# Early Results from a Broad Compatibility Study of Various Materials with Ionic Silver Biocide

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**Ionic silver is baselined for microbial control in spacecraft potable water systems for future exploration missions, but materials compatibility analysis is required to evaluate the passive depletion of ionic silver concentration onto wetted material surfaces over time. Various articles concerning such testing have been published that examine interactions with water containing ionic silver biocide, but most tests have focused on only a couple of materials each and comparing results of different evaluations to one another has proved challenging. This paper reports the first results from static exposure testing of a large array of material coupons to a 400 parts per billion (ppb) aqueous silver fluoride (AgF) solution, using a surface to volume ratio of approximately 2 $cm^{-1}$. The test is designed in two main stages. Stage 1 is a one-week screening to evaluate silver uptake. Materials that perform modestly to well after that week are promoted to Stage 2, which is a longer test with periodic sampling to examine the silver uptake rates over time; these samples are evaluated for other water quality parameters in addition to the remaining silver concentration. In a tangential investigation, select materials that take up some silver in Stage 1 may be "aged" by repeating the Stage 1 test to determine whether repeated exposure reduces silver uptake rate, and successfully aged materials may then continue to Stage 2 testing. The materials under test include metallic and polymeric materials with various surface finishes, treatments, and coatings, as well as select other materials historically used in spacecraft water systems. This test began in August 2019, and thus only includes early results; future follow-on papers will include additional results as the test progresses. The ultimate goal builds a broad, easily comparable data set that can be used to guide material selections for silver biocide-compatible spacecraft water system design.**

## Nomenclature

| | | |
|---|---|---|
| *3D* | = | *three-dimensional* |
| *Ag* | = | silver |
| $Ag^+$ | = | silver ion |
| *AgF* | = | silver fluoride |
| *DI* | = | deionized water |
| ˚*C* | = | degrees Celsius, a unit of temperature |
| *cm* | = | centimeters, a unit of length |
| ˚*F* | = | degrees Fahrenheit, a unit of temperature |

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| | | |
|---|---|---|
| *FDA* | = | *(United States) Food and Drug Administration* |
| *ICP-MS* | = | inductively coupled plasma - mass spectrometry |
| *CWC-I* | = | Contingency Water Container – Iodine-compatible |
| *IPA* | = | *isopropyl alcohol* |
| *ISS* | = | International Space Station |
| *JSC* | = | Johnson Space Center |
| *LCVG* | = | Liquid Cooling and Ventilation Garment |
| *NASA* | = | *(United States) National Aeronautics and Space Administration* |
| *NSF* | = | (United States) National Science Foundation |
| *PEEK* | = | polyether ether ketone |
| *PEI* | = | polyetherimide |
| *PETG* | = | polyethylene terephthalate glycol |
| *PLSS* | = | *Portable Life Support System* |
| *ppb* | = | parts per billion, a unit of concentration |
| *ppm* | = | parts per million, a unit of concentration |
| *PTFE* | = | polytetrafluoroethylene |
| *SWEGs* | = | Spacecraft Water Exposure Guidelines |
| *SWME* | = | Spacesuit Water Membrane Evaporator |
| *S/V* | = | surface area to liquid volume ratio |
| *TBD* | = | *to be determined* |
| *TOC* | = | total organic carbon |
| *USDA* | = | *United States Department of Agriculture* |

## I. Introduction

The NASA Johnson Space Center silver biocide team is performing a materials compatibility test to evaluate the rate of silver (Ag) uptake on diverse substrates to be considered for use in future spacecraft water systems. Several legacy materials used in spacecraft potable water systems over the years, such as commercially pure titanium, Ti-6Al-4V, 316L stainless steel, and Inconel 718, have been tested with silver biocide, and most, if not all, of them have surface reactions with the silver biocide that result in loss of the ion from solution. Tests of various surface treatments have also been performed. In general, the wide range of surface area to volume ratios (S/V) tested and the many differences in the conditions under which the test have been performed has made it difficult to make direct comparison of silver losses across these data sets. To facilitate silver biocide research and material implementation for future spacecraft water systems, the JSC silver biocide team is testing a modestly large variety of materials under a common set of test conditions with the goal to build an easily-comparable list of material candidates.

In order to conduct this comparative material testing, standard solutions of silver fluoride (AgF) in deionized (DI) water are being used to soak coupons of metal alloys, metal alloys with various surface treatments and coatings, ceramics, polymers, lubricants, and elastomers. Coupon testing is being conducted in two stages. In Stage 1, water samples from the coupon soak test are being analyzed after one week for a series of metals, including silver (Ag). Test coupons that show little to no Ag uptake in Stage 1, less than 50% loss of silver, will proceed to a Stage 2 evaluation. In Stage 2, metal analyses, including Ag, will be conducted for longer timeframes, simulating the periods of dormancy expected for long duration missions. The immediate goal of the material tests being conducted through the Stage1 and Stage 2 surveys will be used to collect silver loss rate data on candidate materials. If possible, the data will also be used to help understand the mechanisms, and/or fate, by which the silver was lost. Ultimately, the goal will be to use the silver compatibility data, along with other property data, to build a database of materials that can be considered for use in a wide range of spacecraft water system applications in order to meet future mission requirements. This paper presents initial results acquired to date from the Stage 1 silver loss testing. The data set will continue to be expanded as more results are collected from the Stage 1 and 2 material surveys. Results from the expanded surveys are planned to continue to be reported at this conference over the next few years.

