | 5.83 | 7.75 | 5.83 |

*Table F-25. Criteria 2 Subsystem Scoring for Options 27-29*

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **xEMU** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | None | None | None |
| Added Schedule for Design of TRL 5 Hardware | None | None | None |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | None |
| Added Schedule for Testing of TRL 5 Hardware | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | None |
| Total Timeline (years) | 1 | 1 | 1 |

| **Critieria 2: Minimal Schedule Increase** | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **Integration** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 6 months Br removal | 6 months Br removal | 2 years secondary dosing & 6 months Br removal |
| Added Schedule for Design of TRL 5 Hardware | 6 months Br removal | 6 months Br removal | Br removal |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months Br removal | 4 months Br removal | 4 months secondary dosing & 4 months |
| Added Schedule for Testing of TRL 5 Hardware | 6 months Br removal | 6 months Br removal | Br removal |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | 2.5 years for technology | 2.5 years for technology | 2.5 years for technology |
| Total Schedule (years) | 4.33 | 4.33 | 5.83 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **LSS** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 2 year passive OBr-/buffer release - Based on no previous history with NASA, but assuming TRL 3 for NASA application. | 2 year passive OBr-/buffer release Based on no previous history with NASA, but assuming TRL 3 for NASA application & 3 yrs OBr- monitor research & 1 year pH monitor research | 2 year passive OBr-/buffer release & 3 yrs OBr- monitor research & 1 year pH monitor research |
| Added Schedule for Design of TRL 5 Hardware | 6 months - Based on comparative complexity with passive silver approach | 6 months - based on comparative complexity with passive silver approach & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. | 6 months & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months - low fidelity estimate assuming a design is ready to go at end of in-house testing at NASA. This time will be used to get a contract in place and have a newly designed unit fabricated and delivered. | 4 months - low fidelity estimate assuming a design is ready to go at end of in-house testing at NASA. This time will be used to get a contract in place and have a newly designed unit fabricated and delivered. & 9 months OBr- monitor fab & 9 months pH monitor fab | 4 months & 9 months OBr- monitor fab & 9 months pH monitor fab |
| Added Schedule for Testing of TRL 5 Hardware | 6 months - Assumes full suite of benchtop testing and partially integrated testing. | 6 months & 6 months OBr- monitor testing & 6 months pH monitor testing - Assumes full suite of benchtop testing and partially integrated testing. | 6 months & 6 months OBr- monitor testing & 6 months pH monitor testing |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitors (in parallel) - Based on historic experience with flight hardware of similar complexity (e.g. mini-TOCA) | 2.5 years for technology and monitor |
| Total Schedule (years) | 5.83 | 7.75 | 7.75 |

*Table F-26. Criteria 2 Subsystem Scoring for Options 30-32*

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **xEMU** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | None | None | None |
| Added Schedule for Design of TRL 5 Hardware | None | None | None |
| Added Schedule for Fabrication of TRL 5 Hardware | None | None | None |
| Added Schedule for Testing of TRL 5 Hardware | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. | Some: for iodine impacts on SWME membrane. Drives replacement/resupply schedule. Soak testing timeline 1 yr. |
| Added Schedule for Iteration of TRL 5 Hardware | None | None | None |
| Added Schedule for Flight Qualification | None | None | None |
| Total Timeline (years) | 1 | 1 | 1 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **Integration** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 2 year passive OBr-/buffer release & 6 months Br removal | 2 year passive OBr-/buffer release & 6 months Br removal | years secondary dosing & 6 months Br removal |
| Added Schedule for Design of TRL 5 Hardware | 6 months & 6 months Br removal | 6 months & 6 months Br removal | 6 months Br removal |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months & 4 months Br removal | 4 months & 4 months Br removal | 4 months & 4 months secondary dosing & |
| Added Schedule for Testing of TRL 5 Hardware | 6 months & 6 months Br removal | 6 months & 6 months Br removal | 6 months Br removal |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years for technology | 2.5 years for technology | 2.5 years for technology |
| Total Schedule (years) | 5.83 | 5.83 | 5.83 |

| Critieria 2: Minimal Schedule Increase | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **LSS** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Schedule for Research (to get technology to TRL 4) | 2 year | 2 year passive OBr-/buffer release | 2 year passive OBr-/buffer release & 3 yrs OBr- monitor research & 1 year pH monitor research |
| Added Schedule for Design of TRL 5 Hardware | 6 months | 6 months | 6 months & 1 yr OBr- monitor design & 1 yr pH monitor design/modification. |
| Added Schedule for Fabrication of TRL 5 Hardware | 4 months | 4 months | 4 months & 9 months OBr- monitor fab & 9 months pH monitor fab |
| Added Schedule for Testing of TRL 5 Hardware | 6 months | 6 months | 6 months & 6 months OBr- monitor testing & 6 months pH monitor testing |
| Added Schedule for Iteration of TRL 5 Hardware | None for now. | None for now. | None for now. |
| Added Schedule for Flight Qualification | 2.5 years | 2.5 years for technology | 2.5 years for technology and monitor |
| Total Schedule (years) | 5.83 | 5.83 | 7.75 |

***Table F-27. Summary of Subsystem Schedules and Critical Path Schedule***

Note: The subsystem driving the architecture schedule is highlighted for each option.

| | | Schedule (years) | | | |
|---|---|---|---|---|---|
| Option # | Description | xEMU | LSS | Integration | Critical Path |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 1 | 4.75 | 0 | 4.75 |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 1 | 5 | 0 | 5 |
| 3 | Electrolytic Silver | 5.75 | 5.75 | 4.83 | 5.75 |
| 4 | Electrolytic Silver + Monitoring | 5.75 | 6.75 | 4.83 | 6.75 |
| 5 | Passive Release Silver (ELS or Foam) | 6.25 | 4.83 | 4.83 | 6.25 |
| 6 | Passive Release Silver + Monitoring | 6.25 | 6.75 | 4.83 | 6.75 |
| 7 | Concentrated Salt Solution Silver | 5.25 | 5.75 | 4.83 | 5.75 |
| 8 | Concentrated Salt Soln Ag + Monitoring | 5.25 | 6.75 | 4.83 | 6.75 |
| 9 | DBDMH Solution | 6 | 6.75 | 5.83 | 6.75 |
| 10 | DBDMH Solution + Buffer | 6 | 6.75 | 5.83 | 6.75 |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | 6 | 7.75 | 5.83 | 7.75 |
| 12 | Umpqua Passive Release | 6 | 4.83 | 0 | 6 |
| 13 | Umpqua Passive Release + Buffer | 6 | 5.83 | 0 | 6 |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | 6 | 7.75 | 5.83 | 7.75 |
| 15 | HaloPur BR Passive Release | 6 | 5.83 | 0 | 6 |
| 16 | HaloPur BR Passive Release + Buffer | 6 | 5.83 | 0 | 6 |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | 6 | 7.75 | 5.83 | 7.75 |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 1 | 5.75 | 4.83 | 5.75 |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | 1 | 6.75 | 4.83 | 6.75 |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | 1 | 6.75 | 4.83 | 6.75 |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | 1 | 6.75 | 4.83 | 6.75 |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | 1 | 7.75 | 4.83 | 7.75 |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | 1 | 4.83 | 4.83 | 4.83 |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | 1 | 5.83 | 5.83 | 5.83 |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | 1 | 7.75 | 5.83 | 7.75 |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 5.83 | 5.83 | 5.83 |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 1 | 5.83 | 4.33 | 5.83 |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | 1 | 7.75 | 4.33 | 7.75 |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 7.75 | 5.83 | 7.75 |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 1 | 5.83 | 5.83 | 5.83 |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | 1 | 5.83 | 5.83 | 5.83 |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 7.75 | 5.83 | 7.75 |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 1 | 2 | 0 | 2 |

### F.1.3 Criteria 3: Minimal Cost Increase

Cost estimates were compiled with cooperation from project managers for their respective technology areas. Costs were used when known (e.g., contracts, active projects). When costs were not available, estimates were made based on historical efforts of similar complexity or a bottoms-up estimate of required development activities. For all material research and/or development, a cost of $300K was assumed for research to achieve TRL 4 for a single material. TRL 5 hardware costs for integration and LSS were based on level of complexity and similarity to mini-TOCA hardware. SBIR Phase I and Phase II efforts were estimated at a combined $950K when assumed for development. Assumed costs and totals are provided in Tables F-28 through F-36. The driving costs for all options were the combined LSS and integration costs. For this reason, scoring was based on those costs per the scoring defined in Table F-37. This scoring schema was coordinated with project managers and based on the distribution of costs amongst available options. Note that no costs scored a zero, because if a solution were sufficiently promising, programs and projects would ultimately allocate the required funds.

*Table F-28. Criteria 3 Subsystem Values for Options 1, 2, and 33*

| **Critieria 3: Minimal Cost Increase** | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **xEMU** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | 0 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | 0 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Testing of TRL 5 Hardware | $50,000 | $50,000 | $50,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | 0 |
| Total Cost | $50,000 | $50,000 | $50,000 |

| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
|---|---|---|---|
| **Integration** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | 0 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | 0 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Testing of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | 0 |
| Total Cost | $0 | $0 | $0 |

| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
|---|---|---|---|
| **LSS** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Added Cost for Research (to achieve TRL 4) | $300,000 | 0 | 0 |
| Added Cost for Design of TRL 5 Hardware | $900,000 | $900,000 | 0 |
| Added Costfor Fabrication of TRL 5 Hardware | $450,000 | $450,000 | 0 |
| Added Cost for Testing of TRL 5 Hardware | $450,000 | $450,000 | 0 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,500,000 | $3,500,000 | [redacted] |
| Total Cost | $5,600,000 | $5,300,000 | [redacted] |

## *Table F-29. Criteria 3 Subsystem Values for Options 3-8*

| Critieria 3: Minimal Cost Increase | | | | | | |
|---|---|---|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **xEMU** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Added Cost for Research (to achieve TRL 4) | $600,000 | $600,000 | $600,000 | $600,000 | $600,000 | $600,000 |
| Added Cost for Design of TRL 5 Hardware | $3,000,000 | $3,000,000 | $3,000,000 | $3,000,000 | $3,000,000 | $3,000,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 |
| Added Cost for Testing of TRL 5 Hardware | $300,000 | $300,000 | $300,000 | $300,000 | $300,000 | $300,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $5,400,000 | $5,400,000 | $5,400,000 | $5,400,000 | $5,400,000 | $5,400,000 |
| Total Cost | $11,700,000 | $11,700,000 | $11,700,000 | $11,700,000 | $11,700,000 | $11,700,000 |

| | **Details: Option 3** | **Details Option 4** | **Details Option 5** | **Details Option 6** | **Details Option 7** | **Details Option 8** |
|---|---|---|---|---|---|---|
| **Integration** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Added Cost for Research (to achieve TRL 4) | $950,000 | $950,000 | $950,000 | $1,720,000 | $950,000 | $950,000 |
| Added Cost for Design of TRL 5 Hardware | $250,000 | $250,000 | $250,000 | $700,000 | $250,000 | $250,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $200,000 | $200,000 | $200,000 | $650,000 | $200,000 | $200,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $225,000 | $550,000 | $225,000 | $225,000 |
| Added Cost for Iteration of TRL 5 Hardware | $0 | $0 | $0 | $0 | $0 | $0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $3,000,000 | $6,000,000 | $3,000,000 | $3,000,000 |
| Total Cost | $4,625,000 | $4,625,000 | $4,625,000 | $9,620,000 | $4,625,000 | $4,625,000 |

| | **Details: Option 3** | **Details Option 4** | **Details Option 5** | **Details Option 6** | **Details Option 7** | **Details Option 8** |
|---|---|---|---|---|---|---|
| **LSS** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Added Cost for Research (to achieve TRL 4) | $1,200,000 | $1,500,000 | $770,000 | $1,070,000 | $1,500,000 | $1,800,000 |
| Added Cost for Design of TRL 5 Hardware | $900,000 | $1,800,000 | $450,000 | $1,350,000 | $900,000 | $1,800,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $900,000 | $1,800,000 | $450,000 | $1,350,000 | $900,000 | $1,800,000 |
| Added Cost for Testing of TRL 5 Hardware | $450,000 | $747,000 | $225,000 | $522,000 | $450,000 | $747,000 |
| Added Cost for Iteration of TRL 5 Hardware | $0 | 0 | 0 | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $6,500,000 | $10,790,000 | $3,000,000 | $7,290,000 | $6,500,000 | $10,790,000 |
| Total Cost | $9,950,000 | $16,637,000 | $4,895,000 | $11,582,000 | $10,250,000 | $16,937,000 |

*Table F-30. Criteria 3 Subsystem Values for Options 9-11*

| Critieria 3: Minimal Cost Increase | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **xEMU** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | $600,000 | $600,000 | $600,000 |
| Added Cost for Design of TRL 5 Hardware | $150,000 | $150,000 | $150,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $750,000 | $750,000 | $750,000 |
| Added Cost for Testing of TRL 5 Hardware | $300,000 | $300,000 | $300,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $2,100,000 | $2,100,000 | $2,100,000 |
| Total Cost | $3,900,000 | $3,900,000 | $3,900,000 |

| | | | |
|---|---|---|---|
| | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative cost) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative cost) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative cost) |
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **Integration** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | $1,070,000 | $1,070,000 | $1,070,000 |
| Added Cost for Design of TRL 5 Hardware | $450,000 | $450,000 | $450,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $450,000 | $450,000 | $450,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $225,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $3,000,000 |
| Total Cost | $5,195,000 | $5,195,000 | $5,195,000 |

| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
|---|---|---|---|
| **LSS** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | $1,500,000 | $1,800,000 | $2,400,000 |
| Added Cost for Design of TRL 5 Hardware | $900,000 | $900,000 | $2,700,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $900,000 | $900,000 | $2,700,000 |
| Added Cost for Testing of TRL 5 Hardware | $450,000 | $450,000 | $1,048,500 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $6,500,000 | $6,500,000 | $15,080,000 |
| Total Cost | $10,250,000 | $10,550,000 | $23,928,500 |

*Table F-31. Criteria 3 Subsystem Values for Options 12-14*

| Critieria 3: Minimal Cost Increase | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **xEMU** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | $600,000 | $600,000 | $600,000 |
| Added Cost for Design of TRL 5 Hardware | $150,000 | $150,000 | $150,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $750,000 | $750,000 | $750,000 |
| Added Cost for Testing of TRL 5 Hardware | $300,000 | $300,000 | $300,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $2,100,000 | $2,100,000 | $2,100,000 |
| Total Cost | $3,900,000 | $3,900,000 | $3,900,000 |

| | | | Secondary dosing |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **Integration** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | $770,000 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | $450,000 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | $450,000 |
| Added Cost for Testing of TRL 5 Hardware | 0 | 0 | $225,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | $3,000,000 |
| Total Cost | $0 | $0 | $4,895,000 |

| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
|---|---|---|---|
| **LSS** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | $770,000 | $1,070,000 | $1,370,000 |
| Added Cost for Design of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $819,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $11,580,000 |
| Total Cost | $4,895,000 | $5,195,000 | $18,269,000 |

*Table F-32. Criteria 3 Subsystem Values for Options 15-17*

| Critieria 3: Minimal Cost Increase | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **xEMU** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | $600,000 | $600,000 | $600,000 |
| Added Cost for Design of TRL 5 Hardware | $150,000 | $150,000 | $150,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $750,000 | $750,000 | $750,000 |
| Added Cost for Testing of TRL 5 Hardware | $300,000 | $300,000 | $300,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $2,100,000 | $2,100,000 | $2,100,000 |
| Total Cost | $3,900,000 | $3,900,000 | $3,900,000 |

| | | | |
|---|---|---|---|
| | Assumes HaloPure BR for check valve, no additional cost. | Assumes HaloPure BR for check valve, no additional cost. | Secondary dosing |
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **Integration** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | $770,000 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | $450,000 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | $450,000 |
| Added Cost for Testing of TRL 5 Hardware | 0 | 0 | $225,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | $3,000,000 |
| Total Cost | $0 | $0 | $4,895,000 |

| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
|---|---|---|---|
| **LSS** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Added Cost for Research (to achieve TRL 4) | $1,070,000 | $1,370,000 | $1,670,000 |
| Added Cost for Design of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $819,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $11,580,000 |
| Total Cost | $5,195,000 | $5,495,000 | $18,569,000 |

## *Table F-33. Criteria 3 Subsystem Values for Options 18-21*

| Critieria 3: Minimal Cost Increase | | | | |
|---|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** | **Details: Option 21** |
| **xEMU** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | 0 | 0 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | 0 | 0 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | 0 | 0 |
| Added Cost for Testing of TRL 5 Hardware | $50,000 | $50,000 | $50,000 | $50,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | 0 | 0 |
| Total Cost | $50,000 | $50,000 | $50,000 | $50,000 |

| | **Details: Option 18** | **Details Option 19** | **Details Option 20** | **Details: Option 21** |
|---|---|---|---|---|
| **Integration** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $1,250,000 | $1,250,000 | $1,250,000 | $1,250,000 |
| Added Cost for Design of TRL 5 Hardware | $500,000 | $500,000 | $500,000 | $500,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $400,000 | $400,000 | $400,000 | $400,000 |
| Added Cost for Testing of TRL 5 Hardware | $450,000 | $450,000 | $450,000 | $450,000 |
| Added Cost for Iteration of TRL 5 Hardware | $0 | $0 | $0 | $0 |
| Added Cost for Flight Qualification | $6,000,000 | $6,000,000 | $6,000,000 | $6,000,000 |
| Total Cost | $8,600,000 | $8,600,000 | $8,600,000 | $8,600,000 |

| | **Details: Option 18** | **Details Option 19** | **Details Option 20** | **Details: Option 21** |
|---|---|---|---|---|
| **LSS** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $1,200,000 | $1,500,000 | $770,000 | $1,070,000 |
| Added Cost for Design of TRL 5 Hardware | $900,000 | $1,800,000 | $450,000 | $1,350,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $900,000 | $1,800,000 | $450,000 | $1,350,000 |
| Added Cost for Testing of TRL 5 Hardware | $450,000 | $747,000 | $225,000 | $522,000 |
| Added Cost for Iteration of TRL 5 Hardware | $0 | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $6,500,000 | $10,790,000 | $3,000,000 | $7,290,000 |
| Total Cost | $9,950,000 | $16,637,000 | $4,895,000 | $11,582,000 |

*Table F-34. Criteria 3 Subsystem Values for Options 22-26*

| **Critieria 3: Minimal Cost Increase** | | | | | |
|---|---|---|---|---|---|
| | **Details Option 22** | **Details Option 23** | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **xEMU** | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | 0 | 0 | 0 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | 0 | 0 | 0 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | 0 | 0 | 0 |
| Added Cost for Testing of TRL 5 Hardware | $50,000 | $50,000 | $50,000 | $50,000 | $50,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | 0 | 0 | 0 |
| Total Cost | $50,000 | $50,000 | $50,000 | $50,000 | $50,000 |

| | | | | | |
|---|---|---|---|---|---|
| | | | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative cost) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative cost) | Assumes Umpqua MCV-Br for check valve - with Buffer (conservative cost) |
| | **Details Option 22** | **Details Option 23** | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **Integration** | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $1,250,000 | $1,250,000 | $1,370,000 | $1,370,000 | $1,370,000 |
| Added Cost for Design of TRL 5 Hardware | $500,000 | $500,000 | $700,000 | $700,000 | $700,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $400,000 | $400,000 | $650,000 | $650,000 | $650,000 |
| Added Cost for Testing of TRL 5 Hardware | $450,000 | $450,000 | $450,000 | $450,000 | $450,000 |
| Added Cost for Iteration of TRL 5 Hardware | $0 | $0 | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $6,000,000 | $6,000,000 | $6,000,000 | $6,000,000 | $6,000,000 |
| Total Cost | $8,600,000 | $8,600,000 | $9,170,000 | $9,170,000 | $9,170,000 |

| | **Details Option 22** | **Details Option 23** | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
|---|---|---|---|---|---|
| **LSS** | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $1,500,000 | $1,800,000 | $1,500,000 | $1,800,000 | $2,400,000 |
| Added Cost for Design of TRL 5 Hardware | $900,000 | $1,800,000 | $900,000 | $900,000 | $2,700,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $900,000 | $1,800,000 | $900,000 | $900,000 | $2,700,000 |
| Added Cost for Testing of TRL 5 Hardware | $450,000 | $747,000 | $450,000 | $450,000 | $1,048,500 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $6,500,000 | $10,790,000 | $6,500,000 | $6,500,000 | $15,080,000 |
| Total Cost | $10,250,000 | $16,937,000 | $10,250,000 | $10,550,000 | $23,928,500 |

