NASA Technical Memorandum 108499

# Interim Report on the Space Station Water Degradation Study Covering the First 24 Months of Exposure

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| $\mu$mho/cm | micromho per centimeter |
| AMS | American Metals Society |
| CFU | colony forming units |
| CRES | corrosion resistant |
| mg/L | milligrams per liter |
| Mohm-cm | mega-ohm centimeter |
| MSFC | Marshall Space Flight Center |
| NASA | National Aeronautics and Space Administration |
| NTU | nephelometric turbidity units |
| pH | power of hydrogen |
| p/m | parts per million |
| R2A | designation for agar used in microbial analysis |
| sst | stainless steel |
| Ti | titanium |
| TIC | Total Inorganic Carbon |
| TOC | total organic carbon |
| WDS | water degradation study |
| WRM | water recovery and management |

TECHNICAL MEMORANDUM

# INTERIM REPORT ON THE SPACE STATION WATER DEGRADATION STUDY COVERING THE FIRST 24 MONTHS OF EXPOSURE

## I. INTRODUCTION

The water degradation study (WDS) is a space station supporting development activity designed to demonstrate how water quality changes during long-term, stagnant storage in distribution lines. This interim report covers the first 24 months of WDS activities.

### A. Background

The need for the WDS originally stemmed from the 1991 space station restructure baseline design which called for the water lines to be launched wet and to be undisturbed until the activation of the water recovery and management system approximately 3 years after launch. This “launch-wet-and-wait” scenario fueled concern over whether the biocidal iodine would break down during extended storage, leaving the distribution lines vulnerable to microbial growth, biofouling, and microbial-induced corrosion. These concerns prompted engineers and scientists at Marshall Space Flight Center (MSFC) and at Boeing to investigate the change in water quality under long-term storage conditions. Finding that no known body of data satisfactorily addressed the scenario presented by the 1991 restructure design, MSFC and Boeing developed the WDS as a means to determine how water quality would change under these conditions. The interest in the WDS test results continues because the current design, which resulted from the 1993 redesign activity, requires the water lines to be launched wet.

### B. Scope

The WDS is being conducted as an engineering demonstration activity. As a demonstration, the study emphasizes geometric and material similarity with space station water distribution lines. Because the test fixtures are relatively expensive, the budget for this activity has precluded the use of replication. Thus, although the WDS lends credibility to its results by allowing comparisons among tubes of similar material, initial water quality, or exposure time, it is not a statistical study.

### C. Purpose

The purpose of the WDS is to to determine whether water can be stored for a period of 3 years without jeopardizing system integrity or crew health.

### D. Location

The WDS is being conducted at NASA MSFC in Huntsville, AL, in the north high-bay area of building 4755.

## E. Participation

The WDS investigators include P. McRight of the MSFC Propulsion Laboratory, M. Roman of the MSFC Structures and Dynamics Laboratory, and G. Shaw of Boeing. The test has been conducted by D. Long of the MSFC Systems Analysis and Integration Laboratory. Chemical and microbial analyses have been performed by Boeing Analytical Laboratory personnel. During the first 18 months of the WDS, biofilm analyses were performed by the staff of the MSFC Materials and Processes Laboratory's Microbial Ecology Laboratory. Since the closure of the Microbial Ecology Laboratory, biofilm analyses have been performed by the staff of the Boeing Analytical Laboratory.

## F. Schedule

The WDS began in January 1993 and will be completed in January 1998. Figure 1 presents the detailed schedule (in calendar years).