## II. Test Methodology

### A. Test Strategy

The test survey is conducted in a reproducible format, in which all materials under test have a S/V of 2 $cm^{-1}$, samples are tested under the same conditions, and all analyses done in triplicate. The S/V ratio was chosen as a midpoint between the high S/V found in small pipes and partially filled bellows tanks, typically above 5 $cm^{-1}$, and the low the S/V typical found in full storage tanks, approximately 0.14 $cm^{-1}$.[1,2] Material candidates follow the testing structure illustrated in Figure 1. In Stage 1, coupons of each material are exposed to solutions of AgF at an initial concentration of approximately 400 ppb for one-week. Water samples are then removed and analyzed for metals, including silver, using a 7900 Series Agilent inductively coupled plasma-mass spectrometer (ICP-MS). Reduction of silver concentration to 50 ppb or less over the one week period will generally result in elimination of a material from further evaluation. A material that is observed to maintain the silver concentration from 50 and 200 ppb, less than half of the original amount, will be considered for repeat testing through the Stage 1 screening. Finally, candidate materials that maintain silver concentration at or above 200 ppb, 50% or more of the starting silver concentration, over the week will be moved on to the Stage 2 evaluation. For Stage 2, testing will be conducted for either five weeks or one full year, depending on the material performance observed in Stage 1. The specific sampling plans for the 5 week and 1 year tests will follow as described in Figure 1.

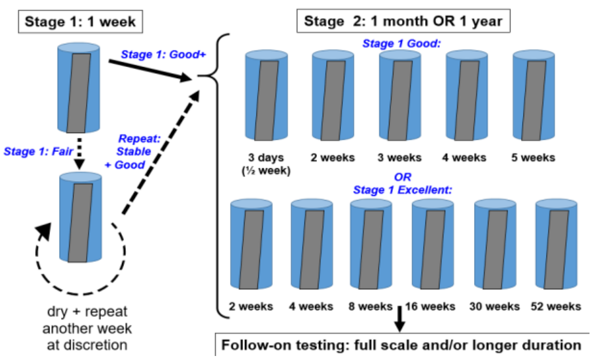


**Figure 1. Material Compatibility Survey Test Structure**

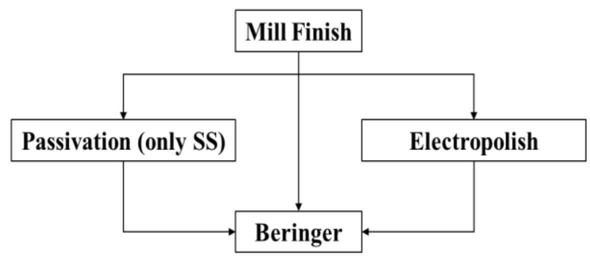


**Figure 2. Metal Processing Testing Tree**

To acquire a baseline analysis for the metal coupons in the Stage 1 screening test, the original mill-finish from the processed coupon will be used. In addition, for a few early samples the metal coupon will be scoured with 120-grit media to acquire a fresh unreacted surface for the raw base metal. Following the baseline tests, select metals will be reevaluated in Stage 1 after additional surface finishes and/or treatments have been performed on the base material. For some materials, especially the legacy spacecraft metals, these surface treatments and coatings will be tested regardless of how they performed in the initial mill-finished Stage 1 test. Figure 2 shows a parametric tree representing the various options and combinations for some of the additional early baseline treatments being considered. Beyond the mill-finish, these treatments include passivation, for stainless steel alloys, electropolishing, and/or a patented high temperature oxidation process developed by one of this paper's authors and referred to herein as the Beringer process after the patent's first author.[5] Ultimately, which materials will be selected to undergo alternative surface treatments as part of the continued Stage 1 testing will made based on the results of the initial tests and per the discretion of the test team. Overall, the various materials being considered for evaluation at the writing of this paper, including both metallic, non-metallic, surface treatments and coatings, are described in **Appendix Tables A1-A4**.

### B. Test Articles

In general, the compatibility study is being performed on rectangular coupons, either fabricated to size or cut from larger sheets. Selected dimensions for the coupons are 1.35 x 1.35 x 0.0625 inches and include a 3/16-inch diameter hole in the middle for mounting onto a test fixture. The test fixture allows two coupons to be stacked in order to achieve the selected 2 $cm^{-1}$ S/V ratio. The fixture consists of a screw on which the coupons can be mounted using washers to separate the coupons, and a nut to hold the test article assembly in place. A few materials and cleaning procedures were considered for the fixture resulting in the selection of polypropylene cleaned per the process described below. The test article stack is then placed into a 120 mL polypropylene container (Qorpak®). The full test article assembly, coupons, test fixture, and container, is illustrated in Figure 3. When possible the preferred method for cutting the coupons to the proper dimensions was performed by water jet. Laser cutting was also explored, but is not the preferred method as the creation of heat-affected zones on the coupon edges has the potential to affect the property and/or behavior of the base material.[3] The soft polymer coupons were cut with a band saw and drill. Whereas peristaltic pump tubing, which is not generally available in sheet form, was cut into short lengths and then in half lengthwise to match the target surface area. Miscellaneous materials, such as lubricants and epoxies, will be tested by applying a thin layer of the material on to a polymeric substrate. Selection of substrates for these test will be based on polymer materials in the Stage 1 tests shown to have minimal silver uptake.