*Table F-35. Criteria 3 Subsystem Values for Options 27-29*

| **Critieria 3: Minimal Cost Increase** | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **xEMU** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | 0 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | 0 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Testing of TRL 5 Hardware | $50,000 | $50,000 | $50,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | 0 |
| Total Cost | $50,000 | $50,000 | $50,000 |

| | | | |
|---|---|---|---|
| | Cost only for Bromine removal for xEMU | Cost only for Bromine removal for xEMU | Secondary dosing |
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **Integration** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $300,000 | $300,000 | $1,370,000 |
| Added Cost for Design of TRL 5 Hardware | $250,000 | $250,000 | $700,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $200,000 | $200,000 | $650,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $450,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $6,000,000 |
| Total Cost | $3,975,000 | $3,975,000 | $9,170,000 |

| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
|---|---|---|---|
| **LSS** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $770,000 | $1,070,000 | $1,370,000 |
| Added Cost for Design of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $819,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $11,580,000 |
| Total Cost | $4,895,000 | $5,195,000 | $18,269,000 |

*Table F-36. Criteria 3 Subsystem Values for Options 30-32*

| Critieria 3: Minimal Cost Increase | | | |
|---|---|---|---|
| | Details: Option 30 | Details Option 31 | Details Option 32 |
| xEMU | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | 0 | 0 | 0 |
| Added Cost for Design of TRL 5 Hardware | 0 | 0 | 0 |
| Added Costfor Fabrication of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Testing of TRL 5 Hardware | $50,000 | $50,000 | $50,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | 0 | 0 | 0 |
| Total Cost | $50,000 | $50,000 | $50,000 |

| | | | |
|---|---|---|---|
| | Assumes HaloPure BR for check valve, cost only for Bromine removal for xEMU. | Assumes HaloPure BR for check valve, cost only for Bromine removal for xEMU. | Secondary dosing |
| | Details: Option 30 | Details Option 31 | Details Option 32 |
| Integration | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $300,000 | $300,000 | $1,370,000 |
| Added Cost for Design of TRL 5 Hardware | $250,000 | $250,000 | $700,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $200,000 | $200,000 | $650,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $450,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $6,000,000 |
| Total Cost | $3,975,000 | $3,975,000 | $9,170,000 |

| | Details: Option 30 | Details Option 31 | Details Option 32 |
|---|---|---|---|
| LSS | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Added Cost for Research (to achieve TRL 4) | $1,070,000 | $1,370,000 | $1,670,000 |
| Added Cost for Design of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Costfor Fabrication of TRL 5 Hardware | $450,000 | $450,000 | $2,250,000 |
| Added Cost for Testing of TRL 5 Hardware | $225,000 | $225,000 | $819,000 |
| Added Cost for Iteration of TRL 5 Hardware | 0 | 0 | 0 |
| Added Cost for Flight Qualification | $3,000,000 | $3,000,000 | $11,580,000 |
| Total Cost | $5,195,000 | $5,495,000 | $18,569,000 |

*Table F-37. Scoring Definitions for Criteria 3: Minimal Cost Increase*

| Cost Range | | Score |
|---|---|---|
| 0 | $8,000,000 | 5 |
| $8,000,001 | $13,000,000 | 4 |
| $13,000,001 | $18,000,000 | 3 |
| $18,000,001 | $25,000,000 | 2 |
| $25,000,001 | up | 1 |

### F.1.4 Criteria 4: Operational Simplicity

For Criteria 4, the existing iodine architecture on ISS was the baseline for operational simplicity and all options were evaluated in comparison with the baseline. Scoring definitions for Criteria 4 are shown in Table F-38.

*Table F-38. Scoring definitions for Criteria 4: Operational Simplicity*

| Score | Criteria 4: Operational Simplicity Scoring Definitions |
|---|---|
| **5** | Improved or no change in subcriteria from the ISS baseline. |
| **4** | Excellent option in this criteria. Minimal impact subcriteria. |
| **3** | Very good option in this criteria. Primarily minimal impacts to subcriteria with few moderate impacts. No more than one significant impact to subcriteria. |
| **2** | Good option in this criteria. Mixture of minimal, moderate, and significant impacts to subcriteria. |
| **1** | Option is acceptable in this criteria. Multiple Significant impacts to subcriteria. |
| **0** | Option is not acceptable in this criteria. |

The raw data for Criteria 4 are shown in Tables F-39 through F-48.

*Table F-39. Criteria 4 Subsystem Values for Options 1, 2, and 33*

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **xEMU** | Option 1 = design change to PWD to | Option 2: Replaceable "end leg" of | Exploration PWD with shortened |
| Crew Interaction (vs Level of Automation) | No Bacteria Filtration Assembly required in UIA | No Bacteria Filtration Assembly required in UIA | No Bacteria Filtration Assembly required in UIA |
| Monitoring/Sensors Required | No change from baseline | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | No change from baseline | No change from baseline |
| Flexibility of timing of crewed ops | No change from baseline | No change from baseline | No change from baseline |
| Reliability of System | No change from baseline | Likely highly reliable b/c new hardware on every mission. | Likely highly reliable b/c new hardware on every mission. |
| Robustness of System | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 5 | 5 | 5 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **Integration** | Option 1 = design change to PWD to | Option 2: Replaceable "end leg" of | Exploration PWD with shortened |
| Crew Interaction (vs Level of Automation) | No change from baseline | No change from baseline | No change from baseline |
| Monitoring/Sensors Required | No change from baseline | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | No change from baseline | No change from baseline |
| Flexibility of timing of crewed ops | No change from baseline | No change from baseline | No change from baseline |
| Reliability of System | No change from baseline | No change from baseline | No change from baseline |
| Robustness of System | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 5 | 5 | 5 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **LSS** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Crew Interaction (vs Level of Automation) | No change from baseline | Potential for more crew interaction for each change-out (vs ACTEX only change-out) | Crew interaction required pre-dormancy for PWD removal and upon return for installing new PWD. |
| Monitoring/Sensors Required | No change from baseline | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | Possibly just QDs for water lines, regular tools for removing other hardware. Design will incorporate human factors for replacement. | No change from baseline |
| Flexibility of timing of crewed ops | Required changeout for ACTEX/resin when required. | Required changeout when microbes are detected or at end and beginning of mission | Required changeout for ACTEX/resin when required. Required PWD changeout pre-dormancy and installation upon return. |
| Reliability of System | ND for reliability of high temperature iodine removal media | Likely highly reliable b/c new hardware on every mission. | Anticipate better reliability than SOA b/c of removal of dead legs. |
| Robustness of System | ND on robustness of high temperature iodine removal media. | No change from baseline | Anticipate more robust than the SOA b/c of removal of the dead legs. |
| **SCORE** | 3 | 3 | 2 |

*Table F-40. Criteria 4 Subsystem Values for Options 3-5*

| **Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency)** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **xEMU** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Crew Interaction (vs Level of Automation) | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. |
| Monitoring/Sensors Required | None expected. | None expected. | None expected. |
| Special Tools or Equipment Required | None expected. | None expected. | None expected. |
| Flexibility of timing of crewed ops | Water flush will be needed periodically to reduce Ag in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush will be needed periodically to reduce Ag in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush will be needed periodically to reduce Ag in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. |
| Reliability of System | Ag is expected to reduce the overall reliability of the system (vs I2) due to concerns with silver plating on metallic components. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. | Ag is expected to reduce the overall reliability of the system (vs I2) due to concerns with silver plating on metallic components. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. | Ag is expected to reduce the overall reliability of the system (vs I2) due to concerns with silver plating on metallic components. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliabilioty hits may occur based on the counterion. |
| Robustness of xEMU when using this biocide | Ag is expected to increase the robustness of the xEMU thermal loop against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Unknown impacts on SWME membrane robustness, but expected to be better than I2. Concerns with robustness based ont he impact of Ag on hardware within the system. | Ag is expected to increase the robustness of the xEMU thermal loop against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Unknown impacts on SWME membrane robustness, but expected to be better than I2. Concerns with robustness based ont he impact of Ag on hardware within the system. | Ag is expected to increase the robustness of the xEMU thermal loop against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Unknown impacts on SWME membrane robustness, but expected to be better than I2. Concerns with robustness based ont he impact of Ag on hardware within the system. |
| **SCORE** | 2 | 2 | 2 |

| **Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency)** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **Integration** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Crew Interaction (vs Level of Automation) | None expected | None expected | None expected |
| Monitoring/Sensors Required | None expected. | None expected | None expected. |
| Special Tools or Equipment Required | None expected | None expected | None expected |
| Flexibility of timing of crewed ops | No crew interaction required | None expected | No crew interaction required |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. |
| **SCORE** | 5 | 5 | 5 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **LSS** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Crew Interaction (vs Level of Automation) | MCV-Ag will need to be replaced periodically which will require crew interaction. | MCV-Ag will need to be replaced periodically which will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. | MCV-Ag will need to be replaced periodically. Passive dosing hardware will need to be replaced periodically. This will require crew interaction. |
| Monitoring/Sensors Required | None expected. | Yes - for silver monitoring. Should be automated, but will require development for feedback control of the electrolysis system. | None expected. |
| Special Tools or Equipment Required | None expected. | None expected. | Tools may be required to remove and reinstall passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. |
| Reliability of System | Some reduction of reliability in this approach due to the requirement of powered operation and concerns with oxidization affecting long-term performance. Unknowns related to effects of contaminants on electrolytic hardware. | Some reduction of reliability in this approach due to the requirement of powered operation and concerns with oxidization affecting long-term performance. Unknowns related to effects of contaminants on electrolytic hardware. Further, if active microbial control relies on monitoring as input data for Ag introduction, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. | No anticipated change from SOA I2. |
| Robustness of System | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and modulate biocide to prevent runaway microbial growth. Provides constant health check of the water system. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. |
| **SCORE** | 4 | 2 | 4 |

*Table F-41. Criteria 4 Subsystem Values for Options 6-8*

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **xEMU** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Crew Interaction (vs Level of Automation) | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. |
| Monitoring/Sensors Required | None expected. | None expected. | None expected. |
| Special Tools or Equipment Required | None expected. | None expected. | None expected. |
| Flexibility of timing of crewed ops | Water flush will be needed periodically to reduce Ag in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush will be needed periodically to reduce Ag in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush will be needed periodically to reduce Ag in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. |
| Reliability of System | Ag is expected to reduce the overall reliability of the system (vs I2) due to concerns with silver plating on metallic components. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliabilioty hits may occur based on the counterion. | Ag is expected to reduce the overall reliability of the system (vs I2) due to concerns with silver plating on metallic components. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliability hits may occur based on the counterion. | Ag is expected to reduce the overall reliability of the system (vs I2) due to concerns with silver plating on metallic components. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliability hits may occur based on the counterion. |
| Robustness of xEMU when using this biocide | Ag is expected to increase the robustness of the xEMU thermal loop against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Unknown impacts on SWME membrane robustness, but expected to be better than I2. Concerns with robustness based ont he impact of Ag on hardware within the system. | Ag is expected to increase the robustness of the xEMU thermal loop against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Unknown impacts on SWME membrane robustness, but expected to be better than I2. Concerns with robustness based ont he impact of Ag on hardware within the system. | Ag is expected to increase the robustness of the xEMU thermal loop against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Unknown impacts on SWME membrane robustness, but expected to be better than I2. Concerns with robustness based ont he impact of Ag on hardware within the system. |
| **SCORE** | 2 | 2 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **Integration** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Crew Interaction (vs Level of Automation) | Depending on controlled dosing mechanism, crew may have to manually introduce additional bioicide when Ag monitor indicates depletion. | None expected | None expected |
| Monitoring/Sensors Required | None expected | None expected. | None expected |
| Special Tools or Equipment Required | Possibly required for secondary dosing capability. | None expected | None expected |
| Flexibility of timing of crewed ops | Minimal flexibility anticipated if system triggers the need for additional biocide. May only be a small window where additional biocide can be added to prevent run-away microbial growth. | No crew interaction required | None expected |
| Reliability of System | Secondary addition of biocide improves reliability of the overall system approach b/c it accounts for off-nominal events, but decreases reliability of the system depending on the approach take to introduce the biocide. | No change expected from baseline. | No change expected from baseline. |
| Robustness of System | Secondary addition of biocide improves reliability of the overall system approach b/c it accounts for off-nominal events, but does not increase robustness over SOA I2 approach. | No change expected from baseline. | No change expected from baseline. |
| **SCORE** | 2 | 5 | 5 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **LSS** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Crew Interaction (vs Level of Automation) | MCV-Ag will need to be replaced periodically which will require crew interaction. Passive dosing hardware will need to be replaced periodically. This will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. | MCV-Ag will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal. | MCV-Ag will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal.Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | Yes - for silver monitoring. Sensing and feedback should be automated. | None expected. | Yes - for silver monitoring. Should be automated, but will require development for feedback control of the dosing system. |
| Special Tools or Equipment Required | Tools may be required to remove and reinstall passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. | None expected. | None expected. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. |
| Reliability of System | If active microbial control relies on monitoring to signal when additional Ag is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. Secondary dosing approach will have to be evaluated for reliability. | Some reduction of reliability in this approach due to the anticipated use of powered operation/pumping components. Possible reduction in reliability due to counterion impacts. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Ag is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. Possible reduction in reliability due to counterion impacts. |
| Robustness of System | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and trigger crew to add additional biocide to prevent runaway microbial growth. Provides constant health check of the water system. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and modulate biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 3 | 4 | 2 |

*Table F-42. Criteria 4 Subsystem Values for Options 9-11*

| **Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency)** | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **xEMU** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. |
| Monitoring/Sensors Required | None expected. | None expected. | None expected in the xEMU hardware. |
| Special Tools or Equipment Required | Some tools/equipment required to facilitate flush/scrub | Some tools/equipment required to facilitate flush/scrub | Some tools/equipment required to facilitate flush/scrub |
| Flexibility of timing of crewed ops | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. |
| Reliability of System | Bromine without a buffer is expected to reduce the overall reliability of the system (vs I2) due to concerns with corrosion on metallic components and uptake of bromine into softgoods. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliability hits may occur based on biproducts of the bromine salt solution. | Bromine without a buffer is expected to reduce the overall reliability of the system (vs I2) due to concerns with corrosion on metallic components and uptake of bromine into softgoods. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliability hits may occur based on biproducts of the bromine salt solution. | Uptake of bromine into softgoods may reduce lifetime of softgoods, and may ultimately reduce reliability unless degradation is well characterized. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliability hits may occur based on biproducts of the bromine salt solution. |
| Robustness of System | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. |
| **SCORE** | 2 | 2 | 2 |

| **Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency)** | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **Integration** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Automation) | None expected | None expected | None expected |
| Monitoring/Sensors Required | None expected. | None expected. | None expected |
| Required | None expected | None expected | None expected |
| ops | No crew interaction required | No crew interaction required | None expected |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. |
| **SCORE** | 5 | 5 | 5 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **LSS** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | MCV-Br will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal. | MCV-Br will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal. | MCV-Br will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction. Dosing hardware will likely require maintenance and/or replacement of pump. .Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | Yes - for OBr-and pH monitoring. Should be automated, but will require development for feedback control of the dosing system. Unclear if there will be a need to add biocide and buffer indepedently. |
| Special Tools or Equipment Required | Tools may be required to remove and reinstall MCV-Br hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. | Tools may be required to remove and reinstall MCV-Br hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. Special equipment will likely be required for calibration of monitoring hardware. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. . Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. |
| Reliability of System | Some reduction of reliability in this approach due to the anticipated use of powered operation/pumping components. Possible reduction in reliability due to biproduct impacts. | Some reduction of reliability in this approach due to the anticipated use of powered operation/pumping components. Possible reduction in reliability due to biproduct impacts. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Br is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. Possible reduction in reliability due to biproduct impacts. |
| Robustness of System | Lack of a buffer can cause serious concerns with corrosion if any pH change in the system occurs. | No expected change from the baseline | Monitoring of OBr- and pH allows insight into the quality of the potable water and enables control of biocide in the system. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and modulate biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 3 | 4 | 2 |

*Table F-43. Criteria 4 Subsystem Values for Options 12-14*

| **Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency)** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **xEMU** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. |
| Monitoring/Sensors Required | None expected. | None expected. | None expected. |
| Special Tools or Equipment Required | Some tools/equipment required to facilitate flush/scrub | Some tools/equipment required to facilitate flush/scrub | Some tools/equipment required to facilitate flush/scrub |
| Flexibility of timing of crewed ops | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. |
| Reliability of System | Bromine without a buffer is expected to reduce the overall reliability of the system (vs I2) due to concerns with corrosion on metallic components and uptake of bromine into softgoods. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. | Uptake of bromine into softgoods may reduce lifetime of softgoods, and may ultimately reduce reliability unless degradation is well characterized. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. | Uptake of bromine into softgoods may reduce lifetime of softgoods, and may ultimately reduce reliability unless degradation is well characterized. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliability hits may occur based on biproducts of the bromine salt solution. |
| Robustness of System | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. |
| **SCORE** | 2 | 2 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **Integration** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | None expected | None expected | Secondary dosing approach may require be entirely crew-initiated (only for off-nominal events), or may be an automated system. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | None beyond system sensors. |
| Special Tools or Equipment Required | None expected | None expected | Secondary dosing may require additional tools or equipment, particularly if this is crew involved vs automated. Automated approach may be as simple a recycling water through the existing dosing system, or may require a separate sub-system to accomplish. |
| Flexibility of timing of crewed ops | No crew interaction required | No crew interaction required | If automated, no crew ops likely required, or at least very infrequently. If crew response, then unlikely to have any flexibility in response time (will be required immediately to prevent out of control microbial growth). |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | Addition of secondary dosing would decrease the reliability of the overall system b/c of additional parts. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | Secondary dosing would add considerable robustness to the system because would provide for response to off-nominal or un-anticipated situations. Crew-involved secondary dosing would be the most robust as it would eliminate the need for additional automated systems. |
| **SCORE** | 5 | 5 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **LSS** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. None above baseline approach | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. None above baseline approach | MCV-Br will need to be replaced periodically. This will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | Yes - for OBr-and pH monitoring. Should be automated, but will require development for feedback control of the dosing system. Unclear if there will be a need to add biocide and buffer indepedently. |
| Special Tools or Equipment Required | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above baseline approach | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above the baseline approach | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. Special equipment will likely be required for calibration of monitoring hardware. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. Calibration of monitors will be required, but anticipate this will also be on a pre-determined schedule which will allow for flexibility based on known crew activities. |
| Reliability of System | No anticipated change from SOA I2. | No anticipated change from SOA I2. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Br is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. |
| Robustness of System | . Lack of a buffer can cause serious concerns with corrosion if any pH change in the system occurs. | No expected change from the baseline | Br is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of OBr- vs I2. Monitoring of OBr- and pH allows insight into the quality of the potable water and enables control of biocide in the system. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and signal for additional biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 4 | 5 | 2 |