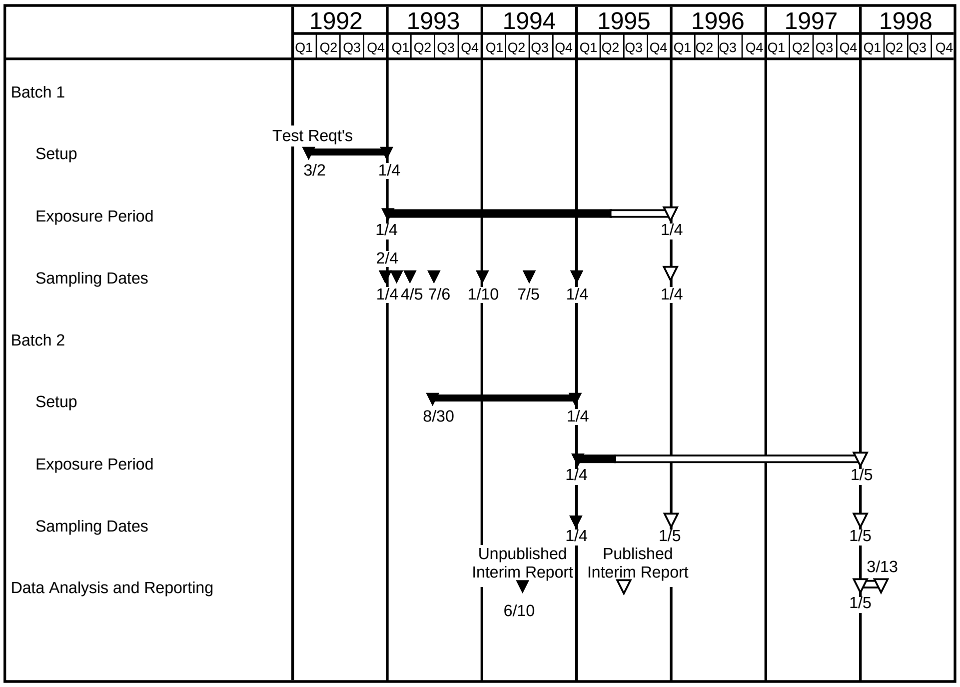

Figure 1. WDS schedule.

## II. MATERIALS AND METHODS

To assess the change in water quality during long-term storage, the WDS has sought to demonstrate the effects of time, tube material, and initial iodine concentration on water quality. The WDS includes time as a parameter for two reasons: (1) to provide intermediate data points within the 3-year exposure period and (2) to gain insight into the rate at which water quality changes take place. Tube material was also included as a parameter because the space station baseline has at various times called for both titanium and stainless steel as the material of construction for the water recovery and management system. At the time the WDS test plans were in preparation, the baseline design called for stainless steel, but a decision to change the material to titanium was pending. By varying the material of construction, the WDS has sought to identify any significant differences in water quality changes stemming from material effects. In addition, the WDS has varied the initial iodine concentration to determine the effectiveness of different concentrations of iodine in the distribution lines before launch. The WDS is being conducted at the ambient temperature of the high-bay area.

## A. Description of the Hardware

The WDS consists of a total of 34 tubes that are configured as straight sections, 10-ft long, with valves at each end as illustrated in figure 2. These tubes are grouped into two batches, designated batch 1 and batch 2. Within each batch, the tubes are grouped into sets according to exposure time. All tubes are stored vertically in a rack until their exposure time is completed. Figure 3 shows this storage rack during November, 1994, after the first 20 tubes (i.e., sets 1 through 5 in batch 1) had been removed for analysis. The tubes at the right are the tubes from batch 2 that, at the time the photograph was taken, had been cleaned but not yet filled with water.

1. Batch 1. The original batch of tubes (batch 1) used in the WDS contained seven sets of four tubes each. As shown in table 1, each set of four tubes includes two tubes made of SAE AMS 4942C titanium (equivalent to ASTM B338 grade 2 tubing) and two tubes made of CRES 316L stainless steel.