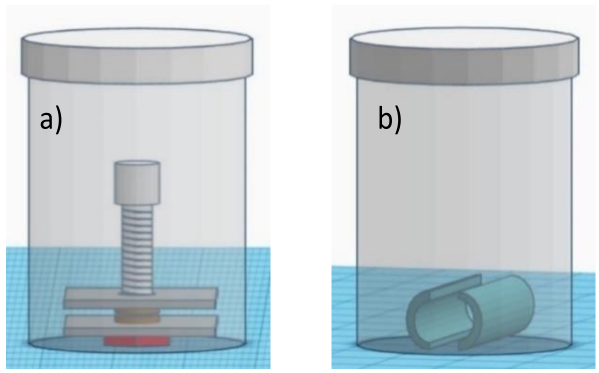


**Figure 3. Typical Stage 1 Test Configuration for evaluating a) coupons and b) polymeric tubing.**

### C. Material Processing, Cleaning and Test Preparation

To scour the metal coupons, 120-grit sanding media was used. Prior to performing tests, the sample coupons, containers, and support hardware were cleaned. Initial procedures used isopropyl alcohol (IPA) and HFE-7100 Engineered Fluid (Novec®) solvents as the cleaning agents for general surface contaminants that may exist on the coupons. Following cleaning, the samples were rinsed in DI water. IPA was selected because it does not contain oxidizing agents that can affect the surface chemistry of the materials. The cleaning agent was therefore considered compatible with metallic, non-halogenated organic, and 3D-printed materials. Novec®, having a fluorinated chemistry, was used for Tygon® and halogenated organic materials. The method selected for cleaning the test fixture hardware was rinsing in 18% nitric acid followed by a DI water rinse. During the cleaning procedures, materials were handled with acetal (Delrin®) forceps, and rinsed samples, containers, and hardware were then stored in an ambient environment for drying overnight. For test prepping purposes, polypropylene was selected as the container material used for solution preparation and transfer due to past observations of stability when silver biocide solution was stored in it.[4] For the Stage 1 tests conducted to date, 24 mL of a 400 ppb AgF stock solution, or 27 mL for tubing samples, was poured into the container using special care to minimize the formation of air bubbles between coupons and surfaces. This was done to ensure the silver solution was in contact with most, if not all, of the coupon's surface area. The sample containers were capped and stored in the dark at ambient temperature and pressure for 1 week. Subsequently, the sample containers were removed and the test fluid decanted to the appropriate sample containers for ICPMS analysis. Stage 2 tests will use more water to allow for additional multiple sample points along with more coupons in the stack to maintain the target S/V ratio.

## III. Silver Loss Results

### A. Test Fixture Development

Preliminary test results using polypropylene screw test fixtures that had been cleaned with 99.5% purity IPA or Novec® alone resulted in variable baseline silver uptake (data not shown). Such variability was determined unacceptable, as it would add uncertainty in attributing silver loss to interactions with the coupon alone. Therefore, baseline test fixture configuration and cleaning verification tests were performed. Three different materials were tested as potential coupon support hardware. Tests were done with both screw bolt and smooth rod parts along with a pair of washers. The screw and rod form factors were selected to ascertain if the variability observed may have been related to the increased surface area and/or contamination on the screw thread pattern resulting from manufacturing. The test fixture materials included: polypropylene, polyether ether ketone (PEEK), and polytetrafluoroethylene (PTFE, Teflon®). In addition, several cleaning methods were also tested, including: (1) either IPA or Novec® (depending on the material), (2) an18% nitric acid solution wash, or (3) IPA or Novec® followed by an 18% nitric acid solution wash. All cleaning options were then followed by a DI water rinse. The addition of nitric acid was included because the source of any potential contamination was unknown and while IPA and Novec can help remove organic contaminants, nitric acid can help remove any potential contamination due to inorganic material.

The silver metal ICP-MS data from these tests is shown in Figure 4. The normalized baseline measurements were evaluated with respect to control Qorpak® containers that had no test fixture materials within them but were otherwise cleaned and filled in the same way. Screw and rod tests were conducted with different stock solutions, hence the different initial AgF stock concentrations shown for the two plots. After a 1-week AgF soak, results showed less than 7% silver loss for all material and cleaning variants. Based on these results, the team selected polypropylene screw bolts rinsed with 18% nitric acid, followed by a DI rinse. The selection of polypropylene for the standard test fixture hardware was driven by the good performance with silver and the lower cost relative to the other candidate materials.