*Table F-44. Criteria 4 Subsystem Values for Options 15-17*

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **xEMU** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. | Crew involvement required to flush/scrub the thermal loop. |
| Monitoring/Sensors Required | None expected. | None expected. | None expected. |
| Special Tools or Equipment Required | Some tools/equipment required to facilitate flush/scrub | Some tools/equipment required to facilitate flush/scrub | Some tools/equipment required to facilitate flush/scrub |
| Flexibility of timing of crewed ops | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. | Water flush may be needed periodically to reduce accumulated bromine in thermal loop. Must be completed after X EVA's. May or may not coincide with other maintenance activities. |
| Reliability of System | Bromine without a buffer is expected to reduce the overall reliability of the system (vs I2) due to concerns with corrosion on metallic components and uptake of bromine into softgoods. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. | Uptake of bromine into softgoods may reduce lifetime of softgoods, and may ultimately reduce reliability unless degradation is well characterized. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. | Uptake of bromine into softgoods may reduce lifetime of softgoods, and may ultimately reduce reliability unless degradation is well characterized. This risk may be decreased as new materials are introduced, but this may then introduce component reliability risks when introducing new materials that are critical to component function/performance. Additional reliability hits may occur based on biproducts of the bromine salt solution. |
| Robustness of System | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. | Unknown impacts on SWME membrane robustness, but expected to be similar to I2. Unknown effectiveness due to potential for rapid evaporation. |
| **SCORE** | 2 | 2 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **Integration** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | None expected | None expected | Secondary dosing approach may require be entirely crew-initiated (only for off-nominal events), or may be an automated system. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | None beyond system sensors. |
| Special Tools or Equipment Required | None expected | None expected | Secondary dosing may require additional tools or equipment, particularly if this is crew involved vs automated. Automated approach may be as simple a recycling water through the existing dosing system, or may require a separate sub-system to accomplish. |
| Flexibility of timing of crewed ops | No crew interaction required | No crew interaction required | If automated, no crew ops likely required, or at least very infrequently. If crew response, then unlikely to have any flexibility in response time (will be required immediately to prevent out of control microbial growth). |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | Addition of secondary dosing would decrease the reliability of the overall system b/c of additional parts. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | Secondary dosing would add considerable robustness to the system because would provide for response to off-nominal or un-anticipated situations. Crew-involved secondary dosing would be the most robust as it would eliminate the need for additional automated systems. |
| **SCORE** | 5 | 5 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **LSS** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Crew Interaction (vs Level of Automation) | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. | MCV-Br will need to be replaced periodically. This will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | Yes - for OBr-and pH monitoring. Should be automated, but will require development for feedback control of the dosing system. Unclear if there will be a need to add biocide and buffer indepedently. |
| Special Tools or Equipment Required | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above baseline approach | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above the baseline approach | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. Special equipment will likely be required for calibration of monitoring hardware. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. Calibration of monitors will be required, but anticipate this will also be on a pre-determined schedule which will allow for flexibility based on known crew activities. |
| Reliability of System | No anticipated change from SOA I2. | No anticipated change from SOA I2. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Br is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. |
| Robustness of System | . Lack of a buffer can cause serious concerns with corrosion if any pH change in the system occurs. | No expected change from the baseline | Br is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of OBr- vs I2. Monitoring of OBr- and pH allows insight into the quality of the potable water and enables control of biocide in the system. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and signal for additional biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 4 | 5 | 2 |

## *Table F-45. Criteria 4 Subsystem Values for Options 18-21*

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | | |
|---|---|---|---|---|
| | Details: Option 18 | Details Option 19 | Details Option 20 | Details: Option 21 |
| **xEMU** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Requires changeout of filter and MCV-I2 in VISE. | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. |
| Monitoring/Sensors Required | No change from baseline | No change from baseline | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | No change from baseline | No change from baseline | No change from baseline |
| Flexibility of timing of crewed ops | No change from baseline | No change from baseline | No change from baseline | No change from baseline |
| Reliability of System | No change from baseline | No change from baseline | No change from baseline | No change from baseline |
| Robustness of System | No change from baseline | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 4 | 4 | 4 | 4 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | | |
|---|---|---|---|---|
| | Details: Option 18 | Details Option 19 | Details Option 20 | Details: Option 21 |
| **Integration** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Crew interaction required to replace UIA filters, but infrequently. This is no change to the baseline. | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. Depending on controlled dosing mechanism, crew may have to manually introduce additional |
| Monitoring/Sensors Required | None expected. | None expected. | None expected. | None expected |
| Special Tools or Equipment Required | None expected | None expected | None expected | Possibly required for secondary dosing capability. |
| Flexibility of timing of crewed ops | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. | No change expected from baseline for changing UIA filters. Minimal flexibility anticipated if system triggers the need for additional biocide. May only be a small window where additional biocide can be added to prevent run-away microbial growth. |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. | Secondary addition of biocide improves reliability of the overall system approach b/c it accounts for off-nominal events, but decreases reliability of the system depending on the approach take to introduce the biocide. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. | Secondary addition of biocide improves reliability of the overall system approach b/c it accounts for off-nominal events, but does not increase robustness over SOA I2 approach. |
| **SCORE** | 5 | 5 | 5 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | | |
|---|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** | **Details: Option 21** |
| **LSS** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS |
| Crew Interaction (vs Level of Automation) | MCV-Ag will need to be replaced periodically which will require crew interaction. | MCV-Ag will need to be replaced periodically which will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. | MCV-Ag will need to be replaced periodically. Passive dosing hardware will need to be replaced periodically. This will require crew interaction. | which will require crew interaction. Passive dosing hardware will need to be replaced periodically. This will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | Yes - for silver monitoring. Should be automated, but will require development for feedback control of the electrolysis system. | None expected. | Yes - for silver monitoring. Sensing and feedback should be automated. |
| Special Tools or Equipment Required | None expected. | None expected. | Tools may be required to remove and reinstall passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. | Tools may be required to remove and reinstall passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. |
| Reliability of System | Some reduction of reliability in this approach due to the requirement of powered operation and concerns with oxidization affecting long-term performance. Unknowns related to effects of contaminants on electrolytic hardware. | Some reduction of reliability in this approach due to the requirement of powered operation and concerns with oxidization affecting long-term performance. Unknowns related to effects of contaminants on electrolytic hardware. Further, if active microbial control relies on monitoring as input data for Ag introduction, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. | No anticipated change from SOA I2. | If active microbial control relies on monitoring to signal when additional Ag is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. Secondary dosing approach will have to be evaluated for reliability. |
| Robustness of System | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and modulate biocide to prevent runaway microbial growth. Provides constant health check of the water system. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and trigger crew to add additional biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 4 | 2 | 4 | 3 |

*Table F-46. Criteria 4 Subsystem Values for Options 22-23*

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | |
|---|---|---|
| | **Details Option 22** | **Details Option 23** |
| **xEMU** | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. |
| Monitoring/Sensors Required | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | No change from baseline |
| Flexibility of timing of crewed ops | No change from baseline | No change from baseline |
| Reliability of System | No change from baseline | No change from baseline |
| Robustness of System | No change from baseline | No change from baseline |
| **SCORE** | 4 | 4 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | |
|---|---|---|
| | **Details Option 22** | **Details Option 23** |
| **Integration** | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. |
| Monitoring/Sensors Required | None expected. | None expected. |
| Special Tools or Equipment Required | None expected | None expected |
| Flexibility of timing of crewed ops | No change expected from baseline. | No change expected from baseline. |
| Reliability of System | No change expected from baseline. | No change expected from baseline. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. |
| **SCORE** | 5 | 5 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | |
|---|---|---|
| | **Details Option 22** | **Details Option 23** |
| **LSS** | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Crew Interaction (vs Level of Automation) | MCV-Ag will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal. | MCV-Ag will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal.Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | Yes - for silver monitoring. Should be automated, but will require development for feedback control of the dosing system. |
| Special Tools or Equipment Required | None expected. | None expected. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. | No anticipated change in MCV-Ag replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. |
| Reliability of System | Some reduction of reliability in this approach due to the anticipated use of powered operation/pumping components. Possible reduction in reliability due to counterion impacts. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Ag is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. Possible reduction in reliability due to counterion impacts. |
| Robustness of System | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. | Ag is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of Ag vs I2. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and modulate biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 4 | 2 |

*Table F-47. Criteria 4 Subsystem Values for Options 24-26*

| **Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency)** | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **xEMU** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. |
| Monitoring/Sensors Required | No change from baseline | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | No change from baseline | No change from baseline |
| Flexibility of timing of crewed ops | No change from baseline | No change from baseline | No change from baseline |
| Reliability of System | No change from baseline | No change from baseline | No change from baseline |
| Robustness of System | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 4 | 4 | 4 |

| **Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency)** | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **Integration** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. |
| Monitoring/Sensors Required | None expected. | None expected. | None expected. |
| Special Tools or Equipment Required | None expected | None expected | None expected |
| Flexibility of timing of crewed ops | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | No change expected from baseline. |
| **SCORE** | 5 | 5 | 5 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **LSS** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | MCV-Br will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal. | MCV-Br will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction, but expected to be minimal. Dosing hardware will likely require maintenance and/or replacement of pump, but expected to be minimal. | MCV-Br will need to be replaced periodically. Anticipated to be fully automated dosing. Crew will likely be required to refill the solution reservior periodically. This will require crew interaction. Dosing hardware will likely require maintenance and/or replacement of pump. .Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | Yes - for OBr-and pH monitoring. Should be automated, but will require development for feedback control of the dosing system. Unclear if there will be a need to add biocide and buffer indepedently. |
| Special Tools or Equipment Required | Tools may be required to remove and reinstall MCV-Br hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. | Tools may be required to remove and reinstall MCV-Br hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. Special equipment will likely be required for calibration of monitoring hardware. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. Anticipate flexibility for salt solution refill of reservoir - expected to be on a schedule that can adjusted well in advance. . Anticipate some level of flexibility for calibration - expected to be on a schedule that can be adjusted well in advance. |
| Reliability of System | Some reduction of reliability in this approach due to the anticipated use of powered operation/pumping components. Possible reduction in reliability due to biproduct impacts. | Some reduction of reliability in this approach due to the anticipated use of powered operation/pumping components. Possible reduction in reliability due to biproduct impacts. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Br is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. Possible reduction in reliability due to biproduct impacts. |
| Robustness of System | Lack of a buffer can cause serious concerns with corrosion if any pH change in the system occurs. | No expected change from the baseline | Monitoring of OBr- and pH allows insight into the quality of the potable water and enables control of biocide in the system. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and modulate biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 3 | 4 | 2 |

*Table F-48. Criteria 4 Subsystem Values for Options 27-29*

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **xEMU** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. |
| Monitoring/Sensors Required | No change from baseline | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | No change from baseline | No change from baseline |
| Flexibility of timing of crewed ops | No change from baseline | No change from baseline | No change from baseline |
| Reliability of System | No change from baseline | No change from baseline | No change from baseline |
| Robustness of System | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 4 | 4 | 4 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **Integration** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. Secondary dosing approach may require be entirely crew-initiated (only for off-nominal events), or may be an automated system. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | None beyond system sensors. |
| Special Tools or Equipment Required | None expected | None expected | Secondary dosing may require additional tools or equipment, particularly if this is crew involved vs automated. Automated approach may be as simple a recycling water through the existing dosing system, or may require a separate sub-system to accomplish. |
| Flexibility of timing of crewed ops | No change expected from baseline. | No change expected from baseline. | If automated, no crew ops likely required, or at least very infrequently. If crew response, then unlikely to have any flexibility in response time (will be required immediately to prevent out of control microbial growth). |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | Addition of secondary dosing would decrease the reliability of the overall system b/c of additional parts. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | Secondary dosing would add considerable robustness to the system because would provide for response to off-nominal or un-anticipated situations. Crew-involved secondary dosing would be the most robust as it would eliminate the need for additional automated systems. |
| **SCORE** | 5 | 5 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **LSS** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. None above baseline approach | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. None above baseline approach | MCV-Br will need to be replaced periodically. This will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | Yes - for OBr-and pH monitoring. Should be automated, but will require development for feedback control of the dosing system. Unclear if there will be a need to add biocide and buffer indepedently. |
| Special Tools or Equipment Required | and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above baseline approach | and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above the baseline approach | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. Special equipment will likely be required for calibration of monitoring hardware. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. Calibration of monitors will be required, but anticipate this will also be on a pre-determined schedule which will allow for flexibility based on known crew activities. |
| Reliability of System | No anticipated change from SOA I2. | No anticipated change from SOA I2. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Br is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. |
| Robustness of System | . Lack of a buffer can cause serious concerns with corrosion if any pH change in the system occurs. | No expected change from the baseline | Br is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of OBr- vs I2. Monitoring of OBr- and pH allows insight into the quality of the potable water and enables control of biocide in the system. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and signal for additional biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 4 | 5 | 2 |

*Table F-49. Criteria 4 Subsystem Values for Options 30-32*

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **xEMU** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. | Requires changeout of Bacterial Filtration Assembly in UIA. |
| Monitoring/Sensors Required | No change from baseline | No change from baseline | No change from baseline |
| Special Tools or Equipment Required | No change from baseline | No change from baseline | No change from baseline |
| Flexibility of timing of crewed ops | No change from baseline | No change from baseline | No change from baseline |
| Reliability of System | No change from baseline | No change from baseline | No change from baseline |
| Robustness of System | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 4 | 4 | 4 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **Integration** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. | Crew interaction required to replace UIA filters, but infrequently. Secondary dosing approach may require be entirely crew-initiated (only for off-nominal events), or may be an automated system. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | None beyond system sensors. |
| Special Tools or Equipment Required | None expected | None expected | Secondary dosing may require additional tools or equipment, particularly if this is crew involved vs automated. Automated approach may be as simple a recycling water through the existing dosing system, or may require a separate sub-system to accomplish. |
| Flexibility of timing of crewed ops | No change expected from baseline. | No change expected from baseline. | If automated, no crew ops likely required, or at least very infrequently. If crew response, then unlikely to have any flexibility in response time (will be required immediately to prevent out of control microbial growth). |
| Reliability of System | No change expected from baseline. | No change expected from baseline. | Addition of secondary dosing would decrease the reliability of the overall system b/c of additional parts. |
| Robustness of System | No change expected from baseline. | No change expected from baseline. | Secondary dosing would add considerable robustness to the system because would provide for response to off-nominal or un-anticipated situations. Crew-involved secondary dosing would be the most robust as it would eliminate the need for additional automated systems. |
| **SCORE** | 5 | 5 | 2 |

| Critieria 4: Operational Simplicity (Flight Ops/Crew Time & Frequency) | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **LSS** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Crew Interaction (vs Level of Automation) | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. | MCV-Br and primary dosing filter will need to be replaced periodically. This will require crew interaction. | MCV-Br will need to be replaced periodically. This will require crew interaction. Minimal crew interaction for and depending on the monitoring approach. Crew-involved sensor calibration may be required periodically. Unknown at this time. |
| Monitoring/Sensors Required | None expected. | None expected. | Yes - for OBr-and pH monitoring. Should be automated, but will require development for feedback control of the dosing system. Unclear if there will be a need to add biocide and buffer indepedently. |
| Special Tools or Equipment Required | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above baseline approach | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. None above the baseline approach | Tools may be required to remove and reinstall MCV-Br and passive dosing hardware. Unknown what the impact of this is, but possibly accomplished with QD's to minimize systemic impact. Special equipment will likely be required for calibration of monitoring hardware. |
| Flexibility of timing of crewed ops | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. | No anticipated change in MCV-Br replacement schedule for crew vs MCV-I2. No anticipated change in primary dosing bed vs SOA I2 approach. Calibration of monitors will be required, but anticipate this will also be on a pre-determined schedule which will allow for flexibility based on known crew activities. |
| Reliability of System | No anticipated change from SOA I2. | No anticipated change from SOA I2. | Some reduction of reliability in this approach due to the anticipated use of powered operation.If active microbial control relies on monitoring to signal when additional Br is required, then the reliability of the system depends on the reliability of the sensor. Reduces overall reliability of the system. |
| Robustness of System | . Lack of a buffer can cause serious concerns with corrosion if any pH change in the system occurs. | No expected change from the baseline | Br is expected to increase the robustness of the water system against microbes due to the "better" broad-spectrum biocidal performance of OBr- vs I2. Monitoring of OBr- and pH allows insight into the quality of the potable water and enables control of biocide in the system. Additional increase in robustness with monitoring b/c the system can accommodate unexpected variations in microbial growth and signal for additional biocide to prevent runaway microbial growth. Provides constant health check of the water system. |
| **SCORE** | 4 | 5 | 2 |

### F.1.5 Criteria 5: Crew Health

For Criteria 5, scores were used as determined by the Task 2 team. The raw data can be found in Appendix B.

### F.1.6 Criteria 6: Low Maturation Risk

For Criteria 6, subcriteria were evaluated based on the quantity of additional data needed for implementation of the architecture option. Table F-50 shows the scoring schema used when evaluating each subsystem after impacts were assigned. Raw data for Criteria 6 is provided in Tables F-51 through F-61.

***Table F-50. Scoring Definitions for Criteria 6: Low Maturation Risk***

| Score | Criteria 6: Low Maturation Risk Scoring Definitions |
|---|---|
| 5 | Improved or no change in subcriteria from the ISS baseline. |
| 4 | Excellent option in this criteria. Minimal impact subcriteria. |
| 3 | Very good option in this criteria. Primarily minimal impacts to subcriteria with few moderate impacts. No more than one significant impact to subcriteria. |
| 2 | Good option in this criteria. Mixture of minimal, moderate, and significant impacts to subcriteria. |
| 1 | Option is acceptable in this criteria. Multiple significant impacts to subcriteria. |
| 0 | Option is not acceptable in this criteria. |

*Table F-51. Criteria 6 Subsystem Values for Options 1, 2, and 33*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **xEMU** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Level of fundamental Research Required | No change from baseline | No change from baseline | No change from baseline |
| Quantity of engineering design needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of health data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | No change from baseline | Likely highly reliable b/c new hardware on every mission. | Likely highly reliable b/c new hardware on every mission. |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 5 | 5 | 5 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **Integration** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Level of fundamental Research Required | No change from baseline | No change from baseline | No change from baseline |
| Quantity of engineering design needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of health data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 5 | 5 | 5 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **LSS** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Level of fundamental Research Required | ND - unknown if material exists or would need to be developed. | Data needed on which portions of PWD actually require swap (risk of microbial growth). | Research needed to determine what happens in the non-biocided volumes of the PWD in non-ISS-like operations and environments. |
| Quantity of engineering design needed | Moderate - would need to move the MCV location nearer to the nozzle - may alter the hot/cold lines being single. Otherwise the design could remain the same. | Considerable redesign needed to be able to swap out the end leg portion of the PWD. | Moderate level of design reuqired to eliminate dead legs. |
| Quantity of health data needed | Assumes that media is not selected unless I2 is prevented from flowing through. | No change from baseline | Need to understand the risk to the crew and/or hardware for various reference missions from microbial growth. May prove different depending on the scenarios and operations. |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | Significant ground test would be needed to prove effectiveness across all operating conditions, long term storage, and resupply needs. | Limited ground testing required to provide change-out procedures and determine resupply requirement | No change from baseline |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| **SCORE** | 2 | 3 | 3 |

## *Table F-52. Criteria 6 Subsystem Values for Options 3-5*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **xEMU** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Level of fundamental Research Required | More material research needed for materials in critical components. Needed to determine impacts. | More material research needed for materials in critical components. Needed to determine impacts. | More material research needed for materials in critical components. Needed to determine impacts. |
| Quantity of engineering design needed | Components in xEMU unlikely to require redesign to accommodate silver. May be as simple as material change. | Components in xEMU unlikely to require redesign to accommodate silver. May be as simple as material change. | Components in xEMU unlikely to require redesign to accommodate silver. May be as simple as material change. |
| Quantity of health data needed | None. Data available in the literature. | None. Data available in the literature. | None. Data available in the literature. |
| Quantity of material compatibility data needed | Significant testing already completed. Still need data on membrane compatibility/concentrated loop. | Significant testing already completed. Still need data on membrane compatibility/concentrated loop. | Significant testing already completed. Still need data on membrane compatibility/concentrated loop. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Terrestrial Data Available | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. |
| **SCORE** | 3 | 3 | 3 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **Integration** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Level of fundamental Research Required | None | None | None |
| Quantity of engineering design needed | None | None | None |
| Quantity of health data needed | None | None | None |
| Quantity of material compatibility data needed | None | None | None |
| Quantity of functional ground test data needed | None | None | None |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. |
| **SCORE** | 5 | 5 | 5 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **LSS** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver (ELS/Foam) |
| Level of fundamental Research Required | Research equired to support MCV-Ag. More data needed on failure modes and lifetime of electrolytic unit. Testing needed to understand time and S/V affects of silver in the LSS water. | Research equired to support MCV-Ag. More data needed on failure modes and lifetime of electrolytic unit. Testing needed to understand time and S/V affects of silver in the LSS water. Significant research needed in Ag monitoring technology. | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA following delivery of hardware to confirm performance and effects of contaminants, etc. |
| Quantity of engineering design needed | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Design needed for controller for electrolytic unit. Significant impact if new design is needed for water heater to accommodate Ag plating. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Design needed for controller for electrolytic unit. Significant impact if new design is needed for water heater to accommodate Ag plating. Significant design needed for Ag monitoring implementation and biocide control. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. |
| Quantity of health data needed | None | None | Data needed on biproducts of ELS/Foam when producing Ag. |
| Quantity of material compatibility data needed | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None needed prior to use for Exploration | None needed prior to use for Exploration | None needed prior to use for Exploration |
| Terrestrial Data Available | No known uses of electrolytic silver dosing in terrestrial applications. | No known uses of electrolytic silver dosing in terrestrial applications. | New technology. No use in terrestrial applications to-date. |
| **SCORE** | 2 | 2 | 1 |