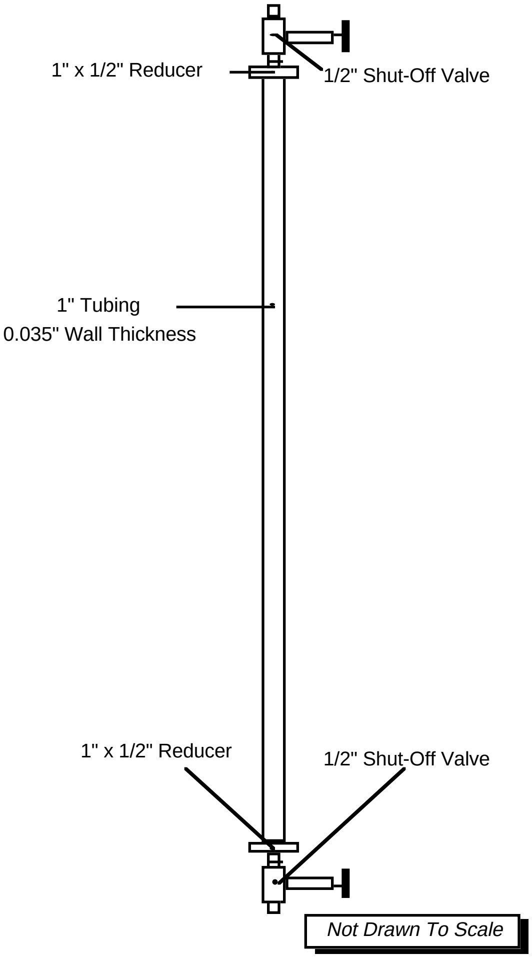

Figure 2. Tube configuration.

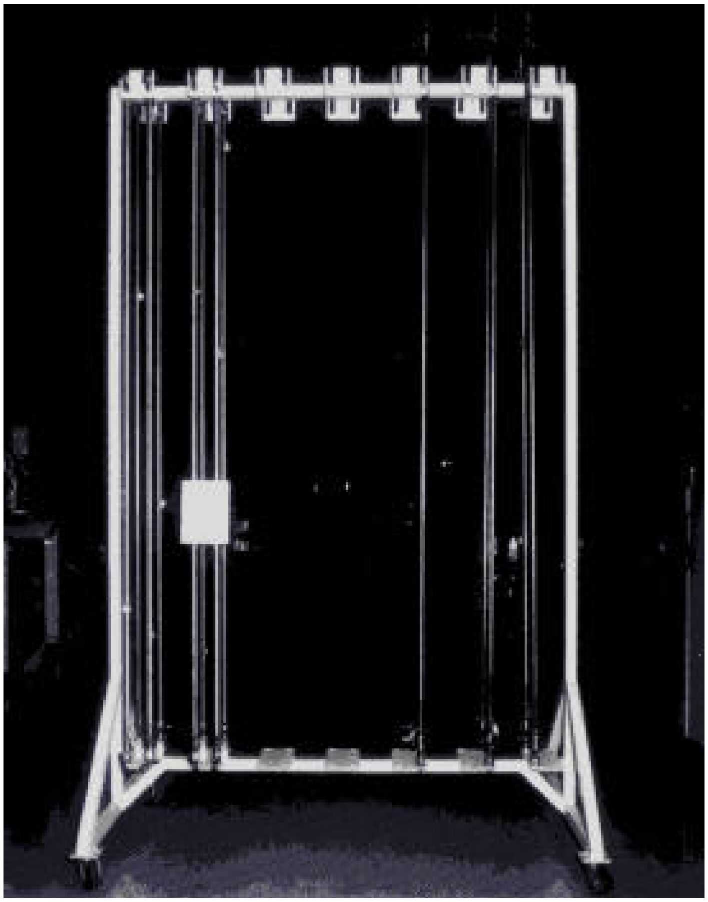

Figure 3. Photograph of tube storage rack (partially loaded).

Table 1. Tube designations within each tube set.

| | Batch 1 (Began January 1993) | | | | Batch 2 (Began January 1995) | | |
|---|---|---|---|---|---|---|---|
| Tube Designation | A | B | C | D | E | F | G |
| Tube Material* | CRES 316L | CRES 316L | Titanium | Titanium | Titanium | Titanium | Titanium |
| Valve Material* | CRES 316L | CRES 316L | CRES 316L | CRES 316L | Titanium | Titanium | Titanium |
| Initial Iodine ($I_2$) Concentration (p/m)† | 4 | 10 | 4 | 10 | 4 | 10 | 0 |

Notes:

* "Titanium" refers to SAE AMS 4942C grade 2 titanium alloy.