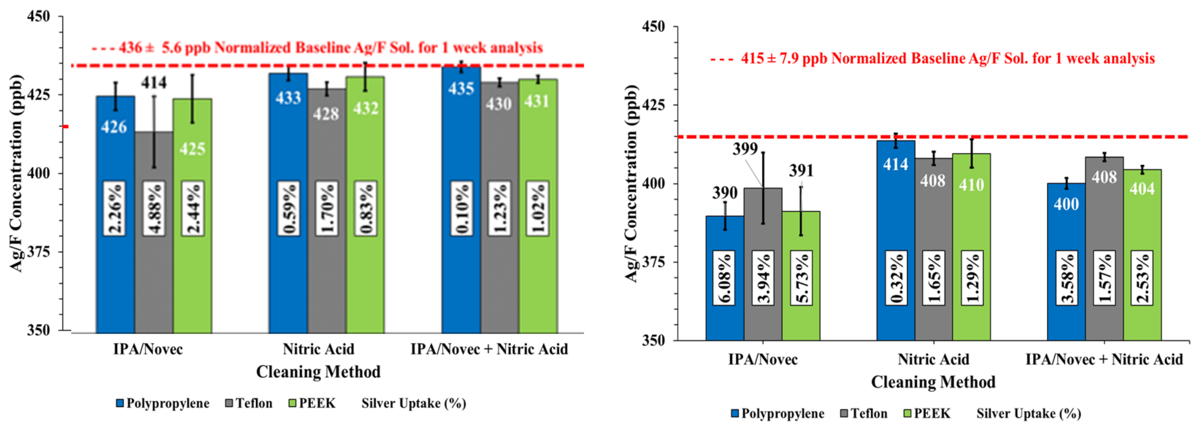


**Figure 4. Test Fixture Configuration and Cleaning Test Results for Screws (Left) and Smooth Rods (Right)**

## B. Metallic and Polymeric Coupons

Stage 1 tests were performed on mill-finish legacy spacecraft potable water system metallic materials (titanium grade 2, titanium grade 5, Inconel 718, and 316L stainless steel), as well as, several additional metal alloys (aluminum series 6061 and 7075). As discussed above, some materials were also scoured with 120 grit media before testing. These preliminary metal results are cataloged in Table 1. The major observation from these tests were that all the tested metal materials had near 100% silver loss within the 1-week period.

Table 2 lists the Stage 1 results from the polymeric materials tested to date. For this material segment, most of the polymers performed well over the 1 week test period. Only two polymers exhibited significant silver losses, EPDM and Viton®. Because Viton is used in spacecraft water systems, this result bears repeating, as grades of Viton and/or manufacturing and cleaning processes could have an impact on silver loss rates. Amongst the 3D-printed coupons, Ultem 9085 demonstrated the least amount of silver uptake, with only 9.70% loss. To the authors' knowledge, this result has not been reported in literature before and could be important as Ultem 9085 is a flight approved 3D-print material. Upon evaluation of the bulk material, regular Ultem had similar results to its 3D-printed counterpart, exhibiting about 11.8% silver uptake. The polymer material with the lowest silver loss was Acrylic (PMMA), with approximately -0.25% loss. Similarly, a number of other polymer materials had silver losses within the accepted measurement error of the ICP-MS, ± 10%. Materials meeting this criteria are considered to be suitable as a potential control material for use in future testing.

**Table 1:** 1-week silver uptake analysis for metallic material coupons with S/V ratio of 2 $cm^{-1}$

| Material | Surface Finish | Original Ag Concentration (ppb) | Ave. (n=3) Remaining [Ag] (ppb) | StDev of Remaining [Ag] (ppb) | Ave. (n=3) Ag Uptake (%) |
|---|---|---|---|---|---|
| Titanium Grade 2 (Commercially Pure) | mill finish | 430 | < 10 | N/A | > 97 |
| | 120-grit scoured | 414 | < 10 | N/A | > 97 |
| Titanium Grade 5 (Ti-6Al-4V) | mill finish | 430 | < 10 | N/A | > 97 |
| | 120-grit scoured | 414 | < 10 | N/A | > 97 |
| Inconel 718 | mill finish | 430 | < 10 | N/A | > 97 |
| | 120-grit scoured | 414 | < 10 | N/A | > 97 |
| Stainless Steel 316L | mill finish | 430 | < 10 | N/A | > 97 |
| | 120-grit scoured | 414 | < 10 | N/A | > 97 |
| Aluminum 6061 | mill finish | 398 | < 10 | N/A | > 97 |
| Aluminum 7075 | mill finish | 398 | < 10 | N/A | > 97 |

**Table 2**: 1-week silver uptake analysis for polymeric material coupons with S/V ratio of 2 $cm^{-1}$

| Material | Surface Finish | Original Ag Concentration (ppb) | Ave. (n=3) Remaining [Ag] (ppb) | StDev of Remaining [Ag] (ppb) | Ave. (n=3) Ag Uptake (%) |
|---|---|---|---|---|---|
| Polylactic Acid (PLA) | 3D-Print Filament | 398 | 206 | 35.3 | 48.3 |
| Acrylonitrile Butadiene Styrene (ABS) | 3D-Print Filament | 398 | 291 | 18 | 26.9 |
| | Bulk Material | 430 | 285 | 11.5 | 33.8 |
| Polyethylene Terephthalate Glycol (PETG) | 3D-Print Filament | 398 | 338 | 20 | 15.0 |
| | Bulk Material | 430 | 361 | 31.0 | 16.1 |
| Polytetra-fluoroethylene (PTFE, Teflon™) | Bulk Material | 430 | 368 | 10.9 | 14.4 |
| Ethylene Propylene Diene Terpolymer (EPDM, Synthetic | Bulk Material | 430 | <10 | N/A | > 97 |
| Fluor elastomer (Viton™) | Bulk Material | 430 | <10 | N/A | > 97 |
| Polyetherimide (PEI, Ultem™) | Bulk Material | 430 | 379 | 3.8 | 11.8 |
| Low Density Polyethylene (LDPE) | Bulk Material | 476 | 397 | 3.8 | 16.7 |
| Polyethylene (PE) | Bulk Material | 476 | 411 | 8.9 | 13.8 |
| Cross-Linked Polyethylene (PEX) | Bulk Material | 476 | 399 | 9.9 | 16.2 |
| High Density Polyethylene (HDPE) | Bulk Material | 476 | 419 | 21 | 12.0 |
| Ultra-High Molecular Weight Polyethylene (UHMWPE) | Bulk Material | 476 | 405 | 43 | 15.1 |
| Polypropylene | Bulk Material | 476 | 463 | 8.1 | 2.90 |
| Polyvinylidene Fluoride (PVDF, Kynar®) | Bulk Material | 476 | 449 | 3.9 | 5.70 |
| Polyvinylchloride (PVC) | Bulk Material | 476 | 448 | 4.8 | 5.96 |