*Table F-53. Criteria 6 Subsystem Values for Options 6-8*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **xEMU** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Level of fundamental Research Required | More material research needed for materials in critical components. Needed to determine impacts. | More material research needed for materials in critical components. Needed to determine impacts. Significant research needed on counterion impacts. | More material research needed for materials in critical components. Needed to determine impacts. Significant research needed on counterion impacts. |
| Quantity of engineering design needed | Components in xEMU unlikely to require redesign to accommodate silver. May be as simple as material change. | Components in xEMU unlikely to require redesign to accommodate silver. May be as simple as material change. May also require additional hardware/design to remove counterion. | Components in xEMU unlikely to require redesign to accommodate silver. May be as simple as material change. May also require additional hardware/design to remove counterion. |
| Quantity of health data needed | None. Data available in the literature. | None. Data available in the literature. | None. Data available in the literature. |
| Quantity of material compatibility data needed | Significant testing already completed. Still need data on membrane compatibility/concentrated loop. | need data on membrane compatibility/concentrated loop. Counterion compatibility data required. | need data on membrane compatibility/concentrated loop. Counterion compatibility data required. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Terrestrial Data Available | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. |
| **SCORE** | 3 | 2 | 2 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **Integration** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Level of fundamental Research Required | Research needed for R&D of secondary dosing approach/technology. | None | None |
| Quantity of engineering design needed | Engineering needed of secondary dosing approach/technology | None | None |
| Quantity of health data needed | None | None | None |
| Quantity of material compatibility data needed | None | None | None |
| Quantity of functional ground test data needed | None | None | None |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. | Significant material compatibility available in the literature. |
| **SCORE** | 3 | 5 | 5 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **LSS** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Level of fundamental Research Required | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA following delivery of hardware to confirm performance and effects of contaminants, etc. Significant research | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA with dosing hardware. | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA with dosing hardware. Significant research needed in Ag monitoring technology. |
| Quantity of engineering design needed | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. Significant design needed for Ag monitoring implementation and biocide control. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. Design needed for dosing hardware. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. Design needed for dosing hardware. Significant design needed for Ag monitoring implementation and biocide control. |
| Quantity of health data needed | Data needed on biproducts of ELS/Foam when producing Ag. | Data needed on counterion effects on health. | Data needed on counterion effects on health. |
| Quantity of material compatibility data needed | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None needed prior to use for Exploration | None needed prior to use for Exploration | None needed prior to use for Exploration |
| Terrestrial Data Available | New technology. No use in terrestrial applications to-date. | Lots of information in the literature about use of silver salt solutions in terrestrial | Lots of information in the literature about use of silver salt solutions in terrestrial |
| **SCORE** | 1 | 2 | 2 |

## *Table F-54. Criteria 6 Subsystem Values for Options 9-11*

| **Criteria 6: Low Maturation Risk** | | Note: buffer adds more risk for maturation, but not sufficient to increase color in this section. | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **xEMU** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | Research needed on biocide biproducts and their effects on the system. Research | Research needed on biocide biproducts and their effects on the system. Research | Research needed on biocide biproducts and their effects on the system. Research |
| Quantity of engineering design needed | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. No existing bromine monitor for space applications. Terrestrial pH monitors readily used, but lack reliability or long-term stability without calibration. |
| Quantity of health data needed | None. | None. | None. |
| Quantity of material compatibility data needed | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Terrestrial Data Available | Some material compatibility data available. Known use in terrestrial applications | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. |
| **SCORE** | 1 | 1 | 1 |

| Criteria 6: Low Maturation Risk | Assumes MCV-Br based on passive release solution with buffer. | Assumes MCV-Br based on passive release solution with buffer. | Assumes MCV-Br based on passive release solution with buffer. |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **Integration** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | Phase I SBIR complete, Phase II in-process. Unlikely to need further fundamental research but unknown. Still working some implementation issues. | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr-. Research needed on bromine monitors and pH monitors |
| Quantity of engineering design needed | Drop-in replacement for I2 approach. | Drop-in replacement for I2 approach. | Drop-in replacement for I2 approach. Significant engineering designed needed for bromine and pH monitors. |
| Quantity of health data needed | More data required at operating concentrations. | More data required at operating concentrations. | More data required at operating concentrations. |
| Quantity of material compatibility data needed | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None required for implementation in Exploration missions | None required for implementation in Exploration missions | None required for implementation in Exploration missions |
| Terrestrial Data Available | Data from development efforts. No "real world" use data. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Data from development efforts. No "real world" use data. Unknown if buffer is required. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Data from development efforts. No "real world" use data. Unknown if buffer is required. Known operations for monitoring and maintenance in Navy applications. However, highly crew-intensive. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) |
| **SCORE** | 3 | 2 | 1 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **LSS** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | Research needed on biocide biproducts and their effects on the system. Research needed to determine pH variations in the system. | Research needed on biocide biproducts and their effects on the system. Research needed to determine pH variations in the system. Research needed to identify optimal buffer and concentrations. | Research needed on biocide biproducts and their effects on the system. Research needed to determine pH variations in the system. Research needed to identify optimal buffer and concentrations. Research needed on bromine monitors and pH monitors |
| Quantity of engineering design needed | Design needed for dosing hardware. Still requires a passive approach for MCV (Umpqua MCV-Br) | Design needed for dosing hardware. Still requires a passive approach for MCV (Umpqua MCV-Br) | Design needed for dosing hardware. Still requires a passive approach for MCV (Umpqua MCV-Br). Design needed for bromine and pH monitors |
| Quantity of health data needed | More data required at operating concentrations. | More data required at operating concentrations. | More data required at operating concentrations. |
| Quantity of material compatibility data needed | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None required for implementation in Exploration missions | None required for implementation in Exploration missions | None required for implementation in Exploration missions |
| Terrestrial Data Available | Some material compatibility data available. Known use in terrestrial applications. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known operations for monitoring and maintenance in Navy applications. However, highly crew-intensive. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) |
| **SCORE** | 2 | 2 | 1 |

## *Table F-55. Criteria 6 Subsystem Values for Options 12-14*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **xEMU** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | Research needed to determine pH variations in the system. | Research needed to determine pH variations in the system. | Research needed to determine pH variations in the system. |
| Quantity of engineering design needed | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. No existing bromine monitor for space applications. Terrestrial pH monitors readily used, but lack reliability or long-term stability without calibration. |
| Quantity of health data needed | None. | None. | None. |
| Quantity of material compatibility data needed | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Terrestrial Data Available | Data from development efforts. No "real world" use data. | Data from development efforts. No "real world" use data. | Data from development efforts. No "real world" use data. |
| **SCORE** | 1 | 1 | 1 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **Integration** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | None | None | Secondary dosing approach needed. |
| Quantity of engineering design needed | None | None | None completed to-date. |
| Quantity of health data needed | None | None | None |
| Quantity of material compatibility data needed | None | None | Captured above. |
| Quantity of functional ground test data needed | None | None | None completed to-date. |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | N/A | N/A | None. |
| **SCORE** | 5 | 5 | 2 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **LSS** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | Phase I SBIR complete, Phase II in-process. Unlikely to need further fundamental research but unknown. Still working some implementation issues. | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr-. Research needed on bromine monitors and pH monitors |
| Quantity of engineering design needed | Drop-in replacement for I2 approach. | Drop-in replacement for I2 approach. | Drop-in replacement for I2 approach. Significant engineering designed needed for bromine and pH monitors. |
| Quantity of health data needed | More data required at operating concentrations. | More data required at operating concentrations. | More data required at operating concentrations. |
| Quantity of material compatibility data needed | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None required for implementation in Exploration missions | None required for implementation in Exploration missions | None required for implementation in Exploration missions |
| Terrestrial Data Available | Data from development efforts. No "real world" use data. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Data from development efforts. No "real world" use data. Unknown if buffer is required. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Data from development efforts. No "real world" use data. Unknown if buffer is required. Known operations for monitoring and maintenance in Navy applications. However, highly crew-intensive. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) |
| **SCORE** | 3 | 2 | 1 |

*Table F-56. Criteria 6 Subsystem Values for Options 15-17*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **xEMU** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | Research needed to determine pH variations in the system. | Research needed to determine pH variations in the system. | Research needed to determine pH variations in the system. |
| Quantity of engineering design needed | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. | Elimination of Hastelloy would require a similar type material (NI-based). May have to consider design changes to accommodate OBr- and prevent corrosion. May have to change LCGV tubing material or design for more frequent replacement. No existing bromine monitor for space applications. Terrestrial pH monitors readily used, but lack reliability or long-term stability without calibration. |
| Quantity of health data needed | None. | None. | None. |
| Quantity of material compatibility data needed | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. | Research on alternative materials for sensors for thermal loop (pressure sensors, RTDs), research onto impacts of bromine uptake into polymers including the SWME membrane and LCVG tubing, corrosion impacts on actual hardware to assess localized oxidation/corrosion. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Terrestrial Data Available | Some material compatibility data available. Known use in terrestrial applications | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. |
| **SCORE** | 1 | 1 | 1 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **Integration** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | used for MCV as well. All impacts | used for MCV as well. | Secondary dosing approach needed. |
| Quantity of engineering design needed | None | None | None completed to-date. |
| Quantity of health data needed | None | None | None |
| Quantity of material compatibility data needed | None | None | Captured above. |
| Quantity of functional ground test data needed | None | None | None completed to-date. |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | N/A | N/A | None. |
| **SCORE** | 5 | 5 | 2 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **LSS** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) |
| Level of fundamental Research Required | Significant developed required to implement HaloPur Passive release in existing system for primary dosing and MCV-Br. | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr-. Research needed on bromine monitors and pH monitors |
| Quantity of engineering design needed | Goal is drop-in replacement for I2 approach, but development is needed to achieve that goal. | Goal is drop-in replacement for I2 approach, but development is needed to achieve that goal. | Drop-in replacement for I2 approach. Significant engineering designed needed for bromine and pH monitors. |
| Quantity of health data needed | More data required at operating concentrations. | More data required at operating concentrations. | More data required at operating concentrations. |
| Quantity of material compatibility data needed | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. | bromine with polymers within the system. Need to understand if existing ACTEX have capability to remove similar |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None required for implementation in Exploration missions | None required for implementation in Exploration missions | None completed to-date. |
| Terrestrial Data Available | Some material compatibility data available. Known use in terrestrial applications. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known operations for monitoring and maintenance in Navy applications. However, highly crew-intensive. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) |
| **SCORE** | 2 | 2 | 1 |

*Table F-57. Criteria 6 Subsystem Values for Options 18-20*

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **xEMU** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| Level of fundamental Research Required | No change from baseline | No change from baseline | No change from baseline |
| Quantity of engineering design needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of health data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| Terrestrial Data Available | data available. | data available. | data available. |
| **SCORE** | 5 | 5 | 5 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **Integration** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| Level of fundamental Research Required | Sigificant research (maybe just literature or market research) needed in Ag capture materials that do not produce biproducts. | Sigificant research (maybe just literature or market research) needed in Ag capture materials that do not produce biproducts. | Sigificant research (maybe just literature or market research) needed in Ag capture materials that do not produce biproducts. |
| Quantity of engineering design needed | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. |
| Quantity of health data needed | Some health data may be required if Ag-capture media produces biproducts. | Some health data may be required if Ag-capture media produces biproducts. | Some health data may be required if Ag-capture media produces biproducts. |
| Quantity of material compatibility data needed | None | None | None |
| Quantity of functional ground test data needed | Significant data will need to be gathered to have sufficient confidence in the Ag-capture media. | Significant data will need to be gathered to have sufficient confidence in the Ag-capture media. | Significant data will need to be gathered to have sufficient confidence in the Ag-capture media. |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | Unknown. | Unknown. | Unknown. |
| **SCORE** | 2 | 2 | 2 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **LSS** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| Level of fundamental Research Required | Research equired to support MCV-Ag. More data needed on failure modes and lifetime of electrolytic unit. Testing needed to understand time and S/V affects of silver in the LSS water. | Research equired to support MCV-Ag. More data needed on failure modes and lifetime of electrolytic unit. Testing needed to understand time and S/V affects of silver in the LSS water. Significant research needed in Ag monitoring technology. | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA following delivery of hardware to confirm performance and effects of contaminants, etc. |
| Quantity of engineering design needed | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Design needed for controller for electrolytic unit. Significant impact if new design is needed for water heater to accommodate Ag plating. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Design needed for controller for electrolytic unit. Significant impact if new design is needed for water heater to accommodate Ag plating. Significant design needed for Ag monitoring implementation and biocide control. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. |
| Quantity of health data needed | None | None | Data needed on biproducts of ELS/Foam when producing Ag. |
| Quantity of material compatibility data needed | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None needed prior to use for Exploration | None needed prior to use for Exploration | None needed prior to use for Exploration |
| Terrestrial Data Available | No known uses of electrolytic silver dosing in terrestrial applications. | No known uses of electrolytic silver dosing in terrestrial applications. | New technology. No use in terrestrial applications to-date. |
| **SCORE** | 2 | 2 | 1 |

*Table F-58. Criteria 6 Subsystem Values for Options 21-23*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **xEMU** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Level of fundamental Research Required | No change from baseline | No change from baseline | No change from baseline |
| Quantity of engineering design needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of health data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| Terrestrial Data Available | data available. | data available. | data available. |
| **SCORE** | 5 | 5 | 5 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **Integration** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Level of fundamental Research Required | Sigificant research (maybe just literature or market research) needed in Ag capture materials that do not produce biproducts. .Research needed for R&D of secondary dosing approach/technology. | Sigificant research (maybe just literature or market research) needed in Ag capture materials that do not produce biproducts. | Sigificant research (maybe just literature or market research) needed in Ag capture materials that do not produce biproducts. |
| Quantity of engineering design needed | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. Engineering needed of secondary dosing approach/technology | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. |
| Quantity of health data needed | Some health data may be required if Ag-capture media produces biproducts. | Some health data may be required if Ag-capture media produces biproducts. | Some health data may be required if Ag-capture media produces biproducts. |
| Quantity of material compatibility data needed | None | None | None |
| Quantity of functional ground test data needed | Significant data will need to be gathered to have sufficient confidence in the Ag-capture media. | Significant data will need to be gathered to have sufficient confidence in the Ag-capture media. | Significant data will need to be gathered to have sufficient confidence in the Ag-capture media. |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | Unknown. | Unknown. | Unknown. |
| **SCORE** | 2 | 2 | 2 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **LSS** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Level of fundamental Research Required | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA following delivery of hardware to confirm performance and effects of contaminants, etc. Significant research needed in Ag monitoring technology. | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA with dosing hardware. | Research required to develop MCV-Ag. Testing needed to understand time and S/V affects of silver in the LSS water. Significant testing required at NASA with dosing hardware. Significant research needed in Ag monitoring technology. |
| Quantity of engineering design needed | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. Significant design needed for Ag monitoring implementation and biocide control. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. Design needed for dosing hardware. | Design needed for MCV-Ag. Need to complete design and test of new non-metallic tubing. Significant impact if new design is needed for water heater to accommodate Ag plating. Design needed for dosing hardware. Significant design needed for Ag monitoring implementation and biocide control. |
| Quantity of health data needed | Data needed on biproducts of ELS/Foam when producing Ag. | Data needed on counterion effects on health. | Data needed on counterion effects on health. |
| Quantity of material compatibility data needed | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. | More needed for balance of plant parts (e.g valves, heater, etc.) More data needed for PWD. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None needed prior to use for Exploration | None needed prior to use for Exploration | None needed prior to use for Exploration |
| Terrestrial Data Available | New technology. No use in terrestrial applications to-date. | Lots of information in the literature about use of silver salt solutions in terrestrial research and applications. | Lots of information in the literature about use of silver salt solutions in terrestrial research and applications. |
| **SCORE** | 1 | 2 | 2 |

*Table F-59. Criteria 6 Subsystem Values for Options 24-26*

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **xEMU** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | No change from baseline | No change from baseline | No change from baseline |
| Quantity of engineering design needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of health data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| Terrestrial Data Available | data available. | data available. | data available. |
| **SCORE** | 5 | 5 | 5 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **Integration** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence. Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- |
| Quantity of engineering design needed | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. MCV-Br is a drop-in replacement for MCV-I2 approach. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. MCV-Br is a drop-in replacement for MCV-I2 approach. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. MCV-Br is a drop-in replacement for MCV-I2 approach. |
| Quantity of health data needed | None. | None | None |
| Quantity of material compatibility data needed | Captured above. | Captured above. | Captured above. |
| Quantity of functional ground test data needed | Significant data will need to be gathered to have sufficient confidence in the Br-capture media.None ground testing yet completed on MCV-Br. | Significant data will need to be gathered to have sufficient confidence in the Br-capture media.None ground testing yet completed on MCV-Br. | Significant data will need to be gathered to have sufficient confidence in the Br-capture media.None ground testing yet completed on MCV-Br. |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | Some Br adsorption data for activated carbon already available. Data from development efforts for MCV-Br. No "real world" use data. Unknown if buffer is required. | Some Br adsorption data for activated carbon already available. Data from development efforts for MCV-Br. No "real world" use data. Unknown if buffer is required. | Some Br adsorption data for activated carbon already available. Data from development efforts for MCV-Br. No "real world" use data. Unknown if buffer is required. |
| **SCORE** | 1 | 1 | 1 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **LSS** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | Research needed on biocide biproducts and their effects on the system. Research needed to determine pH variations in the system. | Research needed on biocide biproducts and their effects on the system. Research needed to determine pH variations in the system. Research needed to identify optimal buffer and concentrations. | Research needed on biocide biproducts and their effects on the system. Research needed to determine pH variations in the system. Research needed to identify optimal buffer and concentrations. Research needed on bromine monitors and pH monitors |
| Quantity of engineering design needed | Design needed for dosing hardware. Still requires a passive approach for MCV (Umpqua MCV-Br) | Design needed for dosing hardware. Still requires a passive approach for MCV (Umpqua MCV-Br) | Design needed for dosing hardware. Still requires a passive approach for MCV (Umpqua MCV-Br). Design needed for bromine and pH monitors |
| Quantity of health data needed | More data required at operating concentrations. | More data required at operating concentrations. | More data required at operating concentrations. |
| Quantity of material compatibility data needed | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None required for implementation in Exploration missions | None required for implementation in Exploration missions | None required for implementation in Exploration missions |
| Terrestrial Data Available | Some material compatibility data available. Known use in terrestrial applications. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known operations for monitoring and maintenance in Navy applications. However, highly crew-intensive. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) |
| **SCORE** | 2 | 2 | 1 |