† Actual initial concentration of residual iodine in tubes A and C was 3.31 p/m. Actual initial concentration in tubes B and D was 9.75 p/m. Actual initial concentration in tubes E, F, and G not available.

Although the original WDS test requirements[1] called for the titanium tubes to have titanium valves, concerns over cost and lead time led the investigators to agree to substitute stainless steel valves. The decision to use stainless steel valves was based on two factors: (1) the prediction of minimal galvanic effects between stainless steel and titanium and (2) the apparent likelihood that the water recovery and management (WRM) subsystem would include both stainless steel and titanium components. As a result, both the stainless steel and titanium tubes in batch 1 have stainless steel union bonnet valves (Whitey model No. SS-12NRS8).

Within each set of four tubes, two tubes (one of each material) had an initial residual iodine concentration of 10 p/m, while the other two tubes had 4 p/m. As table 2 shows, each set of four tubes is exposed for a different duration, ranging from 1 to 36 months in various increments.

Table 2. Exposure times and tube quantities.

| Tube Set | Exposure Time, Months | Tube Quantities | |
|---|---|---|---|
| | | Batch 1 | Batch 2 |
| 1 | 1 | 4 | – |
| 2 | 3 | 4 | – |
| 3 | 6 | 4 | – |
| 4 | 12 | 4 | 3 |
| 5 | 18 | 4 | – |
| 6 | 24 | 4 | – |
| 7 | 36 | 4 | 3 |
| | TOTAL | 28 | 6 |

2. Batch 2. After observing that the dissolved nickel levels in batch 1 increased above space station specifications in both the stainless and titanium tubes, the WDS investigators concluded that either the stainless steel valve bodies or a lubricant in the valves was donating nickel to the water. Because all of the batch 1 test fixtures included these valves, the WDS investigators commissioned additional tests using titanium tubes with titanium valves which do not have a nickel-rich antiseize lubricant.[2] These all-titanium test fixtures constitute batch 2. These tubes were placed into service in January, 1995, 2 years after batch 1 exposure began.

Batch 2 consists of two tube sets, each of which contains three tubes. These tube sets are designated as set 4 and set 7, because the exposure times (12 and 36 months, respectively) are identical to sets 4 and 7 in batch 1 (table 2). The tubes in the batch 2 tube sets are designated as tubes E, F, and G and have nominal initial iodine concentrations of 4, 10, and 0 p/m, respectively, as shown in table 1.

## B. Description of the Water

The water used for the WDS was tap water processed through a mixed bed deionizer, an ultraviolet light sterilizer, a second mixed deionizer that served as a prefilter before entering the Nanopure II® laboratory water purification system, and a 0.2-micron filter. The Nanopure II® processed the water to a nominal resistivity of 18 Mohm-cm. The treated water was then used to fill the tubes and a sterilization cart that recirculated the water through the serially connected tubes at a minimum of 250 °F for 1 h. The water was iodinated after it reached room temperature. The initial chemical and microbiological parameters were analyzed and are shown in table 3. Finally, the tube valves were closed, and the exposure period began.

Table 3. Initial water quality parameters and specified limits.