| Material | Surface Finish | Original Ag Concentration (ppb) | Ave. (n=3) Remaining [Ag] (ppb) | StDev of Remaining [Ag] (ppb) | Ave. (n=3) Ag Uptake (%) |
|---|---|---|---|---|---|
| Fluorinated Ethylene Propylene (FEP) | Bulk Material | 476 | 374 | 56 | 21.6 |
| Polyphenylene Oxide (PPO, Noryl®) | Bulk Material | 476 | 453 | 5.0 | 4.83 |
| Perfluoroelastomer (FFKM, Kalrez®, Chemraz®) | Bulk Material | 476 | 482 | 4.4 | -1.16 |
| Polycarbonate (PC, Lexan™) | Bulk Material | 476 | 397 | 3.7 | 16.7 |
| High-Impact Polystyrene (HIPS) | Bulk Material | 476 | 405 | 34 | 15.0 |
| Polyoxymethylene Acetal (Copolymer) | Bulk Material | 476 | 420 | 8.4 | 11.9 |
| Polyoxymethylene Delrin® (Homopolymer) | Bulk Material | 476 | 376 | 6.8 | 21.0 |
| Acrylonitrile Styrene Acrylate (ASA) | 3D-Print Filament | 476 | 362 | 13 | 23.9 |
| Ultem 9085 | 3D-Print Filament | 476 | 430 | 18 | 9.70 |
| Ethyl Vinyl Acetate (EVA) | Bulk Material | 445 | 358 | 51 | 19.5 |

Table 3 lists the Stage 1 results from the ceramic materials tested to date. Amongst the three materials evaluated, only samples of Magnesia Partially Stabilized Zirconia (MSZ) underperformed in comparison to the other candidate ceramic materials. As MSZ is currently used as a gear material in pumps currently used in specific water systems, the plan is to re-test this material to confirm these results. Otherwise, the other ceramic materials showed very promising Stage 1 results.

**Table 3:** 1-week silver uptake analysis for ceramic material coupons with S/V ratio of 2 $cm^{-1}$.

| Material | Surface Finish | Original Ag Concentration (ppb) | Ave. (n=3) Remaining [Ag] (ppb) | StDev of Remaining [Ag] (ppb) | Ave. (n=3) Ag Uptake (%) |
|---|---|---|---|---|---|
| 99.8% Alumina | Bulk Material | 445 | 441 | 11 | 0.98 |
| Magnesia Partially Stabilized Zirconia (MSZ) | Bulk Material | 445 | 114 | 17 | 74.5 |
| Synthetic Sapphire | Bulk Material | 445 | 443 | 11 | 0.36 |

### C. Peristaltic tubing ICP-MS and TOC analysis

A final polymeric material tested as part of the silver materials survey was peristaltic tubing materials with phthalate-free formulations and compliant to NSF standards.[6,7] Although these materials are not being considered for potential flight applications, testing was conducted to assess the use of these materials in components being used and/or considered for use in various silver biocide ground tests. For ground test applications, tube materials exhibiting minimal silver uptake are required. Similarly, tube materials that exhibit minimal leaching of total organic are desired, in order to (1) have test systems that best simulate the water expected to be generated in spacecraft water systems, and (2) to prevent the introduction of potential contaminates that might interfere with the biocide test results. Figure 5 (a) graphically compares the silver uptake results for the candidate tube materials, while Figure 5 (b) compares the total organic carbon (TOC) levels leached from the materials at the end the 1-week test. For the materials tested, Tygon Chemical® tubing, also known as Norprene® Chemical, resulted in only 2%

silver loss, the lowest reported to date in this evaluation. As such, this material has been advanced to Stage 2 testing. PharmaPure® tubing will also undergo Stage 2 tests due to both its reasonably low silver uptake and its low TOC leachables.