*Table F-60. Criteria 6 Subsystem Values for Options 27-29*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **xEMU** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | No change from baseline | No change from baseline | No change from baseline |
| Quantity of engineering design needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of health data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| Terrestrial Data Available | data available. | data available. | data available. |
| **SCORE** | 5 | 5 | 5 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **Integration** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence. Secondary dosing approach needed. |
| Quantity of engineering design needed | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. No research on secondary dosing approach completed to-date. |
| Quantity of health data needed | None | None | None |
| Quantity of material compatibility data needed | None | None | Captured above. |
| Quantity of functional ground test data needed | Significant data will need to be gathered to have sufficient confidence in the Br-capture media. | Significant data will need to be gathered to have sufficient confidence in the Br-capture media. | Significant data will need to be gathered to have sufficient confidence in the Br-capture media.None ground testing yet completed on MCV-Br. |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | Some Br adsorption data for activated carbon already available. | Some Br adsorption data for activated carbon already available. | Some Br adsorption data for activated carbon already available.No data available on secondary dosing approaches. |
| **SCORE** | 2 | 2 | 1 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **LSS** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | Phase I SBIR complete, Phase II in-process. Unlikely to need further fundamental research but unknown. Still working some implementation issues. | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr-. Research needed on bromine monitors and pH monitors |
| Quantity of engineering design needed | Drop-in replacement for I2 approach. | Drop-in replacement for I2 approach. | Drop-in replacement for I2 approach. Significant engineering designed needed for bromine and pH monitors. |
| Quantity of health data needed | More data required at operating concentrations. | More data required at operating concentrations. | More data required at operating concentrations. |
| Quantity of material compatibility data needed | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None required for implementation in Exploration missions | None required for implementation in Exploration missions | None required for implementation in Exploration missions |
| Terrestrial Data Available | Data from development efforts. No "real world" use data. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Data from development efforts. No "real world" use data. Unknown if buffer is required. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Data from development efforts. No "real world" use data. Unknown if buffer is required. Known operations for monitoring and maintenance in Navy applications. However, highly crew-intensive. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) |
| **SCORE** | 3 | 2 | 1 |

## *Table F-61. Criteria 6 Subsystem Values for Options 30-32*

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **xEMU** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | No change from baseline | No change from baseline | No change from baseline |
| Quantity of engineering design needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of health data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of material compatibility data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional ground test data needed | No change from baseline | No change from baseline | No change from baseline |
| Quantity of functional flight data needed | No change from baseline | No change from baseline | No change from baseline |
| Terrestrial Data Available | data available. | data available. | data available. |
| **SCORE** | 5 | 5 | 5 |

| **Criteria 6: Low Maturation Risk** | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **Integration** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence. Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence. Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to confirm activated carbon is sufficient to fully capture OBr- or if new material is required for adequate confidence. Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr-. Secondary dosing approach needed. |
| Quantity of engineering design needed | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. MCV-Br is a drop-in replacement for MCV-I2 approach. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media. MCV-Br is a drop-in replacement for MCV-I2 approach. | New design or modified design of the UIA filters will be required to accommodate silver ad/absorption media.Drop-in replacement for I2 approach. But no engineering design completed so far for secondary dosing. |
| Quantity of health data needed | None | None | None |
| Quantity of material compatibility data needed | Captured above. | Captured above. | Captured above. |
| Quantity of functional ground test data needed | Significant data will need to be gathered to have sufficient confidence in the Br-capture media.None ground testing yet completed on MCV-Br. | Significant data will need to be gathered to have sufficient confidence in the Br-capture media.None ground testing yet completed on MCV-Br. | Significant data will need to be gathered to have sufficient confidence in the Br-capture media.None ground testing yet completed on MCV-Br. |
| Quantity of functional flight data needed | None | None | None |
| Terrestrial Data Available | Some Br adsorption data for activated carbon already available. Data from development efforts for MCV-Br. No "real world" use data. Unknown if buffer is required. | Some Br adsorption data for activated carbon already available. Data from development efforts for MCV-Br. No "real world" use data. Unknown if buffer is required. | Some data for Br adsorption data on activated carbon available. Data from development efforts for MCV-Br. No "real world" use data. Unknown if buffer is required. No terrestrial data on secondary dosing approach., |
| **SCORE** | 1 | 1 | 1 |

| Criteria 6: Low Maturation Risk | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **LSS** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Level of fundamental Research Required | Significant developed required to implement HaloPur Passive release in existing system for primary dosing and MCV-Br. | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr- | Research needed to identify buffer-adding approach to existing resin and to design for controlled release in tandem and at appropriate concentrations for released OBr-. Research needed on bromine monitors and pH monitors |
| Quantity of engineering design needed | Goal is drop-in replacement for I2 approach, but development is needed to achieve that goal. | Goal is drop-in replacement for I2 approach, but development is needed to achieve that goal. | Drop-in replacement for I2 approach. Significant engineering designed needed for bromine and pH monitors. |
| Quantity of health data needed | More data required at operating concentrations. | More data required at operating concentrations. | More data required at operating concentrations. |
| Quantity of material compatibility data needed | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. | Need to understand compatibility of bromine with polymers within the system. Need to |
| Quantity of functional ground test data needed | None completed to-date. | None completed to-date. | None completed to-date. |
| Quantity of functional flight data needed | None required for implementation in Exploration missions | None required for implementation in Exploration missions | None completed to-date. |
| Terrestrial Data Available | Some material compatibility data available. Known use in terrestrial applications. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) | Some material compatibility data available. Known use in terrestrial applications. Unknown if buffer is applied to maintain pH. Known operations for monitoring and maintenance in Navy applications. However, highly crew-intensive. Known concern with resistance build-up by microbial population over time (higher than I2 or Ag) |
| **SCORE** | 2 | 2 | 1 |

### F.1.7 Criteria 7: Sustaining Engineering

When assessing the best technical option, Criterias 2, 3, and 6 (Schedule, Cost, and Low Maturation, respectively) were eliminated from the trade. Criteria 7 was added to capture the on-going impacts of an architecture solutions, specifically the sustaining engineering and logistics for each option. Additionally, all subsystems were evaluated as whole rather than individually. Criteria 7 scoring is shown in Table F-62. Raw data for Criteria 7 is provided in Tables F-63 through F-73.

***Table F-62. Scoring Definitions for Criteria 7: Sustaining Engineering***

| Score | Criteria 7: Sustaining Engineering Scoring Definitions |
|---|---|
| 5 | Improved or no change in subcriteria from the ISS baseline. |
| 4 | Excellent option in this criteria. Minimal impact subcriteria. |
| 3 | Very good option in this criteria. Primarily minimal impacts to subcriteria with few moderate impacts. No more than one significant impact to subcriteria. |
| 2 | Good option in this criteria. Mixture of minimal, moderate, and significant impacts to subcriteria. |
| 1 | Option is acceptable in this criteria. Multiple significant impacts to subcriteria. |
| 0 | Option is not acceptable in this criteria. |

*Table F-63. Criteria 7 Architecture Scores for Options 1, 2, and 33*

| **Criteria 7: Sustaining Engineering** | | | |
|---|---|---|---|
| | **Details: Option 1** | **Details Option 2** | **Details Option 33** |
| **xEMU** | Option 1 = design change to PWD to achieve iodine removal @ or closer to nozzle | Option 2: Replaceable "end leg" of PWD as a consumable - may be as simple as tubing swap rather than extensive hardware replacement. | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| | | | |
| **LSS** | | | |
| Hardware Modified - Approach Change | None | Option 2: Consumable "end leg" of PWD - replaced when microbes detected or after dormant period. | None |
| Resupply - Replacement Parts/Consumables for | None | Option 2: Consumable "end leg" of PWD - replaced when microbes detected or after dormant period. | None |
| Dormancy - Hardware change-out | None | Option 2: Consumable "end leg" of PWD - replaced when microbes detected or after dormant period. | Consumable PWD with every mission change-out. |
| Dormancy - Other consumables | None above baseline. | None above baseline. | None above baseline. |
| Resupply - Consumables for Dosing hardware | None above baseline. | None above baseline. | None above baseline. |
| Resupply - "Fresh" Biocide | None | None | None |
| Additional Power | None | None | None |
| **SCORE** | 4 | 3 | 2 |

*Table F-64. Criteria 7 Architecture Scores for Options 3-5*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details: Option 3** | **Details Option 4** | **Details Option 5** |
| **xEMU** | Electrolytic Silver | Electrolytic Silver + Monitoring | Passive Release Silver |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V |
| Dormancy - Hardware change-out | None. | Sensor replacement possible after dormancy | None. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | Consumables expected for recalibrating the silver monitor. | None above baseline approach. |
| Resupply - "Fresh" Biocide | None expected - potentially reduces resupply mass with no fresh biocide required for primary dosing. | None expected. | None above baseline approach. |
| **Score** | 4 | 4 | 4 |

*Table F-65. Criteria 7 Architecture Scores for Options 6-8*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details Option 6** | **Details Option 7** | **Details Option 8** |
| **xEMU** | Passive Release Silver + Monitoring | Concentrated Salt Solution Silver | Concentrated Salt Soln Ag + Monitoring |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of the Ag sensor. | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if |
| Dormancy - Hardware change-out | Sensor replacement possible after dormancy | None. | Sensor replacement possible after dormancy |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Consumables expected for recalibrating the silver monitor. | duration. Assume infrequent replacement for dosing pump. | Consumables expected for recalibrating the silver monitor. |
| Resupply - "Fresh" Biocide | Secondary dosing method will require additional fresh biocide in a TBD form. | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution vs MCV's. |
| **Score** | 3 | 3 | 3 |

## *Table F-66. Criteria 7 Architecture Scores for Options 9-11*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details: Option 9** | **Details Option 10** | **Details Option 11** |
| **xEMU** | DBDMH Solution | DBDMH Solution + Buffer | DBDMH Solution + Buffer + Monitoring (OBr- & pH) |
| Resupply - Replacement Parts/Consumables for xEMU | Possible solution to Hastelloy sensors is more frequent replacement. Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). Significant replacement and calibration of pH sensor required. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump.Consumables expected for recalibrating the Br monitor and pH monitor. |
| Resupply - "Fresh" Biocide | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. |
| **Score** | 3 | 3 | 2 |

*Table F-67. Criteria 7 Architecture Scores for Options 12-14*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details Option 12** | **Details Option 13** | **Details Option 14** |
| **xEMU** | Umpqua Passive Release | Umpqua Passive Release + Buffer | Monitoring (OBr- & pH) |
| Resupply - Replacement Parts/Consumables for xEMU | Possible solution to Hastelloy sensors is more frequent replacement. Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule unkown, but expected to be similar to I2. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| **Score** | 3 | 3 | 2 |

*Table F-68. Criteria 7 Architecture Scores for Options 15-17*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details Option 15** | **Details Option 16** | **Details Option 17** |
| **xEMU** | HaloPur BR Passive Release | HaloPur BR Passive Release + Buffer | Monitoring (OBr- & pH) |
| Resupply - Replacement Parts/Consumables for xEMU | Possible solution to Hastelloy sensors is more frequent replacement. Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. | Possible need to replace LCVG more frequently due to uptake of bromine in tubing resulting in degradation. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | Replacement schedule unknown, but expected to be similar to I2, or slightly higher. | To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| **Score** | 3 | 3 | 2 |

## *Table F-69. Criteria 7 Architecture Scores for Options 18-20*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details: Option 18** | **Details Option 19** | **Details Option 20** |
| **xEMU** | I2 for xEMU & Electrolytic Silver for Vehicle LS | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V | MCV-Ag replacement schedule unknown - unknown impact on M/V |
| Dormancy - Hardware change-out | None. | Sensor replacement possible after dormancy | None. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None. | Consumables expected for recalibrating the silver monitor. | None above baseline approach. |
| Resupply - "Fresh" Biocide | None expected - potentially reduces resupply mass with no fresh biocide required for primary dosing. | None expected. | None above baseline approach. |
| **Score** | 4 | 4 | 4 |

## *Table F-70. Criteria 7 Architecture Scores for Options 21-23*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details: Option 21** | **Details Option 22** | **Details Option 23** |
| **xEMU** | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Ag replacement schedule unknown - unknown impact on M/V. Unknown lifetime of the Ag sensor. | unknown impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if | impact on M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). Unknown lifetime of the |
| Dormancy - Hardware change-out | Sensor replacement possible after dormancy | None. | Sensor replacement possible after dormancy |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Consumables expected for recalibrating the silver monitor. | duration. Assume infrequent replacement for dosing pump. | Consumables expected for recalibrating the silver monitor. |
| Resupply - "Fresh" Biocide | Secondary dosing method will require additional fresh biocide in a TBD form. | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution vs MCV's. |
| **Score** | 3 | 3 | 3 |

*Table F-71. Criteria 7 Architecture Scores for Options 24-26*

| **Criteria 7: Sustaining Engineering** | | | |
|---|---|---|---|
| | **Details: Option 24** | **Details Option 25** | **Details Option 26** |
| **xEMU** | I2 for xEMU & DBDMH Solution for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). | MCV-Br replacement schedule similar to I2 consumables - no change in M/V. Unknown lifetime of dosing pumps and tubing (particularly if peristaltic). Significant replacement and calibration of pH sensor required. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump. | Pump replacement anticipated after some duration. Assume infrequent replacement for dosing pump.Consumables expected for recalibrating the Br monitor and pH monitor. |
| Resupply - "Fresh" Biocide | Unknown M:V ratio for salt solution vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. | Unknown M:V ratio for salt solution + buffer vs MCV's. |
| **Score** | 3 | 3 | 2 |

*Table F-72. Criteria 7 Architecture Scores for Options 27-29*

| Criteria 7: Sustaining Engineering | | | |
|---|---|---|---|
| | **Details: Option 27** | **Details Option 28** | **Details Option 29** |
| **xEMU** | I2 for xEMU & Umpqua Passive Release for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | MCV-Br replacement schedule unkown, but expected to be similar to I2. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| **Score** | 3 | 3 | 2 |

*Table F-73. Criteria 7 Architecture Scores for Options 30-32*

| **Criteria 7: Sustaining Engineering** | | | |
|---|---|---|---|
| | **Details: Option 30** | **Details Option 31** | **Details Option 32** |
| **xEMU** | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS |
| Resupply - Replacement Parts/Consumables for xEMU | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) | Possibly extra SWME membranes due to breakdown over time. (ND) |
| Hardware Eliminated from xEMU | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. | Requires Bacterial Filtration Assembly in UIA. |
| | | | |
| **LSS** | | | |
| Resupply - Replacement Parts/Consumables for LSS | Replacement schedule unknown, but expected to be similar to I2, or slightly higher. | To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. | MCV-Br replacement schedule unkown, but expected to be similar to I2. To fit in same envelope, will reduce total amount of biocide with addition of buffer - which will increase consumable mass. If lifetime is maintained, expect increase in V in the hardware. Unknown lifetime of sensors, but added M/V for those. |
| Dormancy - Hardware change-out | None. | None. | Sensor replacement reuqired for pH. Require frequent calibration and change-out. |
| Dormancy - Other consumables | None. | None. | None. |
| Resupply - Consumables for Dosing hardware | None above baseline approach. | None above baseline approach. | Consumables expected for recalibrating the silver monitor and pH monitor. |
| Resupply - "Fresh" Biocide | None above baseline approach. | None above baseline approach. | Secondary dosing method will require additional fresh biocide in a TBD form. |
| **Score** | 3 | 3 | 2 |

## F.2 Levels of Optimism

Criteria scores at three levels of optimism, with respect to the baseline, were generated for all missions. Levels of optimism were labeled Pessimistic, Likely, and Optimistic. Scores in Criteria 1, 4, and 7 were re-evaluated for all options. Where impacts were noted due to unknowns with the architecture, additional points were identified and classified as Likely or Unlikely. Likely points denoted unknowns that had high probability of yielding favorable results based on engineering judgement. Unlikely points denoted unknowns which involved considerable risk or were known to involve significant challenges. Likely points were added to baseline scores to generate the Likely scores. This resulted in scores that assumed some of the unknowns resulted in favorable results for the Option. Both Likely and Unlikely points were added to baseline scores to generate the Optimistic scores. This resulted in scores that assumed that nearly all the unknowns resulted in favorable results for the option.

Similarly, the baseline scores were reviewed to identify where assumptions were made in favor of an option, but unknowns still existed. Points corresponding to these assumptions were deducted from baseline scores to generate Pessimistic scores. This resulted in scores that assumed that very few of the unknowns resulted in favorable results for the option.

Table F-74 shows the number of points deducted (for Pessimistic scores) or added (for Likely or Optimistic scores). Tables F-75 through F-77 provides the rationale for each of the points for each option.

## *Table F-74. Points Deducted or Awarded to Architecture Options for Each Level of Optimism*

| Option # | Description | Points Added (deducted) for *Pessimistic* Scores | | | Points Added for *Likely* Scores | | | Points Added for *Optimistic* Scores | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1: Minimal M/P/V Increase | 4: Operational Simplicity | 7: Sustaining Engineering | 1: Minimal M/P/V Increase | 4: Operational Simplicity | 7: Sustaining Engineering | 1: Minimal M/P/V Increase | 4: Operational Simplicity | 7: Sustaining Engineering |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 2 | 1 |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 0 | -1 | 0 | 1 | 1 | 1 | 1 | 2 | 1 |
| 3 | Electrolytic Silver | -1 | 0 | -1 | 2 | 2 | 1 | 2 | 3 | 1 |
| 4 | Electrolytic Silver + Monitoring | -1 | -1 | -1 | 2 | 2 | 1 | 2 | 3 | 1 |
| 5 | Passive Release Silver (ELS or Foam) | -1 | 0 | -1 | 1 | 2 | 1 | 1 | 3 | 1 |
| 6 | Passive Release Silver + Monitoring | -1 | 0 | -1 | 1 | 1 | 0 | 2 | 1 | 1 |
| 7 | Concentrated Salt Solution Silver | -1 | 0 | -1 | 1 | 2 | 2 | 3 | 3 | 2 |
| 8 | Concentrated Salt Soln Ag + Monitoring | -1 | -1 | -1 | 1 | 2 | 2 | 3 | 3 | 2 |
| 9 | DBDMH Solution | -1 | -1 | -1 | 1 | 1 | 1 | 3 | 2 | 2 |
| 10 | DBDMH Solution + Buffer | -1 | -1 | -1 | 1 | 1 | 1 | 3 | 2 | 2 |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | -1 | -1 | -1 | 0 | 1 | 1 | 1 | 2 | 1 |
| 12 | Umpqua Passive Release | -1 | -1 | 0 | 1 | 1 | 1 | 2 | 2 | 2 |
| 13 | Umpqua Passive Release + Buffer | -1 | -1 | 0 | 1 | 1 | 1 | 2 | 2 | 2 |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | -1 | -1 | 0 | 0 | 1 | 1 | 1 | 2 | 1 |
| 15 | HaloPur BR Passive Release | -1 | -1 | 0 | 1 | 1 | 1 | 2 | 2 | 2 |
| 16 | HaloPur BR Passive Release + Buffer | -1 | -1 | 0 | 1 | 1 | 1 | 2 | 2 | 2 |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | -1 | -1 | 0 | 0 | 1 | 1 | 1 | 2 | 1 |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | -1 | -1 | -1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | -1 | -1 | -1 | 2 | 2 | 1 | 2 | 2 | 1 |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | -1 | -1 | -1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | -1 | -1 | -1 | 1 | 1 | 0 | 2 | 1 | 1 |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | -1 | -1 | -1 | 2 | 0 | 2 | 2 | 0 | 2 |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | -1 | -1 | -1 | 1 | 2 | 2 | 3 | 2 | 2 |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | -1 | -1 | -1 | 1 | 0 | 1 | 2 | 0 | 1 |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | -1 | -1 | -1 | 0 | 0 | 1 | 2 | 0 | 1 |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | -1 | -1 | -1 | 0 | 1 | 1 | 1 | 2 | 1 |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | -1 | -1 | 0 | 0 | 0 | 2 | 0 | 0 | 2 |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | -1 | -1 | 0 | 0 | 0 | 2 | 0 | 0 | 2 |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | -1 | -1 | 0 | 0 | 1 | 1 | 1 | 2 | 1 |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | -1 | -1 | 0 | 0 | 0 | 2 | 0 | 0 | 2 |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | -1 | -1 | 0 | 0 | 0 | 2 | 0 | 0 | 2 |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | -1 | -1 | 0 | 0 | 1 | 1 | 1 | 2 | 1 |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |

## *Table F-75. Rationale for Pessimistic Scoring Adjustments*

| Option # | Description | Points Added (deducted) for *Pessimistic* Scores: 1: Minimal M/P/V Increase | Points Added (deducted) for *Pessimistic* Scores: 4: Operational Simplicity | Points Added (deducted) for *Pessimistic* Scores: 7: Sustaining Engineering | Rationale for Points: 1: Minimal M/P/V Increase | Rationale for Points: 4: Operational Simplicity | Rationale for Points: 7: Sustaining Engineering |
|---|---|---|---|---|---|---|---|
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 0 | 0 | 0 | | | |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 0 | -1 | 0 | | LSS: -1 pt based on assumption that tools are already available to change out the end leg of the PWD. | |
| 3 | Electrolytic Silver | -1 | 0 | -1 | xEMU: -1 pt based on assumptions that changes to materials will not significantly increase the mass or the volume of the xEMU hardware.<br>LSS (driver on scores): -1 pt based on assumption that MCV-Ag hardware will be minimally larger than MCV-I2 and that resupply will be similar. | | LSS: -1 pt based on assumption that MCV-Ag hardware resupply will be similar to MCV-I2. |
| 4 | Electrolytic Silver + Monitoring | -1 | -1 | -1 | | LSS: -1 pt based on assumption that similar crew time will be required to change out MCV-Ag as is | |
| 5 | Passive Release Silver (ELS or Foam) | -1 | 0 | -1 | | | |
| 6 | Passive Release Silver + Monitoring | -1 | 0 | -1 | | | |
| 7 | Concentrated Salt Solution Silver | -1 | 0 | -1 | | | |
| 8 | Concentrated Salt Soln Ag + Monitoring | -1 | -1 | -1 | | LSS: -1 pt based on assumption that similar crew time will be required to change out MCV-Ag as is | |
| 9 | DBDMH Solution | -1 | -1 | -1 | LSS: -1 pt based on assumption that pump replacement will be infrequent and the power requirement will be small. | LSS: -1 pt based on crew time required for biocide replacement/resupply is negligible. | LSS: -1 pt based on assumption that pump replacement will be infrequent - resulting in limited required spares |
| 10 | DBDMH Solution + Buffer | -1 | -1 | -1 | | | |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | -1 | -1 | -1 | | | |
| 12 | Umpqua Passive Release | -1 | -1 | 0 | LSS: -1 pt based on assumption that passive release Br will be similar in mass and volume as MCV-I2. | LSS: -1 pt based on assumption that crew time required for biocide replacement/resupply is negligible. | |
| 13 | Umpqua Passive Release + Buffer | -1 | -1 | 0 | | | |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | -1 | -1 | 0 | | | |
| 15 | HaloPur BR Passive Release | -1 | -1 | 0 | | | |
| 16 | HaloPur BR Passive Release + Buffer | -1 | -1 | 0 | | | |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | -1 | -1 | 0 | | | |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | -1 | -1 | -1 | LSS: -1 pt based on assumption that MCV-Ag hardware will be minimally larger than MCV-I2 and that resupply will be similar. | LSS: -1 pt based on assumption that similar crew time will be required to change out MCV-Ag as is required for MCV-I2. | LSS: -1 pt based on assumption that MCV-Ag hardware resupply will be similar to MCV-I2. |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | -1 | -1 | -1 | | | |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | -1 | -1 | -1 | | | |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | -1 | -1 | -1 | | | |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | -1 | -1 | -1 | | | |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | -1 | -1 | -1 | | | |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | -1 | -1 | -1 | LSS: -1 pt based on assumption that pump replacement will be infrequent and the power requirement will be small. | LSS: -1 pt based on crew time required for biocide replacement/resupply is negligible. | LSS: -1 pt based on assumption that pump replacement will be infrequent - resulting in limited required spares |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | -1 | -1 | -1 | | | |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | -1 | -1 | -1 | | | |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | -1 | -1 | 0 | LSS: -1 pt based on assumption that passive release Br will be similar in mass and volume as MCV-I2. | LSS: -1 pt based on assumption that crew time required for biocide replacement/resupply is negligible. | |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | -1 | -1 | 0 | | | |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | -1 | -1 | 0 | | | |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | -1 | -1 | 0 | | | |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | -1 | -1 | 0 | | | |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | -1 | -1 | 0 | | | |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 0 | 0 | 0 | | | |

# *Table F-76. Rationale for Likely Scoring Adjustments*

| Option # | Description | Points Added for *Likely* Scores: 1: Minimal M/P/V Increase | Points Added for *Likely* Scores: 4: Operational Simplicity | Points Added for *Likely* Scores: 7: Sustaining Engineering | Rationale for Likely Points: 1: Minimal M/P/V Increase | Rationale for Likely Points: 4: Operational Simplicity | Rationale for Likely Points: 7: Sustaining Engineering |
|---|---|---|---|---|---|---|---|
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 1 | 2 | 1 | xEMU: +1 pt if SWME membranes shown to survive mission lifetime in presence of I2 biocide. | LSS: +1 pt added if high temperature I2 removal media shows similar performance and changeout schedule as ambient temperature removal media. +1 pt if high temperature I2 removal media shows consistent performance after challenge with contaminants and after periods of dormancy. | xEMU: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 1 | 1 | 1 | LSS: +1 pt added if end leg is shown to require replacement only prior to dormancy/after return from dormancy (limits resupplied units) | LSS: +1 pt if ACTEX replacement is only required prior to or following dormancy (no unplanned replacement) | xEMU: +1 pt added if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 3 | Electrolytic Silver | 2 | 2 | 1 | LSS: +1 pt added if mass/volume of electrolytic unit + power supply + controller is similar to total mass of ACTEX + Silver dosing hardware OR 1 point added if MCV-Ag is similar in mass to MCV-I2. If both are true, than +1 pt can be added if the SWME membrane does not require replacement during missions duration due to Ag biocide. | xEMU: +1 pt if SWME does not have to be replaced mid-mission. +1 pt added if new Ag-compatible hardware in thermal loop shows full life operation without issues due to Ag incompatibility | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs. |
| 4 | Electrolytic Silver + Monitoring | 2 | 2 | 1 | LSS: +1 pt if mass/volume of electrolytic unit + power supply + controller is similar to total mass of ACTEX + Silver dosing hardware. +1 pt if MCV-Ag is similar in mass to MCV-I2. | Both xEMU and LSS have baseline values of 2. So equal numbers of improvements in both systems have to be realized to have an increase in overall points. xEMU: +1 pt if SWME does not have to be replaced mid-mission. +1 pt if new Ag-compatible hardware in thermal loop shows full life operation without issues due to Ag incompatibility. LSS: +1 pt if electrolytic unit is demonstrated to be robust against contamination/oxidation (e.g. survives mission duration per requirements without unacceptable reduction in performance) . +1 pt if silver monitor calibration is required only rarely or can be automated. +1 pt if silver monitor is shown to be exceptionally reliable (due to dependency on control). | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs AND silver monitor consumable costs are smaller than the ACTEX filter resupply costs. |
| 5 | Passive Release Silver (ELS or Foam) | 1 | 2 | 1 | LSS: +1 pt added if passive silver dosing hardware is similar in mass/volume as passive I2 dosing hardware AND the MCV-Ag (which may be the same as the passive dosing hardware) is similar in mass/volume as the MCV-I2. | xEMU: +1 pt if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if xPLSS is shown to be highly robust with varying quantities of Ag (microbial and functionally). | xEMU: +1 pt added if SWME doesn't have to be replaced AND resupply of passive release silver hardware and biocide resupply requires no additional mass beyond SOA ACTEX+I2 resupply. |
| 6 | Passive Release Silver + Monitoring | 1 | 1 | 0 | LSS: +1 pt if primary passive silver dosing hardware is similar in mass to I2 passive dosing approach. | LSS: +1 pt if secondary dosing approach requires no crew interaction AND is shown to be exceptionally reliable. | |
| 7 | Concentrated Salt Solution Silver | 1 | 2 | 2 | LSS: +1 pt MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2 | xEMU: +1 pt if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if xPLSS is shown to be highly robust with varying quantities of Ag (microbial and functionally). | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |
| 8 | Concentrated Salt Soln Ag + Monitoring | 1 | 2 | 2 | LSS: +1 pt if MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2. | xEMU: +1 pt added if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if xPLSS is shown to be highly robust with varying quantities of Ag (microbial and functionally). | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | DBDMH Solution | 1 | 1 | 1 | LSS: +1 pt if MCV-Br is similar in mass, volume, and replacement frequency as MCV-I2 | xEMU: +1 pt if system flush is shown to be unneccesary. | LSS: +1 pt if MCV-Br has same hardware and launch costs to resupply as MCV-I2. AND +1 pt if LCVG requires no replacement throughout the mission.*SEE NOTE |
| 10 | DBDMH Solution + Buffer | 1 | 1 | 1 | LSS: +1 pt if MCV-Br is similar in mass, volume, and replacement frequency as MCV-I2 | xEMU: +1 pt if system flush is shown to be unneccesary. | For this option, xEMU and LSS have equal baseline scores. To modify, both xEMU AND LSS must increase by a point for the architecture to increase by one point in the Criteria. LSS: +1 pt if MCV-Br has same hardware and launch costs to resupply as MCV-I2. AND +1 pt if LCVG requires no replacement throughout the mission.*SEE NOTE |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | 0 | 1 | 1 | | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 12 | Umpqua Passive Release | 1 | 1 | 1 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2 | xEMU: + 1 pt if system flush is shown to be unneccesary. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. |
| 13 | Umpqua Passive Release + Buffer | 1 | 1 | 1 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2 | xEMU: + 1 pt if system flush is shown to be unneccesary. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | 0 | 1 | 1 | | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 15 | HaloPur BR Passive Release | 1 | 1 | 1 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2 | xEMU: + 1 pt if system flush is shown to be unneccesary. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. |
| 16 | HaloPur BR Passive Release + Buffer | 1 | 1 | 1 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2 | xEMU: + 1 pt if system flush is shown to be unneccesary. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | 0 | 1 | 1 | | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 1 | 0 | 1 | LSS: +1 pt if the Ag removal hardware is shown to be similar mass/volume as the removal hardware on ISS. | | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs. |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | 2 | 2 | 1 | LSS: +1 pt if mass/volume of electrolytic unit + power supply + controller is similar to total mass of ACTEX + Silver dosing hardware. +1 pt if MCV-Ag is similar in mass to MCV-I2. | Both xEMU and LSS have baseline values of 2. So equal numbers of improvements in both systems have to be realized to have an increase in overall points. xEMU: +1 pt if SWME does not have to be replaced mid-mission. +1 pt if new Ag-compatible hardware in thermal loop shows full life operation without issues due to Ag incompatibility. LSS: +1 pt if electrolytic unit is demonstrated to be robust against contamination/oxidation (e.g. survives mission duration per requirements without unacceptable reduction in performance) . +1 pt if silver monitor calibration is required only rarely or can be automated. +1 pt if silver monitor is shown to be exceptionally reliable (due to dependency on control). | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs AND silver monitor consumable costs are smaller than the ACTEX filter resupply costs. |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | 1 | 0 | 1 | LSS: +1 pt if the Ag removal hardware is shown to be similar mass/volume as the removal hardware on ISS. | | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | 1 | 1 | 0 | LSS: +1 pt if primary passive silver dosing hardware is similar in mass to I2 passive dosing approach. | LSS: +1 pt if secondary dosing approach requires no crew interaction AND is shown to be exceptionally reliable. | |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | 2 | 0 | 2 | LSS: +1 pt if dosing hardware and controller + biocide resupply is ~ equivalent to ACTEX I2 approach. +1 pt if MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2. | | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | 1 | 2 | 2 | LSS: +1 pt if MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2. | xEMU: +1 pt added if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if xPLSS is shown to be highly robust with varying quantities of Ag (microbial and functionally). | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | 1 | 0 | 1 | LSS: +1 pt if MCV-Br is similar in mass, volume, and replacement frequency as MCV-I2. | | LSS: +1 pt if resupply costs of dosing pump repair/replacement parts and biocide solution is similar to ACTEX resupply costs. |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | 0 | 0 | 1 | | | LSS: +1 pt if resupply costs of the dosing pump repair/replacement parts is similar to ACTEX resupply costs. |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 0 | 1 | 1 | | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 0 | 1 | 1 | | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 0 | 1 | 1 | | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 0 | 0 | 0 | | | |

# *Table F-77. Rationale for Optimistic Scoring Adjustments*

| Option # | Description | Points Added for *Optimistic* Scores | | | Rationale for Optimistic Points | | |
|---|---|---|---|---|---|---|---|
| | | 1: Minimal M/P/V Increase | 4: Operational Simplicity | 7: Sustaining Engineering | 1: Minimal M/P/V Increase | 4: Operational Simplicity | 7: Sustaining Engineering |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 1 | 2 | 1 | xEMU: +1 pt if SWME membranes shown to survive mission lifetime in presence of I2 biocide. | LSS: +1 pt added if high temperature I2 removal media shows similar performance and changeout schedule as ambient temperature removal media. +1 pt if high temperature I2 removal media shows consistent performance after challenge with contaminants and after periods of dormancy. | xEMU: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 1 | 2 | 1 | LSS: +1 pt added if end leg is shown to require replacement only prior to dormancy/after return from dormancy (limits resupplied units) | LSS: +1 pt if ACTEX replacement is only required prior to or following dormancy (no unplanned replacement). +1 pt if crew time required for PWD end leg replacement is similar to frequency and complexity of ACTEX replacement | xEMU: +1 pt added if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 3 | Electrolytic Silver | 2 | 3 | 1 | LSS: +1 pt added if mass/volume of electrolytic unit + power supply + controller is similar to total mass of ACTEX + Silver dosing hardware OR 1 point added if MCV-Ag is similar in mass to MCV-I2. If both are true, than +1 pt can be added if the SWME membrane does not require replacement during missions duration due to Ag biocide. | xEMU: +1 pt if SWME does not have to be replaced mid-mission. +1 pt added if new Ag-compatible hardware in thermal loop shows full life operation without issues due to Ag incompatibility. +1 pt if xEMU system flush is shown to be uneccesary or can be automated. Note that if all three occur, 3 pts can only be added IF the electrolytic unit is demonstrated to be robust against contamination/oxidation. | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs. |
| 4 | Electrolytic Silver + Monitoring | 2 | 3 | 1 | LSS: +1 pt if mass/volume of electrolytic unit + power supply + controller is similar to total mass of ACTEX + Silver dosing hardware. +1 pt if MCV-Ag is similar in mass to MCV-I2. | Both xEMU and LSS have baseline values of 2. So equal numbers of improvements in both systems have to be realized to have an increase in overall points. xEMU: +1 pt if SWME does not have to be replaced mid-mission. +1 pt if new Ag-compatible hardware in thermal loop shows full life operation without issues due to Ag incompatibility. +1 pt if xEMU system flush is shown to be uneccesary or can be automated. LSS: +1 pt if electrolytic unit is demonstrated to be robust against contamination/oxidation (e.g. survives mission duration per requirements without unacceptable reduction in performance) . +1 pt if silver monitor calibration is required only rarely or can be automated. +1 pt if silver monitor is shown to be exceptionally reliable (due to dependency on control). | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs AND silver monitor consumable costs are smaller than the ACTEX filter resupply costs. |
| 5 | Passive Release Silver (ELS or Foam) | 1 | 3 | 1 | LSS: +1 pt added if passive silver dosing hardware is similar in mass/volume as passive I2 dosing hardware AND the MCV-Ag (which may be the same as the passive dosing hardware) is similar in mass/volume as the MCV-I2. | xEMU: +1 pt if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if system flush can be automated (vs requiring crew involvement). +1 pt if xPLSS is shown to be highly robust with varying quantities of Ag (microbial and functionally). | xEMU: +1 pt added if SWME doesn't have to be replaced AND resupply of passive release silver hardware and biocide resupply requires no additional mass beyond SOA ACTEX+I2 resupply. |
| 6 | Passive Release Silver + Monitoring | 2 | 1 | 1 | LSS: +1 pt based on assumption that primary passive silver dosing hardware is similar in mass to I2 passive dosing approach. +1 pt if secondary dosing hardware and controller is very small, requiring no resupply, and no additional supplies for dormancy | LSS: +1 pt if secondary dosing approach requires no crew interaction AND is shown to be exceptionally reliable. | xEMU: +1 pt if SWME does not have to be replaced AND secondary dosing method requires no additional mass beyond SOA ACTEX + I2 resupply |
| 7 | Concentrated Salt Solution Silver | 3 | 3 | 2 | LSS: +1 pt MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2. +1 pt if no additional supplies for maintenance or dormancy are required, +1 pt if MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2 | xEMU: +1 pt if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if system flush can be automated (vs requiring crew involvement). +1 pt if xPLSS is shown to be highly robust with varying quantities of Ag (microbial and functionally). | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8 | Concentrated Salt Soln Ag + Monitoring | 3 | 3 | 2 | LSS: +1 pt if MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2. +1 pt if dosing hardware and controller + biocide resupply is ~ equivalent to ACTEX + I2 approach. +1 pt if no additional supplies for maintenance or dormancy are required | xEMU: +1 pt added if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if xPLSS is shown to be highly robust with varying quantities of Ag (microbial and functionally). +1 pt if system flush can be automated (vs requiring crew involvement). | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |
| 9 | DBDMH Solution | 3 | 2 | 2 | LSS: +1 pt if MCV-Br is similar in mass, volume, and replacement frequency as MCV-I2. +1 pt if dosing hardware and controller + biocide resupply + containment (possibly double or triple containment required) is ~ equivalent to ACTEX + I2 approach. +1 pt if no additional supplies for maintenance or dormancy are required. | xEMU: +1 pt if system flush is shown to be unneccesary. +1 pt if soft goods in xPLSS show no uptake of Br. | LSS: +1 pt if MCV-Br has same hardware and launch costs to resupply as MCV-I2. AND +1 pt if LCVG requires no replacement throughout the mission.*SEE NOTE |
| 10 | DBDMH Solution + Buffer | 3 | 2 | 2 | LSS: +1 pt if MCV-Br is similar in mass, volume, and replacement frequency as MCV-I2. +1 pt if dosing hardware and controller + biocide resupply + containment (possibly double or triple containment required) is ~ equivalent to ACTEX + I2 approach. +1 pt if no additional supplies for maintenance or dormancy are required. | xEMU: +1 pt if system flush is shown to be unneccesary. +1 pt if soft goods in xPLSS show no uptake of Br. | For this option, xEMU and LSS have equal baseline scores. To modify, both xEMU AND LSS must increase by a point for the architecture to increase by one point in the Criteria. LSS: +1 pt if MCV-Br has same hardware and launch costs to resupply as MCV-I2. AND +1 pt if LCVG requires no replacement throughout the mission. |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | 1 | 2 | 1 | LSS: +1 pt based on assumption that pH Monitor is long-life | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust, +1 pt based on assumption that pH monitor has minimal or no required calibration. | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 12 | Umpqua Passive Release | 2 | 2 | 2 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2. +1 pt if Br shown not to decrease life of LCVG hardware | xEMU: + 1 pt if system flush is shown to be unneccesary. +1 pt if soft goods in xPLSS show no uptake of Br. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. +1 pt if LCVG requires no replacement throughout the mission. |
| 13 | Umpqua Passive Release + Buffer | 2 | 2 | 2 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2. +1 pt if Br shown not to decrease life of LCVG hardware | xEMU: + 1 pt if system flush is shown to be unneccesary. +1 pt if soft goods in xPLSS show no uptake of Br. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. +1 pt if LCVG requires no replacement throughout the mission. |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | 1 | 2 | 1 | LSS: +1 pt based on assumption that pH Monitor is long-life | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust, +1 pt based on assumption that pH monitor has minimal or no required calibration. | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 15 | HaloPur BR Passive Release | 2 | 2 | 2 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2. +1 pt if Br shown not to decrease life of LCVG hardware | xEMU: + 1 pt if system flush is shown to be unneccesary. +1 pt if soft goods in xPLSS show no uptake of Br. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. +1 pt if LCVG requires no replacement throughout the mission. |
| 16 | HaloPur BR Passive Release + Buffer | 2 | 2 | 2 | xEMU: +1 pt if Hastelloy sensors replaced with alternative material AND MCV-Br mass/ volume/ resupply is ~ the same as MCV-I2. +1 pt if Br shown not to decrease life of LCVG hardware | xEMU: + 1 pt if system flush is shown to be unneccesary. +1 pt if soft goods in xPLSS show no uptake of Br. | xEMU: +1 pt if sensors do not have to be replaced at higher frequency than with I2 exposure. +1 pt if LCVG requires no replacement throughout the mission. |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | 1 | 2 | 1 | LSS: +1 pt based on assumption that pH Monitor is long-life | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust, +1 pt based on assumption that pH monitor has minimal or no required calibration. | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 1 | 0 | 1 | LSS: +1 pt if the Ag removal hardware is shown to be similar mass/volume as the removal hardware on ISS. | | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs. |