| Parameter | Units | Specified Values |  |  | Initial Samples (Batch 1) |  |
|---|---|---|---|---|---|---|
|  |  | Nominal | Maximum | Minimum | Tubes A&C | Tubes B&D |
| pH |  | 7 | 6 | 8 | 8.2 | 7.5 |
| Conductivity | µmho/cm | 3.3 |  |  | 2.69 | 2.14 |
| Turbidity | NTU |  | 11 |  | 0.7 | 0.8 |
| Iodine, residual | p/m | 4, 10 |  |  | 3.31 | 9.75 |
| Iodide | p/m |  |  |  | 2.43 | 2.35 |
| Total Iodine | p/m |  |  |  | 5.74 | 12.1 |
| Chromium | mg/L |  | 0.05 |  | <0.010 | <0.005 |
| Iron | mg/L |  | 0.3 |  | <0.005 | <0.005 |
| Nickel | mg/L |  | 0.05 |  | <0.009 | 0.039 |
| Molybdenum | mg/L |  |  |  |  | <0.020 |
| Titanium | mg/L |  |  |  |  | <0.001 |
| TOC | mg/L |  | 1 |  | <1 | <1.0 |
| TIC | mg/L |  |  |  |  | <1.0 |
| Total Carbon | mg/L |  |  |  |  | <1.0 |
| R2A - 7 day | CFU/100mL |  | 1 |  | <1 | <1 |
| Total Solids | mg/L |  | 2 |  | <10 | <10 |
| Color | color units |  | 15 |  | <1 | <1 |
| Cadmium | mg/L |  | 0.01 |  | <0.001 | <0.001 |
| Copper | mg/L |  | 1 |  | <0.005 | <0.005 |
| Lead | mg/L |  | 0.05 |  | <0.010 | <0.010 |
| Manganese | mg/L |  | 0.05 |  | 0.002 | <0.001 |
| Silver | mg/L |  | 0.05 |  | <0.002 | <0.002 |
| Zinc | mg/L |  | 5 |  | 0.002 | <0.001 |
| Selenium | mg/L |  | 0.01 |  | <0.010 | <0.010 |

### C. Sampling and Analysis

As each set completes its planned exposure time, the tubes are removed from the tube storage rack and taken to the chemical laboratory inside building 4755. Water from the tubes is aseptically collected for chemical and microbial analysis, and drained tubing sections are taken to the microbiological laboratory for biofilm assessment. The chemical and microbial analyses are conducted using the same methods employed for the space station water recovery test. These methods are extensively documented.[3]

## III. RESULTS AND DISCUSSION

At the time of this writing, six of the seven sets of tubes from batch 1 have been analyzed, representing 1, 3, 6, 12, 18, and 24 months of exposure. Since batch 2 exposure began only recently, no batch 2 data are available at the time of this writing. As can be seen in figures 4 through 12 and in the raw data included in the appendix, significant water quality changes have occurred, with the most significant changes occurring in the concentrations of iodine, iodide, and total organic carbon (TOC).

When reading the graphs in this section, the reader should note that any values falling below the detection limits are plotted as zero values. For a more precise presentation of the data, the reader may consult the appendix.

## A. Microbial Analysis

Despite the observed decline in biocide (residual iodine) concentrations, the microbial population has been effectively controlled for 24 months. Results of plate counts on R2A media incubated for 7 days at 28 °C, were reported as <1 colony forming unit per 100 mL (CFU/100mL) in 24 of the 28 tubes assayed for bacteria. As shown in Table 4, the microorganisms isolated in the water from the remaining 4 tubes were diverse and were present in very small populations under differing test conditions.

Table 4. Microorganisms Isolated in water samples.

| **Tube Designation** | **Exposure Time (Months)** | **Microorganism** | **Population* (CFU/100mL)** |
|---|---|---|---|
| A | 1 | *Methylobacterium* species | 32 |
| C | 24 | *Sphingomonas paucimobilis* | 1 |
| | | Unidentified Gram-negative rod[†] | 1 |
| D | 6 | Unidentified Gram-negative rod[†] | 1 |
| D | 24 | *Moraxella osloensis* | 1 |

* Results of plate counts on R2A media incubated for 7 days at 28 ˚C.

[†] The same unidentified Gram-negative rod was isolated in tube C at 24 months and in tube D at 6 months.

The bacteria identified during the WDS are not considered pathogenic and could be removed if treated in the space station’s water system. These bacteria, with the exception of the ones reported as unidentified Gram-negative rods, are not related even though the source of the water used to fill the lines was the same. The low concentration, infrequent isolation, and diversity of the microorganisms recovered from the WDS, suggest that the bacteria might have been introduced to the water during sampling and/or processing.