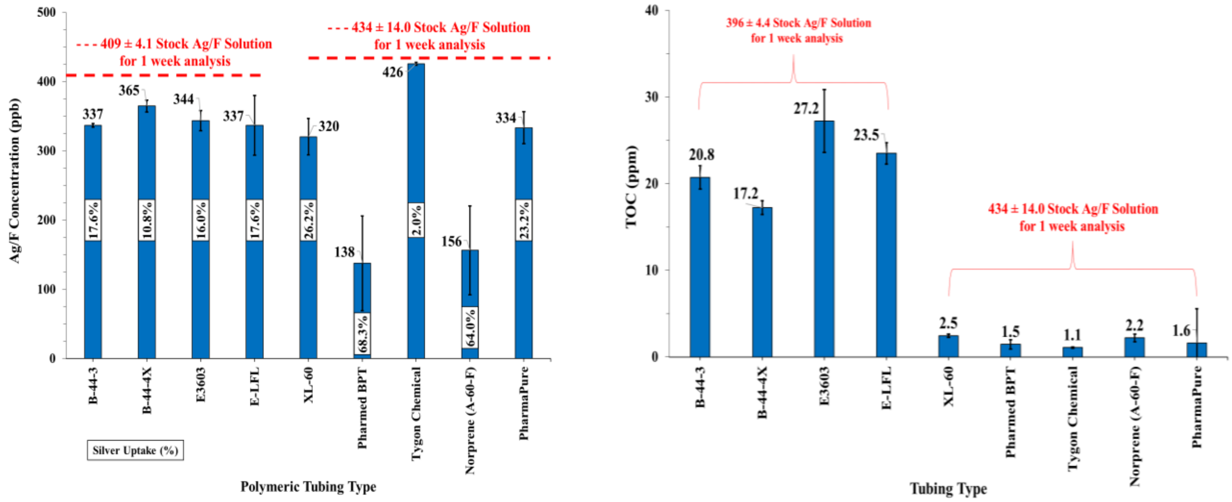


**Figure 5. Analysis for polymeric tubing materials, Silver Uptake Data (Left) and TOC Data (Right).**

## IV. Conclusions and Forward Work

The JSC silver biocide team has initiated a broad silver material compatibility study. The purpose of the study is to provide silver loss rate data for a wide variety of materials when exposed to approximate silver fluoride solutions of 400 ppb under controlled conditions, including standard surface area to volume ratios. Initial assessments included establishing a baseline analysis on the test containers and test support materials. This analysis has resulted in selecting polypropylene screws and washers to support the coupons, polypropylene containers and a standard cleaning method using 18% nitric acid wash with DI water rinse.

As expected, the first group of metallic coupons assessed in the study, whether mill finished or 120-grit scoured, demonstrated near 100% silver losses within a 1-week period. In future tests, various forms of surface passivation and/or coatings will be assessed. These treatments will be expected to result in at least some improved performance in the rates of silver loss. Also as expected, most of the polymeric materials exhibited significantly low silver uptake. Most of the polymeric coupons performed sufficiently well to move on to the Stage 2 assessment. In addition, there were a handful of materials that showed promise for being fully compatible with silver, e.g., FFKM, ETFE and PMMA. Only two of the polymer materials (EPDM and Viton) tested poorly and are planned to be retested. The Stage 2 assessment of the polymer materials will include trace metal analysis, as well as, measurements of TOC, pH, and conductivity. Although other material properties must be assessed in addition to the rate of silver loss, moving toward the use of more, and/or all, polymeric wetted materials of construction for future water systems is an avenue being actively pursued. Should a 3D-printed material be needed in applications where silver exposure might be expected, Ultem 9085 appears to be a highly promising candidate. Similarly, the use of other engineered polymers, such as PEEK, are of particular interest for their silver compatibility, lightweight and mechanical strength. Finally, for use in ground testing, the peristaltic tubing Tygon Chemical® displayed little silver loss, in the range of only 2%. This low loss rate even despite the multilayer construction of the tube and the exposure of those layers to the bulk solution resulting from the preparation of the coupons. Additional pump testing is underway to evaluate the silver uptake and TOC release characteristics under conditions of active flow. The PharmaPure® tubing is being similarly evaluated based on its advertised long service life and the vendor's recommendation for suitability in the ground test applications being proposed.

Stage 1 and 2 testing is currently ongoing, and additional results are expected to be reported next year as part of this same conference forum. Future test candidates include more metals with both alternative surface treatments, additional polymers, other common sensor materials, lubricants and epoxies. Ultimately, the goal will be to develop a database of candidate materials that can be selected from to meet the functional requirements of future spacecraft water systems, especially those that may employ silver-based biocide technologies.

## Appendix

The below tables list the materials currently under consideration for inclusion in this test.

### A.1 Metallic Material Testing List

| Material Description | Category | Rationale for Inclusion |
|---|---|---|
| Titanium Grade 2 (Commercially Pure) | Metal | Used in Orion and ISS potable water systems |
| Titanium Grade 5 (Ti-6Al-4V) | Metal Alloy | Used in Orion and ISS potable water systems and PLSS Thermal Control Loop wetted materials (Backplate) |
| Inconel 718 | Metal Alloy | Used in ISS potable water system and PLSS Thermal Control Loop wetted materials (Pump) |
| Inconel 625 | Metal Alloy | Used in ISS potable water system and PLSS Thermal Control Loop wetted materials (Backplate) |
| Incolloy® 020 (Carpenter® 20) | Metal Alloy | Compatible with Silver Bromide solution |
| Hastelloy C-276 | Metal Alloy | Used in ISS potable water system and PLSS Thermal Control Loop wetted materials (Pump) |
| Stainless Steel 304 | Metal Alloy | Used in Orion and ISS potable water systems |
| Stainless Steel 316L | Metal Alloy | Same as above |
| Stainless Steel 321 | Metal Alloy | Same as above |
| Stainless Steel 15-5 PH | Metal Alloy | Same as above |
| Stainless Steel 17-4 | Metal Alloy | Same as above |
| Stainless Steel 17-7 | Metal Alloy | Same as above |
| Stainless Steel 430 | Metal Alloy | Same as above |
| Stainless Steel A286 | Metal Alloy | Same as above |
| Steel 4142 (Chromoly) | Metal Alloy | Used in commercial sewage and water systems |
| Galvanized Steel | Metal Alloy | Alternate material for compatibility consideration |
| Monel 400 | Metal Alloy | Used in naval applications |
| Zinc 988 | Metal Alloy | Alternate material for compatibility consideration |
| Aluminum 6061 | Metal Alloy | PLSS Thermal Control Loop wetted materials |
| Aluminum 7075 | Metal Alloy | PLSS Thermal Control Loop wetted materials |
| Stellite 6B (Cobalt alloy) | Metal Alloy | PLSS Thermal Control Loop wetted materials (Pump) |
| Bronze | Metal Alloy | Used in household potable water systems |
| Brass 280 (Muntz Metal) | Metal Alloy | Used in structural naval applications due to its corrosion resistance |
| Jeweler's Brass (85% Cu, 15% Zn) | Metal Alloy | Used in commercial sewage and water systems |
| Copper | Metal | Used in commercial sewage and household water systems |
| 0.999 Fine Silver | Metal | Solid source of the biocidal ion |