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|---|---|---|---|---|---|---|---|
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | 2 | 2 | 1 | LSS: +1 pt if mass/volume of electrolytic unit + power supply + controller is similar to total mass of ACTEX + Silver dosing hardware. +1 pt if MCV-Ag is similar in mass to MCV-I2. | Both xEMU and LSS have baseline values of 2. So equal numbers of improvements in both systems have to be realized to have an increase in overall points. xEMU: +1 pt if SWME does not have to be replaced mid-mission. +1 pt if new Ag-compatible hardware in thermal loop shows full life operation without issues due to Ag incompatibility. +1 pt if xEMU system flush is shown to be uneccesary or can be automated. LSS: +1 pt if electrolytic unit is demonstrated to be robust against contamination/oxidation (e.g. survives mission duration per requirements without unacceptable reduction in performance) . +1 pt if silver monitor calibration is required only rarely or can be automated. +1 pt if silver monitor is shown to be exceptionally reliable (due to dependency on control). | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs AND silver monitor consumable costs are smaller than the ACTEX filter resupply costs. |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | 1 | 0 | 1 | LSS: +1 pt if the Ag removal hardware is shown to be similar mass/volume as the removal hardware on ISS. | | xEMU/LSS: +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) AND MCV-Ag resupply costs are similar to MCV-I2 resupply costs. |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | 2 | 1 | 1 | LSS: +1 pt based on assumption that primary passive silver dosing hardware is similar in mass to I2 passive dosing approach. +1 pt if secondary dosing hardware and controller is very small, requiring no resupply, and no additional supplies for dormancy | LSS: +1 pt if secondary dosing approach requires no crew interaction AND is shown to be exceptionally reliable. | xEMU: +1 pt if SWME does not have to be replaced AND secondary dosing method requires no additional mass beyond SOA ACTEX + I2 resupply |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | 2 | 0 | 2 | LSS: +1 pt if dosing hardware and controller + biocide resupply is ~ equivalent to ACTEX I2 approach. +1 pt if MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2 OR +1 pt if no additional supplies for maintenance or dormancy are required | | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | 3 | 2 | 2 | LSS: +1 pt if MCV-Ag is similar in mass, volume, and replacement frequency as MCV-I2. +1 pt if dosing hardware and controller + biocide resupply is ~ equivalent to ACTEX + I2 approach. +1 pt if no additional supplies for maintenance or dormancy are required | xEMU: +1 pt added if Ag-compatible materials are successfully implemented in xPLSS with no material compatibility issues. +1 pt if system flush can be automated (vs requiring crew involvement). | LSS: +1 pt if MCV-Ag has same hardware and launch costs to resupply as MCV-I2. +1 pt if dosing pump repair/replacement parts are similar to ACTEX resupply costs. |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | 2 | 0 | 1 | LSS: +1 pt if MCV-Br is similar in mass, volume, and replacement frequency as MCV-I2., +1 pt if the dosing hardware and controller + biocide + containment (possibly double or triple) resupply is ~ equivalent to ACTEX + I2 approach | | LSS: +1 pt if resupply costs of dosing pump repair/replacement parts and biocide solution is similar to ACTEX resupply costs. |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | 2 | 0 | 1 | LSS: +1 pt if the dosing hardware and controller + biocide resupply + containment (noted at possibly double or triple) is ~equvalen to ACTEX + I2 approach. +1 pt if no additional supplies are required for maintenance or dormancy. | | LSS: +1 pt if resupply costs of the dosing pump repair/replacement parts is similar to ACTEX resupply costs. |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 2 | 1 | LSS: +1 pt based on assumption that pH Monitor is long-life | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust, +1 pt based on assumption that pH monitor has minimal or no required calibration. | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 2 | 1 | LSS: +1 pt based on assumption that pH Monitor is long-life | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust, +1 pt based on assumption that pH monitor has minimal or no required calibration. | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | 0 | 0 | 2 | | | LSS/xEMU: +1 pt if MCV-Br resupply costs are similar to MCV-I2. +1 pt if xPLSS/SWME membrane is shown to survive mission lifetime (no resupply) |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 1 | 2 | 1 | LSS: +1 pt based on assumption that pH Monitor is long-life | LSS: +1 pt based on assumption that the pH sensor is exceptionally robust, +1 pt based on assumption that pH monitor has minimal or no required calibration. | LSS: +1 pt based on assumption that the pH monitor has very low mass and very low calibration/tooling mass requirements. |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 1 | 1 | 1 | LSS: +1 pts based on assumption that PWD can be reused for more than one mission without swapout beyond ACTEX and Microbial filter. | LSS: +1 pt based on assumption that PWD can be removed and replaced in a single step (not one prior to dormancy and one after dormancy) | LSS: +1 pt if PWD can be used for more than one mission. |

# Appendix G: Data from Architecture Trade Study

## G.1 Weighting Factor Validation

A pair-wise comparison was done to determine weighting factors for architecture-level evaluation criteria after TIM #2 to provide confidence in the weighting factors developed real-time during the TIM. The pair-wise comparison used inputs from key stakeholders and members of the SE team as decision makers. The results are shown in Figures G-1 and G2. This exercise demonstrated that the relative ranking of importance of the evaluation criteria did not change significantly. To further test sensitivity to the weighting factors, a run of the scores was done using the pair-wise comparison weighting factors. This demonstrated that ranking of options did not change. Based on this exercise, the weighting factors developed during TIM #2, with stakeholder concurrence, were used to compile the assessment scores.

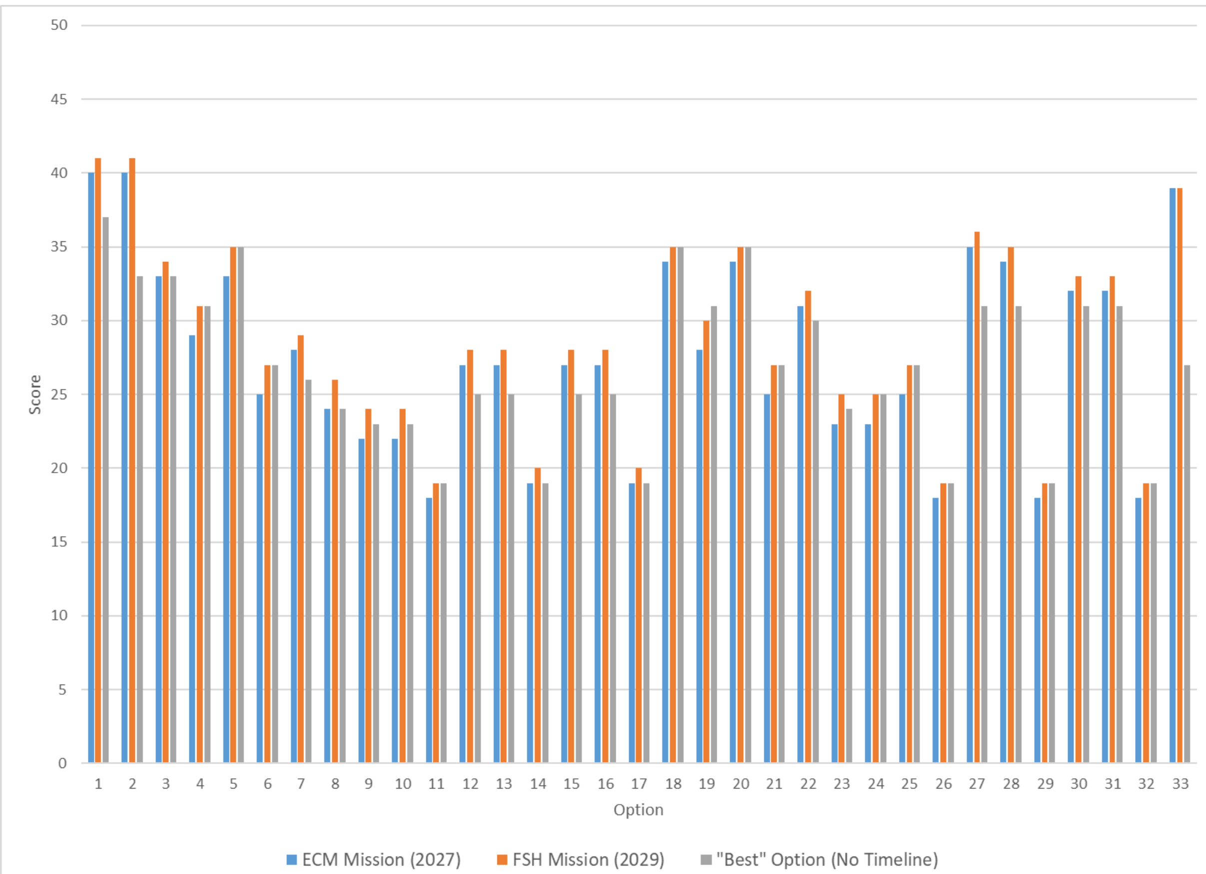


*Figure G-1. Baseline Scores Calculated Using Weighting Factors Specified in TIM #2*

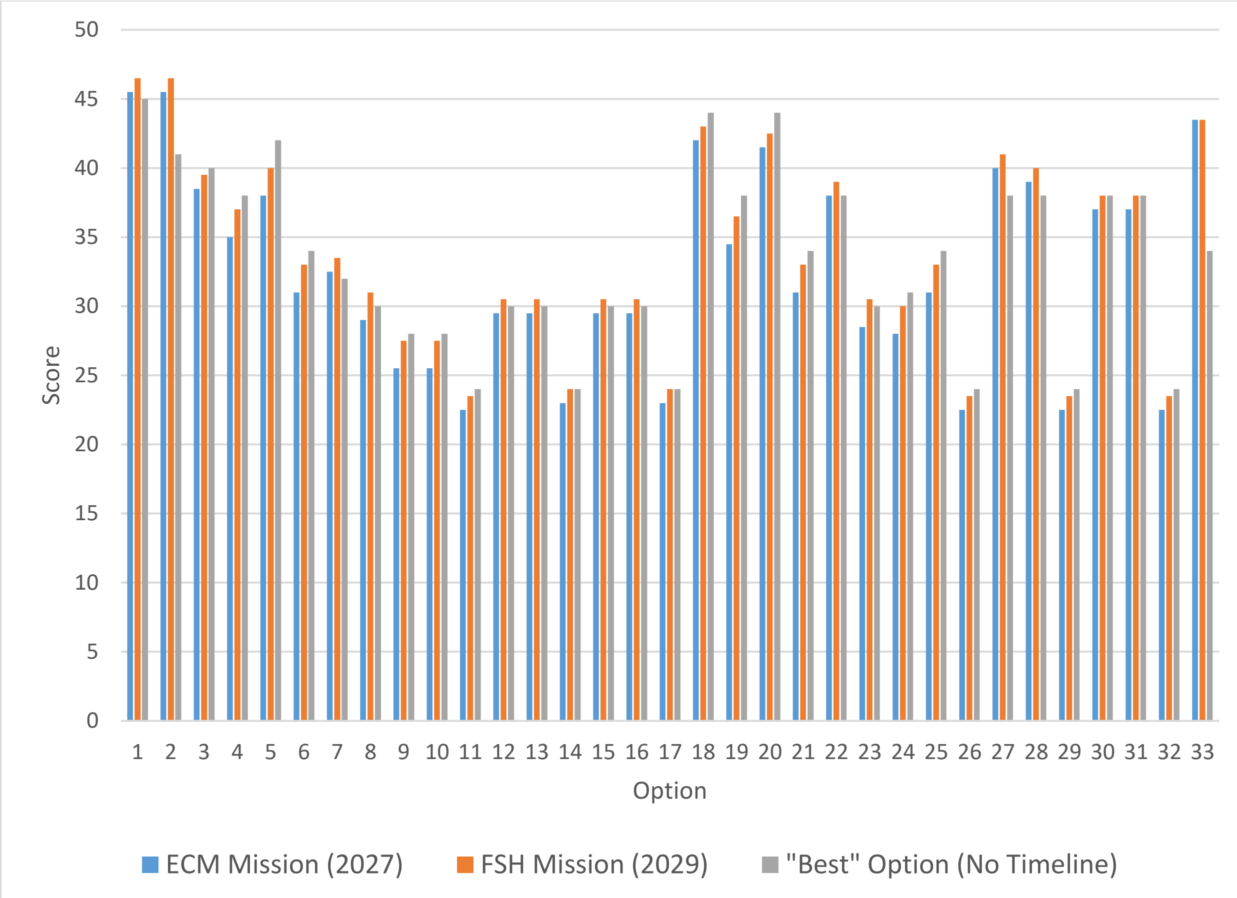


***Figure G-2. Baseline Scores Using Weighting Factors Determined from Pair-wise Comparisons***

## G.2 Scores and Ranking

Tables G-1 through G-3 provide the final scores and ranking for all options with the ECM mission, the FSH mission, and Best Technical, respectively.

## *Table G-1. ECM Architecture Scores and Ranking*

| | | ECM (2027) Scores | | | | ECM (2027) Rank | | | |
|---|---|---|---|---|---|---|---|---|---|
| Option # | Description | Pessimistic Scores | Baseline Scores | Likely Scores | Optimistic Scores | Pessimistic Scores | Baseline Scores | Likely Scores | Optimistic Scores |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 40 | 40 | 46 | 46 | 2 | 2 | 2 | 2 |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 38 | 40 | 44 | 46 | 3 | 2 | 3 | 2 |
| 33 | Exploration PWD with shortened non-biocide legs and no | 39 | 39 | 39 | 43 | 1 | 1 | 1 | 1 |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 31 | 35 | 35 | 35 | 4 | 4 | 10 | 12 |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 30 | 34 | 36 | 36 | 7 | 5 | 7 | 8 |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for | 30 | 34 | 36 | 36 | 7 | 5 | 7 | 8 |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for | 30 | 34 | 34 | 34 | 7 | 5 | 12 | 18 |
| 3 | Electrolytic Silver | 31 | 33 | 41 | 43 | 4 | 8 | 4 | 4 |
| 5 | Passive Release Silver (ELS or Foam) | 31 | 33 | 39 | 41 | 4 | 8 | 5 | 5 |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 28 | 32 | 32 | 32 | 10 | 10 | 14 | 20 |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for | 28 | 32 | 32 | 32 | 10 | 10 | 14 | 20 |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle | 27 | 31 | 35 | 35 | 12 | 12 | 10 | 12 |
| 4 | Electrolytic Silver + Monitoring | 25 | 29 | 37 | 39 | 14 | 13 | 6 | 7 |
| 7 | Concentrated Salt Solution Silver | 26 | 28 | 34 | 40 | 13 | 14 | 12 | 6 |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | 24 | 28 | 36 | 36 | 15 | 14 | 7 | 8 |
| 12 | Umpqua Passive Release | 23 | 27 | 31 | 35 | 16 | 16 | 16 | 12 |
| 13 | Umpqua Passive Release + Buffer | 23 | 27 | 31 | 35 | 16 | 16 | 16 | 12 |
| 15 | HaloPur BR Passive Release | 23 | 27 | 31 | 35 | 16 | 16 | 16 | 12 |
| 16 | HaloPur BR Passive Release + Buffer | 23 | 27 | 31 | 35 | 16 | 16 | 16 | 12 |
| 6 | Passive Release Silver + Monitoring | 23 | 25 | 29 | 31 | 16 | 20 | 21 | 24 |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | 21 | 25 | 29 | 31 | 21 | 20 | 21 | 24 |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | 21 | 25 | 25 | 29 | 21 | 20 | 26 | 26 |
| 8 | Concentrated Salt Soln Ag + Monitoring | 20 | 24 | 30 | 36 | 23 | 23 | 20 | 8 |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for | 19 | 23 | 29 | 33 | 24 | 24 | 21 | 19 |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | 19 | 23 | 25 | 27 | 24 | 24 | 26 | 27 |
| 9 | DBDMH Solution | 18 | 22 | 26 | 32 | 26 | 26 | 24 | 20 |
| 10 | DBDMH Solution + Buffer | 18 | 22 | 26 | 32 | 26 | 26 | 24 | 20 |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | 15 | 19 | 21 | 25 | 28 | 28 | 28 | 28 |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | 15 | 19 | 21 | 25 | 28 | 28 | 28 | 28 |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 14 | 18 | 20 | 24 | 30 | 30 | 30 | 30 |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | 14 | 18 | 20 | 24 | 30 | 30 | 30 | 30 |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 14 | 18 | 20 | 24 | 30 | 30 | 30 | 30 |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 14 | 18 | 20 | 24 | 30 | 30 | 30 | 30 |

## *Table G-2. FSH Architecture Scores and Ranking*

| | | FSH (2029) Scores | | | | FSH (2029) Ranking | | | |
|---|---|---|---|---|---|---|---|---|---|
| Option # | Description | Pessimistic Scores | Baseline Scores | Likely Scores | Optimistic Scores | Pessimistic Scores | Baseline Scores | Likely Scores | Optimistic Scores |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 41 | 41 | 47 | 47 | 1 | 1 | 1 | 1 |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 39 | 41 | 45 | 47 | 2 | 1 | 2 | 1 |
| 33 | Exploration PWD with shortened non-biocide legs and no "dead legs". Otherwise ISS-like. | 39 | 39 | 39 | 43 | 2 | 3 | 5 | 4 |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 32 | 36 | 36 | 36 | 5 | 4 | 10 | 12 |
| 5 | Passive Release Silver (ELS or Foam) | 33 | 35 | 41 | 43 | 4 | 5 | 4 | 4 |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 31 | 35 | 37 | 37 | 7 | 5 | 8 | 10 |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for Vehicle LS | 31 | 35 | 37 | 37 | 7 | 5 | 8 | 10 |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for Vehicle LS | 31 | 35 | 35 | 35 | 7 | 5 | 12 | 18 |
| 3 | Electrolytic Silver | 32 | 34 | 42 | 44 | 5 | 9 | 3 | 3 |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 29 | 33 | 33 | 33 | 10 | 10 | 14 | 22 |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for Vehicle LS | 29 | 33 | 33 | 33 | 10 | 10 | 14 | 22 |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | 28 | 32 | 36 | 36 | 12 | 12 | 10 | 12 |
| 4 | Electrolytic Silver + Monitoring | 27 | 31 | 39 | 41 | 13 | 13 | 5 | 6 |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | 26 | 30 | 38 | 38 | 15 | 14 | 7 | 8 |
| 7 | Concentrated Salt Solution Silver | 27 | 29 | 35 | 41 | 13 | 15 | 12 | 6 |
| 12 | Umpqua Passive Release | 24 | 28 | 32 | 36 | 17 | 16 | 16 | 12 |
| 13 | Umpqua Passive Release + Buffer | 24 | 28 | 32 | 36 | 17 | 16 | 16 | 12 |
| 15 | HaloPur BR Passive Release | 24 | 28 | 32 | 36 | 17 | 16 | 16 | 12 |
| 16 | HaloPur BR Passive Release + Buffer | 24 | 28 | 32 | 36 | 17 | 16 | 16 | 12 |
| 6 | Passive Release Silver + Monitoring | 25 | 27 | 31 | 33 | 16 | 20 | 21 | 22 |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for Vehicle LS | 23 | 27 | 31 | 33 | 21 | 20 | 21 | 22 |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | 23 | 27 | 27 | 31 | 21 | 20 | 26 | 26 |
| 8 | Concentrated Salt Soln Ag + Monitoring | 22 | 26 | 32 | 38 | 23 | 23 | 16 | 8 |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | 21 | 25 | 31 | 35 | 24 | 24 | 21 | 18 |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | 21 | 25 | 27 | 29 | 24 | 24 | 26 | 27 |
| 9 | DBDMH Solution | 20 | 24 | 28 | 34 | 26 | 26 | 24 | 20 |
| 10 | DBDMH Solution + Buffer | 20 | 24 | 28 | 34 | 26 | 26 | 24 | 20 |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | 16 | 20 | 22 | 26 | 28 | 28 | 28 | 28 |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | 16 | 20 | 22 | 26 | 28 | 28 | 28 | 28 |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | 15 | 19 | 21 | 25 | 30 | 30 | 30 | 30 |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 15 | 19 | 21 | 25 | 30 | 30 | 30 | 30 |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 15 | 19 | 21 | 25 | 30 | 30 | 30 | 30 |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 15 | 19 | 21 | 25 | 30 | 30 | 30 | 30 |