## B. Biofilm Analysis

Biofilm assessments of the tubes, conducted by the staff of the MSFC Materials and Processes Laboratory, concluded that no biofilm growth occurred in the first 18 months of the test. Biofilm testing of the 24-month samples was performed by Boeing Analytical Laboratory personnel. Although no bacteria was isolated on the surface of three of the four tubes analyzed, two bacterial colonies (2 CFU/25 cm$^{2}$) were isolated on the surface of tube C. One of the bacteria was identified as *Sphingomonas paucimobilis* and the other was a Gram-negative rod that the laboratory was not able to identify. The unidentified bacteria is similar to the one previously isolated from the water of tube D (1 CFU/100 mL; 6-month sample). The relevance of this observation is not clear at this time. No physical indication of biofilm accumulation on the surfaces was found in tube C, although bacteria were isolated (at very low levels). The conditions of this test (i.e., the sterile tubes and the water with extremely low levels of TOC) effectively discouraged microbial growth and therefore biofilm.

### C. Total Organic Carbon

TOC, as illustrated in figure 4, has increased in all four tubes. TOC levels began below the detection limit and generally remained low during the first 3 months of exposure. After 1 month's exposure, TOC levels reached 1.15 and 1.19 mg/L in tube A and tube B (both stainless steel), exceeding the specified maximum of 1.0 mg/L. This increase is not readily explained, especially since all TOC values were reported under 1.0 mg/L in the 3-month samples. In the 6-month samples, all four tubes were at or above the specified upper limit. TOC levels in tubes B, C, and D have been slightly increasing during the test. The increase in TOC levels has been more significant in tube A. It appears that the TOC levels began increasing as residual iodine was depleted. Increases in TOC levels have not correlated with the few times bacteria have been detected in the water samples. Although the exact cause of the TOC increase is unclear, possible causes could include undetected microbial activity or leaching of a seal material or lubricant in the valves.

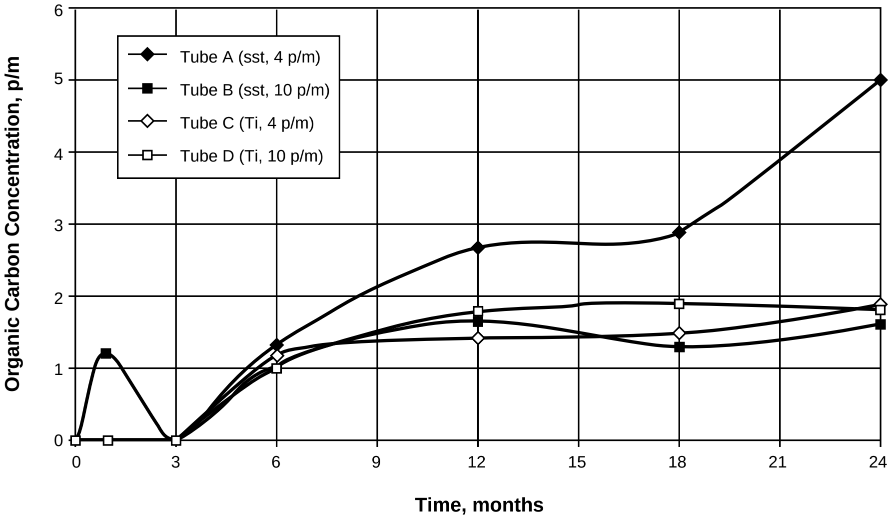

Figure 4. Graph of TOC concentration versus time.

### D. Iodine

Figure 5 illustrates the change in iodine and iodide concentrations versus time. In general, the WDS has demonstrated rapid depletion of iodine, similar to that observed by other investigators.[4] Iodine levels decreased significantly in all four tubes throughout the 24-month exposure period. Within the first month, the iodine level in tube C, a titanium tube, had fallen from its initial level of 3.31 p/m to less than 0.10 p/m. By the third month, the iodine level in tube A, a stainless tube, had fallen from 3.31 p/m to less than 0.10 p/m. By the sixth month, the iodine levels in all four tubes had fallen well below the specified minimum of 2 p/m. Extremely low levels of iodine were detected in some of the tubes at the 18-month sample, but its presence is not considered significant since the concentrations were near the detection limits. The titanium tubes with the initial iodine concentration of 9.75 p/m showed the greatest survival of iodine; however, even these levels fell below the specified minimum between the third and sixth month.