### A.2 Polymeric Material Testing List

| Material Description | Category | Rationale for Inclusion |
|---|---|---|
| Polylactic Acid (PLA) | 3D Printer Filament | Alternate material for compatibility consideration, particularly in test fixtures |
| Acrylonitrile Butadiene Styrene (ABS) | 3D Printer Filament and Nonhalogenated Organic | Same as above |
| Polyethylene Terephthalate Glycol (PETG) | 3D Printer Filament and Nonhalogenated Organic | Same as above |
| Acrylonitrile Styrene Acrylate (ASA) | 3D Printer Filament | Same as above |
| Ultem 9085 | 3D Printer Filament | Flight approved 3D print filament with no prior silver biocide testing |

| Material Description | Category | Rationale for Inclusion |
|---|---|---|
| Tygon® B-44-3 | Halogenated Organic | Phthalate-free flexible tubing, used in food and beverage transfer applications. FDA compliant, and meets NSF 51 standard. |
| Tygon® B-44-4X | Halogenated Organic | Same as above |
| Tygon® E3603 | Halogenated Organic | Same as above |
| Tygon® E-LFL | Halogenated Organic | Same as above |
| Tygon® XL-60 | Halogenated Organic | Same as above |
| Masterflex Norprene (A-60-F) | Halogenated Organic | Same as above |
| Masterflex PharmaPure | Halogenated Organic | Same as above |
| PharMed BPT | Halogenated Organic | Same as above |
| Tygon® Chemical | Halogenated Organic | Same as above |
| Polytetra-fluoroethylene (PTFE, Teflon™) | Halogenated Organic | Considered generally inert and used in several experimental systems |
| Ethylene Chloro-trifluoroethylene (ECTFE, Halar®) | Halogenated Organic | USDA/FDA approved and NSF 61 compliant for potable tubing |
| Ethylene Tetrafluoro-ethylene (ETFE, Tefzel™) | Halogenated Organic | Same as above |
| F-ETFE | Halogenated Organic | Common sensor O-Ring material |
| Polyvinylidene Fluoride (PVDF, Kynar®) | Halogenated Organic | USDA/FDA approved and NSF 61 compliant for potable tubing |
| Perfluoralkoxy (Hyflon®, PFA) | Halogenated Organic | Alternate material for compatibility consideration |
| Fluorinated Ethylene Propylene (FEP) | Halogenated Organic | USDA/FDA approved and NSF 61 compliant for potable tubing, used as CWC-I bladder material |
| Polychloro-trifluoroethylene (PCTFE, Kel-F®) | Halogenated Organic | Remarkable chemical, radiation, and flammable resistance characteristics |
| Polyphenylene Sulfide (PPS, Ryton®) | Nonhalogenated Organic | Alternate material for compatibility consideration |
| Polyphenylsulfone (PPSU, Radel®) | Nonhalogenated Organic | Same as above |
| Polyphenylene Oxide (PPO modified, Noryl®) | Nonhalogenated Organic | Same as above |
| Polyethylene (PE) | Nonhalogenated Organic | Same as above |
| Low Density Polyethylene (LDPE) | Nonhalogenated Organic | Same as above |
| High Density Polyethylene (HDPE) | Nonhalogenated Organic | Used in ISS potable water systems |
| Ultra-High Molecular Weight Polyethylene (UHMWPE) | Nonhalogenated Organic | Alternate material for compatibility consideration |
| Cross-Linked Polyethylene (PEX) | Nonhalogenated Organic | Used in household potable water systems, flexible, and potentially stronger than traditional flexible tubing |
| Polyether Ether Ketone (PEEK) | Nonhalogenated Organic | Used in ISS potable water systems |
| Polypropylene (PP) | Nonhalogenated Organic | PLSS Thermal Control Loop wetted materials (SWME) and ISS potable water systems |
| Ethylene Vinyl Acetate (EVA) | Nonhalogenated Organic | PLSS Thermal Control Loop wetted materials (LCVG) |
| Polycarbonate (PC, Lexan™) | Nonhalogenated Organic | Used in ISS potable Water Systems |
| Thermoplastic Polyurethane (Texin® 985) | Nonhalogenated Organic | Material used in Pentair bladder tanks on ISS |
| Polymethyl-methacrylate (PMMA, Acrylic) | Nonhalogenated Organic | Alternate material for compatibility consideration |
| Polyoxymethylene Acetal (Copolymer) | Nonhalogenated Organic | Used in ISS potable water systems |
| Polyoxymethylene Delrin® (Homopolymer) | Nonhalogenated Organic | Used in ISS potable water systems |
| Grey Silicone Rubber | Nonhalogenated Organic | Alternate material for compatibility consideration |
| Polyvinyl Chloride (PVC) | Halogenated Organic | FDA certified for use in terrestrial potable water systems |
| High Impact Polystyrene (HIPS) | Nonhalogenated Organic | Alternate material for compatibility consideration |
| Nylon (Natural) | Nonhalogenated Organic | ISS potable water systems |