# *Table G-3. Best Technology Architecture Scores and Ranking*

| | | Best Technology Bands Scores | | | | Best Technology Bands Ranking | | | |
|---|---|---|---|---|---|---|---|---|---|
| Option # | Description | Pessimistic Scores | Baseline Scores | Likely Scores | Optimistic Scores | Pessimistic Scores | Baseline Scores | Likely Scores | Optimistic Scores |
| 1 | I2 with design change to PWD to achieve iodine removal @ or closer to nozzle | 37 | 37 | 45 | 45 | 1 | 1 | 1 | 1 |
| 5 | Passive Release Silver (ELS or Foam) | 31 | 35 | 43 | 45 | 2 | 2 | 2 | 1 |
| 18 | I2 for xEMU & Electrolytic Silver for Vehicle LS | 29 | 35 | 39 | 39 | 4 | 2 | 6 | 9 |
| 20 | I2 for xEMU & Passive Release Silver (ELS or Foam) for | 29 | 35 | 39 | 39 | 4 | 2 | 6 | 9 |
| 3 | Electrolytic Silver | 29 | 33 | 43 | 45 | 4 | 5 | 2 | 1 |
| 2 | I2 with Replaceable "end leg" of PWD as a consumable | 31 | 33 | 39 | 41 | 2 | 5 | 6 | 6 |
| 4 | Electrolytic Silver + Monitoring | 25 | 31 | 41 | 43 | 12 | 11 | 4 | 4 |
| 19 | I2 for xEMU & Electrolytic Silver + Monitoring for Vehicle LS | 25 | 31 | 41 | 41 | 12 | 11 | 4 | 6 |
| 27 | I2 for xEMU & Umpqua Passive Release for Vehicle LS | 27 | 31 | 35 | 35 | 7 | 7 | 11 | 19 |
| 28 | I2 for xEMU & Umpqua Passive Release + Buffer for | 27 | 31 | 35 | 35 | 7 | 7 | 11 | 19 |
| 30 | I2 for xEMU & HaloPur BR Passive Release for Vehicle LS | 27 | 31 | 35 | 35 | 7 | 7 | 11 | 19 |
| 31 | I2 for xEMU & HaloPur BR Passive Release + Buffer for | 27 | 31 | 35 | 35 | 7 | 7 | 11 | 19 |
| 22 | I2 for xEMU & Concentrated Salt Solution Silver for Vehicle LS | 24 | 30 | 38 | 38 | 14 | 13 | 9 | 11 |
| 6 | Passive Release Silver + Monitoring | 23 | 27 | 31 | 35 | 15 | 15 | 17 | 19 |
| 21 | I2 for xEMU & Passive Release Silver + Monitoring for | 21 | 27 | 31 | 35 | 17 | 15 | 17 | 19 |
| 25 | I2 for xEMU & DBDMH Solution + Buffer for Vehicle LS | 21 | 27 | 29 | 33 | 17 | 15 | 23 | 25 |
| 33 | Exploration PWD with shortened non-biocide legs and no | 27 | 27 | 27 | 33 | 7 | 14 | 27 | 25 |
| 7 | Concentrated Salt Solution Silver | 22 | 26 | 36 | 42 | 16 | 18 | 10 | 5 |
| 12 | Umpqua Passive Release | 21 | 25 | 31 | 37 | 17 | 19 | 17 | 13 |
| 13 | Umpqua Passive Release + Buffer | 21 | 25 | 31 | 37 | 17 | 19 | 17 | 13 |
| 15 | HaloPur BR Passive Release | 21 | 25 | 31 | 37 | 17 | 19 | 17 | 13 |
| 16 | HaloPur BR Passive Release + Buffer | 21 | 25 | 31 | 37 | 17 | 19 | 17 | 13 |
| 24 | I2 for xEMU & DBDMH Solution for Vehicle LS | 19 | 25 | 29 | 31 | 23 | 19 | 23 | 27 |
| 8 | Concentrated Salt Soln Ag + Monitoring | 18 | 24 | 34 | 40 | 24 | 24 | 15 | 8 |
| 23 | I2 for xEMU & Concentrated Salt Soln Ag + Monitoring for Vehicle LS | 18 | 24 | 34 | 38 | 24 | 24 | 15 | 11 |
| 9 | DBDMH Solution | 17 | 23 | 29 | 37 | 26 | 26 | 23 | 13 |
| 10 | DBDMH Solution + Buffer | 17 | 23 | 29 | 37 | 26 | 26 | 23 | 13 |
| 14 | Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) | 15 | 19 | 23 | 27 | 28 | 28 | 28 | 28 |
| 17 | HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) | 15 | 19 | 23 | 27 | 28 | 28 | 28 | 28 |
| 29 | I2 for xEMU & Umpqua Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 15 | 19 | 23 | 27 | 28 | 28 | 28 | 28 |
| 32 | I2 for xEMU & HaloPur BR Passive Release + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 15 | 19 | 23 | 27 | 28 | 28 | 28 | 28 |
| 11 | DBDMH Solution + Buffer + Monitoring (OBr- & pH) | 13 | 19 | 23 | 27 | 32 | 28 | 28 | 28 |
| 26 | I2 for xEMU & DBDMH Solution + Buffer + Monitoring (OBr- & pH) for Vehicle LS | 13 | 19 | 23 | 27 | 32 | 28 | 28 | 28 |

## G.3 Activity Mapping

A total of 56 activities were identified to close gaps in knowledge or technology for all biocides. Table G-4 provides the full list of activities. Each of the activities was then mapped to individual architectures. Table G-5 shows the specific architectures impacted by a given activity. An "X" in a given field indicates the activity will address a known gap within that architecture. Architectures are highlighted to reference green, yellow, and red categories as defined in Table A-1.

*Table G-4. Complete List of Biocide Development Activities*

| Activity # | Description |
|---|---|
| 1 | Complete testing of iodine to evaluate material compatibility and long-term functional compatibility with SWME polypropylene membrane. |
| 2 | Conduct a literature review of iodine removal media that is similarly efficient with “hot” water as the SOA media is with cold water. |
| 3 | Conduct test to evaluate reliability of “hot water” iodine removal media for long-term “hot” water applications |
| 4 | Conduct test to evaluate robustness of “hot water” iodine removal media for long-term “hot” water applications |
| 5 | Complete design modifications of PWD to accommodate change-out of leg with no biocide. |
| 6 | Conduct testing to assess iodine effectivity when exposed to metal over time (does Iodine change to non-biocidal form?). |
| 7 | Conduct testing to evaluate iodine depletion rates over time in a stored water system. |
| 8 | Conduct test and analysis to determine the sections of PWD that require replacement (vs. replacing the entire assembly) for microbial control during nominal operation. |
| 9 | Conduct test and analysis to determine the sections of PWD that require replacement (vs. replacing the entire assembly) for microbial control after periods of dormancy. |
| 10 | Identify Ag-removal media for OGA protection and complete design modifications to replace I2 media in OGA IEB. |
| 11 | Complete silver monitor development (already funded). |
| 12 | Conduct testing and redesign of biocide passive release Ag-dosing system for passive release applications and Ag-based MCV. |
| 13 | Conduct testing to inform silver monitor/sensor ConOps for dormancy (determine whether sensor remains in place, requires removal and/or replacement, etc). |
| 14 | Develop secondary dosing method if architecture requires control of silver concentration and the primary dosing method is passive. |
| 15 | Conduct testing and analysis to determine the mass: volume ratios of silver biocide salt solutions, passive solutions, and electrolytic solution and predicted resupply rates. |
| 16 | Conduct robustness testing of electrolytic silver dosing hardware (e.g., long-term operation contaminant impacts, corrosion impacts). |
| 17 | Conduct reliability testing of silver biocide technology: long-term operation. |
| 18 | Conduct reliability testing of silver biocide technology for continuous vs. intermittent operation. |
| 19 | Conduct reliability testing of silver biocide technology for dormancy impacts. |

| | |
|---|---|
| 20 | Conduct testing to determine the required frequency of flushing xEMU thermal loop when operated with Ag biocide (need same for Br approach). |
| 21 | Conduct testing of Ag monitor to inform ConOps: required frequency of calibration and required tools and consumables. |
| 22 | Develop and test tubing that is Ag compatible due to the high S/V ratio and anticipated plating. |
| 23 | Identify material (vs. AgCl) for passive release Ag options that does not produce a counterion with material compatibility issues. |
| 24 | Develop a salt dosing system for Ag salt solutions. |
| 25 | Conduct evaluation of balance of plant components compatibility with silver plating (e.g., valves, sensors, pumps) in the LSS. |
| 26 | Conduct testing to evaluate rate and effects of silver biocide depletion during water storage. |
| 27 | Conduct testing to determine the quantity of Cl- released with passive AgCl approaches and evaluate systems material compatibility. |
| 28 | Conduct bromine palatability testing |
| 29 | Conduct testing and/or analysis to determine whether sensors in the xEMU backplate use Hastelloy for housing material or sensing material. Identify new sensors/sensor materials if necessary. |
| 30 | Conduct testing and analysis to determine the mass: volume ratios of bromine biocide salt solutions and passive solutions and their predicted resupply rates. |
| 31 | Conduct testing and analysis to identify acceptable buffer for bromine in the water system. |
| 32 | Develop and test buffer-introduction approaches for bromine biocide solutions and buffer resupply rate. |
| 33 | Conduct testing to evaluate long-term stability of buffer with bromine in xEMU and LSS systems. |
| 34 | Identify Br-removal media for OGA protection and complete design modifications to replace I2 media in OGA IEB. |
| 35 | Develop and test OBr-monitor/sensor. |
| 36 | Adapt existing pH monitor technology or develop new pH monitor technology for space. |
| 37 | Conduct testing to inform bromine and pH monitor/sensor ConOps for dormancy (determine whether sensors remain in place, require removal and/or replacement, etc.). |
| 38 | Develop secondary dosing method if architecture requires active control of bromine or buffer concentration and the primary dosing method is passive. |
| 39 | Conduct testing and redesign of biocide passive release Br-dosing system for passive release applications and Br-based MCV. |
| 40 | Conduct reliability testing of bromine biocide technology: long-term operation. |
| 41 | Conduct testing to evaluate impacts of OBr- only and OBr- with buffer on xEMU thermal loop and components. |

| | |
|---|---|
| 42 | Conduct testing of Br and pH monitors/sensors to inform ConOps: required frequency of calibration and required tools and consumables. |
| 43 | Conduct testing to evaluate bromine and buffer depletion rates (simultaneous and independent) in stagnant and flowing systems. |
| 44 | Conduct reliability testing of silver biocide technology for dormancy impacts. |
| 45 | Conduct testing of OBr- uptake in LCVG tubing (ethylene vinyl acetate) and determine effect on material life. |
| 46 | Conduct testing to evaluate biproducts/counterions produced from hydantoin bromine biocide. |
| 47 | Complete testing of OBr- to evaluate material compatibility and long-term functional compatibility with SWME polypropylene membrane. |
| 48 | Develop a bromine hydantoin dosing system. |
| 49 | Conduct testing to evaluate shelf-life of bromine biocides and buffer. |
| 50 | Conduct kinetic and breakthrough testing of Ag capture media (to inform confidence in media). |
| 51 | Conduct testing to evaluate effect of Ag + I2 mixing at various concentrations to determine worst-case scenario for media failure and biocide mixing. |
| 52 | Conduct kinetic and breakthrough testing of Br capture media (to inform confidence in media). |
| 53 | Conduct testing to evaluate effect of Br/OBr- + I2 mixing at various concentrations to determine worst-case scenario for media failure and biocide mixing. |
| 54 | Conduct testing to collect Ag absorption/desorption data to predict filter lifetime/replacement schedule. |
| 55 | Conduct testing to collect Br/OBr- absorption/desorption data to predict filter lifetime/replacement schedule. |
| 56 | Develop SWEG from bromine biocide. |

# *Table G-5. Development Activities Mapped to Specific Architectures*

| | Architecture Option | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Total Options | Top 10 Options |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Activity # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | Impacted | Impacted |
| 1 | X | X | | | | | | | | | | | | | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 18 | 10 |
| 2 | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 |
| 3 | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 |
| 4 | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 |
| 5 | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 |
| 6 | X | X | | | | | | | | | | | | | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 18 | 10 |
| 7 | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | 3 | 2 |
| 8 | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | 2 | 1 |
| 9 | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | 2 | 1 |
| 10 | | | X | X | X | X | X | X | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 12 | 9 |
| 11 | | | | X | | X | | X | | | | | | | | | | | X | | X | | X | | | | | | | | | | | 6 | 3 |
| 12 | | | X | X | X | X | X | X | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 12 | 9 |
| 13 | | | | X | | X | | X | | | | | | | | | | | X | | X | | X | | | | | | | | | | | 6 | 3 |
| 14 | | | | | | X | | | | | | | | | | | | | | | X | | | | | | | | | | | | | 2 | 0 |
| 15 | | | | | | | X | X | | | | | | | | | | | | | | X | X | | | | | | | | | | | 4 | 3 |
| 16 | | | X | X | | | | | | | | | | | | | | X | X | | | | | | | | | | | | | | | 4 | 4 |
| 17 | | | X | X | X | X | X | X | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 12 | 9 |
| 18 | | | X | X | | | X | X | | | | | | | | | | X | X | | | X | X | | | | | | | | | | | 8 | 7 |
| 19 | | | X | X | X | X | X | X | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 12 | 9 |
| 20 | | | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | 6 | 5 |
| 21 | | | | X | | X | | X | | | | | | | | | | | X | | X | | X | | | | | | | | | | | 6 | 3 |
| 22 | | | X | X | X | X | X | X | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 12 | 9 |
| 23 | | | | | X | X | | | | | | | | | | | | | | X | X | | | | | | | | | | | | | 4 | 2 |
| 24 | | | | | | | X | X | | | | | | | | | | | | | | X | X | | | | | | | | | | | 4 | 3 |
| 25 | | | X | X | X | X | X | X | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 12 | 9 |
| 26 | | | X | X | X | X | X | X | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 12 | 9 |
| 27 | | | | | X | X | | | | | | | | | | | | | | X | X | | | | | | | | | | | | | 4 | 2 |
| 28 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| 29 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | 9 | 2 |
| 30 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| 31 | | | | | | | | | | X | X | | X | X | | X | X | | | | | | | | X | X | | X | X | | X | X | | 12 | 3 |
| 32 | | | | | | | | | | X | X | | X | X | | X | X | | | | | | | | X | X | | X | X | | X | X | | 12 | 3 |
| 33 | | | | | | | | | | X | X | | X | X | | X | X | | | | | | | | X | X | | X | X | | X | X | | 12 | 3 |
| 34 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| 35 | | | | | | | | | | | X | | | X | | | X | | | | | | | | | X | | | X | | | X | | 6 | 0 |
| 36 | | | | | | | | | | | X | | | X | | | X | | | | | | | | | X | | | X | | | X | | 6 | 0 |
| 37 | | | | | | | | | | | X | | | X | | | X | | | | | | | | | X | | | X | | | X | | 6 | 0 |
| 38 | | | | | | | | | | | | | | X | | | X | | | | | | | | | | | | X | | | X | | 4 | 0 |
| 39 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| 40 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| 41 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | 9 | 2 |
| 42 | | | | | | | | | | | X | | | X | | | X | | | | | | | | | X | | | X | | | X | | 6 | 0 |
| 43 | | | | | | | | | | | X | | | X | | | X | | | | | | | | | X | | | X | | | X | | 6 | 0 |
| 44 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| 45 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | 9 | 2 |
| 46 | | | | | | | | | X | X | X | | | | | | | | | | | | | X | X | X | | | | | | | | 6 | 2 |
| 47 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | 9 | 2 |
| 48 | | | | | | | | | X | X | X | | | | | | | | | | | | | X | X | X | | | | | | | | 6 | 2 |
| 49 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| 50 | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 6 | 4 |
| 51 | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 6 | 4 |
| 52 | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | X | X | X | | 9 | 4 |
| 53 | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | X | X | X | | 9 | 4 |
| 54 | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | 6 | 4 |
| 55 | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | X | X | X | | 9 | 4 |
| 56 | | | | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | X | X | X | X | X | X | X | X | X | | 18 | 6 |
| # Activities Required to Close Gaps | 6 | 6 | 10 | 13 | 10 | 14 | 11 | 14 | 14 | 17 | 22 | 12 | 15 | 21 | 12 | 15 | 21 | 14 | 17 | 14 | 18 | 15 | 18 | 15 | 18 | 23 | 13 | 16 | 22 | 13 | 16 | 22 | 5 | | |

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|---|---|---|---|

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| **1. REPORT DATE** *(DD-MM-YYYY)* | **2. REPORT TYPE** | **3. DATES COVERED** *(From - To)* |
|---|---|---|
| 04/14/2021 | Technical Memorandum | |

| | |
|---|---|
| **4. TITLE AND SUBTITLE**<br>Assessment of Biocide Impacts on Life Support (LS) and Extravehicular Activity (EVA) Architectures | **5a. CONTRACT NUMBER** |
| | **5b. GRANT NUMBER** |
| | **5c. PROGRAM ELEMENT NUMBER** |
| **6. AUTHOR(S)**<br>Abney, Morgan B.; McCarley, Kevin S.; Delzeit, Lance D.; Montgomery, Eliza L.; Callahan, Micheal; Gazda, Daniel B.; Williams, Spencer; Feather, martin S.; Cornford, Steven L.; Steele, John W. | **5d. PROJECT NUMBER** |
| | **5e. TASK NUMBER** |
| | **5f. WORK UNIT NUMBER**<br>869021.01.23.01.01 |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**<br>NASA Langley Research Center<br>Hampton, VA 23681-2199 | **8. PERFORMING ORGANIZATION REPORT NUMBER**<br>NESC-RP-20-01518 |
| **9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**<br>National Aeronautics and Space Administration<br>Washington, DC 20546-0001 | **10. SPONSOR/MONITOR'S ACRONYM(S)**<br>NASA |
| | **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**<br>NASA/TM-20210013644 |

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified - Unlimited
Subject Category Space Transportation and Safety
Availability: NASA STI Program (757) 864-9658

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The Project Manager for the Human Exploration and Operations Mission Directorate's Advanced Exploration Systems Life Support Systems (LSS) project, requested a NASA Engineering and Safety Center (NESC) assessment to evaluate potable water system biocide options impacting Gateway, Human Lander Systems, Foundation Surface Habitat, and Exploration Command Module missions. The assessment focused on identifying feasible biocide options, evaluating the impacts of their implementation on crew health, extravehicular activity hardware, and LSS hardware, and conducting a trade on architecture options. This report contains the outcome of the NESC assessment.

**15. SUBJECT TERMS**
Extravehicular Activity; Life Support; NASA Engineering and Safety Center; International Space Station

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
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