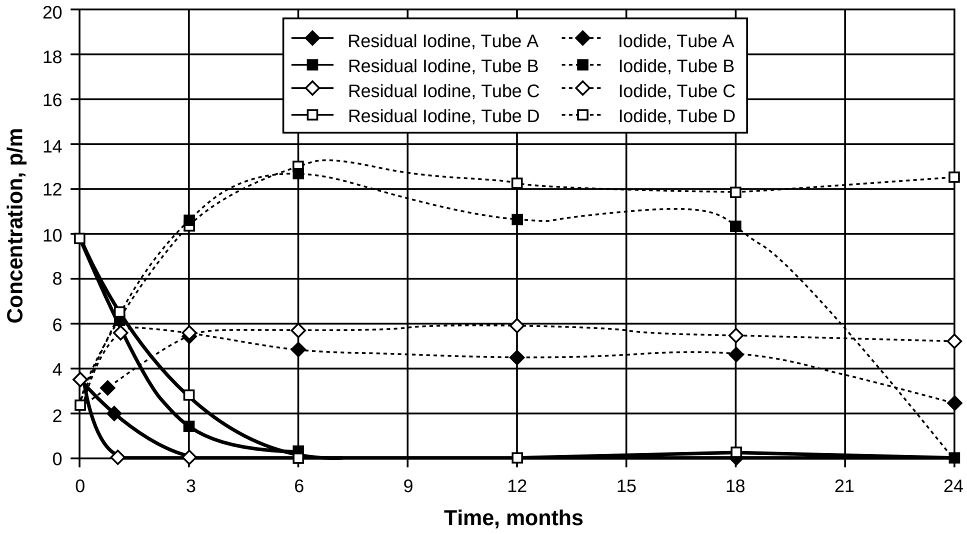

Figure 5. Graph of iodine and iodide concentration versus time.

## E. Iodide

As expected, in all cases the decline in residual iodine concentration was mirrored by a commensurate increase in iodide concentration. Figure 5 shows that iodide concentrations decayed over time. An unexplained drop in the iodide concentration was reported in the 24-month sample from tube B (from 10.4 to <1 mg/L). Although tube A also experienced a decrease in iodine concentration at 24 months, the decrease was much smaller. Hopefully, future samples will provide further insight into the significance of these decreases.

## F. Chloride

As can be seen in figure 6, chloride concentrations have varied from below the detection limit (0.04 p/m) to 0.17 p/m. These are considered to be extremely small concentrations, and the fluctuations are not considered significant, even though the scale of the graph causes them to appear so.

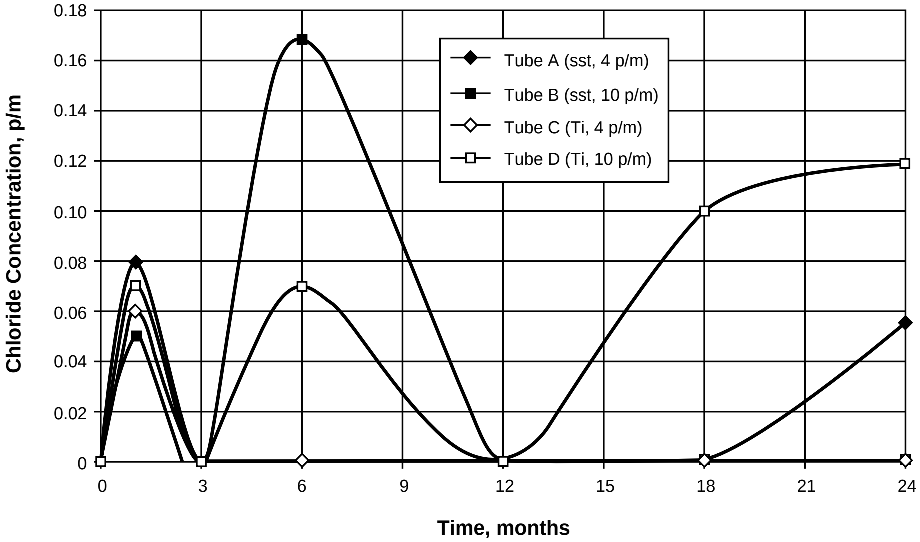

Figure 6. Graph of chloride concentration versus time.