| Material Description | Category | Rationale for Inclusion |
|---|---|---|
| Ethylene Propylene Diene Terpolymer (EPDM, Synthetic Rubber) | Nonhalogenated Elastomer | Alternate material for compatibility consideration |
| Fluoroelastomer (FKM, Viton™) | Halogenated Elastomer | PLSS Thermal Control Loop wetted materials (LCVG) and O-ring seal material |
| Perfluoroelastomer (FFKM, Kalrez®, Chemraz®) | Halogenated Elastomer | Common O-ring seal material |
| Epoxylite® E234 Epoxy Impregnating Resin | Epoxy Resin | PLSS Thermal Control Loop wetted materials (Pump), apply to TBD substrate |
| Henkel EA 9313 Epoxy | Epoxy | PLSS Thermal Control Loop wetted materials (SWME), apply to TBD substrate |
| Bimodal Polyethylene Resin (Hypertherm – 2399 NT) | Resin | Alternate material for compatibility consideration, apply to TBD substrate. High oxidation resistance, advantages in chemical permeability, and NSF 61 compliant |
| Polyetherimide (PEI, Ultem™) | Nonhalogenated Organic | Alternate material for compatibility consideration based on Ultem 9085 (3D Print Filament acceptable for flight operations) |
| Vespel SP-1 | Nonhalogenated Organic | PLSS Thermal Control Loop wetted materials |
| Vespel SP-211 | Nonhalogenated Organic | Same as above |

### A.3 Alternate Material Testing List

| Material Description | Category | Rationale for Inclusion |
|---|---|---|
| Magnesia Partially Stabilized Zirconia (MSZ) | Ceramic | PLSS Thermal Control Loop wetted materials (Pump) |
| Synthetic Sapphire | Mineral | PLSS Thermal Control Loop wetted materials |
| 99.8% Alumina | Mineral | PLSS Thermal Control Loop wetted materials |

### A.4 Surface Treatments, Coatings, and Lubricants Testing List

| Material Description | Category | Rationale for Inclusion |
|---|---|---|
| Beringer et, al. | Surface Treatment | Oxidation and silver passivation process for metal alloys |
| Tiodize Type IV | Coating | Teflon-impregnated titanium coating to provide low friction and antigalling characteristics in tubing systems, apply to TBD titanium substrate |
| SilcoNert 2000 – EPS (Electropolished) | Coating | Used on stainless steel alloys to stop surface adsorption and reactivity with active chemical compounds, apply to TBD stainless steel substrate |
| Dursan® | Coating | Improve fouling and corrosion resistance of tubing products and meets NSF-51 standard, apply to TBD substrate |
| FEP | Coating | apply to TBD substrate |
| Teflon™ | Coating | Same as above |
| ETFE | Coating | Same as above |
| ECTFE | Coating | Same as above |
| Hyflon® PFA | Coating | Same as above |
| Kynar® | Coating | Same as above |
| Kel-F® | Coating | Same as above |
| PEEK | Coating | Same as above |
| Polyethylenes: PEX, PE, LDPE, HDPE, UHMWPE | Coating | Same as above |
| PP | Coating | Same as above |
| PPS | Coating | Same as above |
| Acrylic | Coating | Same as above |
| PC | Coating | Same as above |
| Silicone | Coating | Same as above |

| Material Description | Category | Rationale for Inclusion |
|---|---|---|
| Diamond-like Carbon Coating (Titankote™) | Coating | Carbon-based coating for metal alloys, apply to TBD substrate |
| Polymer Infused Composite Diamond Coating (Endura® Series 1000) | Coating | Carbon-based coating for metal alloys, apply to TBD substrate |
| Parylene | Coating | Alternate material recommended by Delzeit and Vance at NASA Ames Research Center, previously tested on 316L stainless steel |
| GoldShield® | Coating | Alternate material recommended by Venkateswaran at NASA Jet Propulsion Laboratory, previously tested in aluminum pipes for biofilm prevention |
| Polyamide 11 Rilsan® | Coating | Used in potable water piping systems and meets NSF-61 standard, apply to TBD substrate |
| Braycote 601 EF | Lubricant | PLSS Thermal Control Loop wetted materials, apply to TBD substrate |
| Krytox™ | Lubricant | ISS Potable Water Systems, apply to TBD substrate |
| DEFT® 44 GN-7 Water Reducible Epoxy | Primer | Alternate material for compatibility consideration |

## Acknowledgments

The authors would like to thank the Advanced Exploration Systems Life Support Systems Project for their support of this research. Chemical analysis by Leopoldo Romero, Stacey Moller, and Chris Carrier is invaluable. JSC teammates Phillip Hicks, Dean Muirhead, and Otto Estrada, and interns Ryan Ogilvie and Natalia Agosto-Berrios have also contributed extensively to the planning and execution of this research.

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