## G. Nickel

Figure 7 shows the change in nickel concentration over time. In all tubes, the nickel levels exceeded the specified maximum limit (0.05 mg/L) within the first month. Although the source of the nickel has not been clearly identified, the stainless steel does not appear to be the primary source, since the nickel levels are not markedly different between the stainless steel and titanium tubes. The WDS investigators suspect that the valves may be donating nickel to the water since the valves were found to contain a nickel-rich antiseize lubricant.

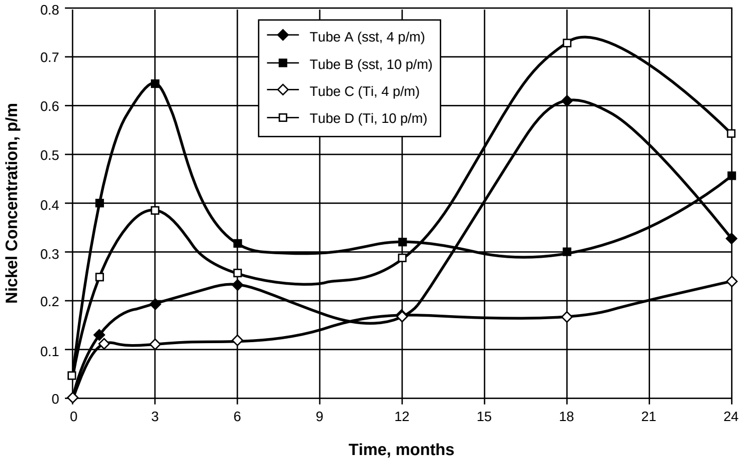

Figure 7. Graph of nickel concentration versus time.

## H. Iron

As shown in figure 8, iron ions have been detected in the water from the stainless steel tubes. Iron concentrations have generally increased in these tubes, ranging from trace levels to nearly 0.5 p/m, with the higher concentrations usually occurring in the tubes with the higher initial iodine concentration (tube B). The presence of iron is believed to indicate an interaction between the anions in the water and the stainless steel tubes and valves. The very small presence of iron in tubes C and D (the titanium tubes) suggests that the same interaction may be occurring with the stainless steel valves attached to these tubes.

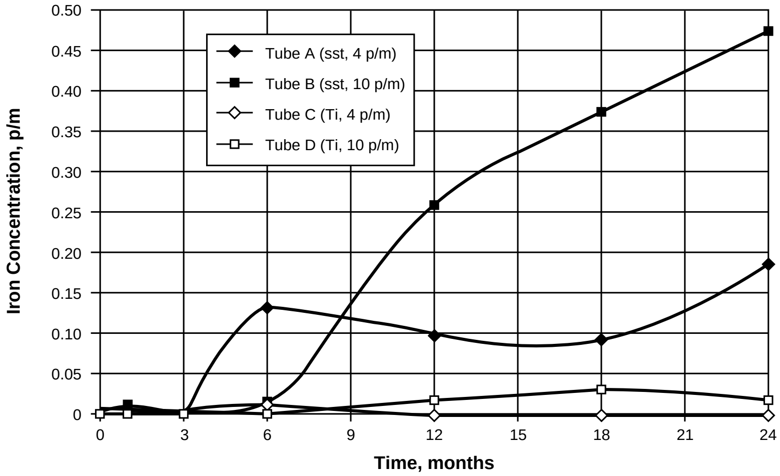

Figure 8. Graph of iron concentration versus time.

## I. Chromium

Figure 9 shows the increase in chromium concentration. Chromium concentration has increased in the stainless steel tubes, with more dramatic increases in the tube with higher initial iodine levels (i.e., tube B). These increases indicate that chromium is involved in the chemical interaction with iodine. The negligible chromium levels in the titanium tubes are not unexpected, since the titanium alloy contains little chromium. Thus far, all chromium measurements have been below the specified maximum level of 0.05 p/m.

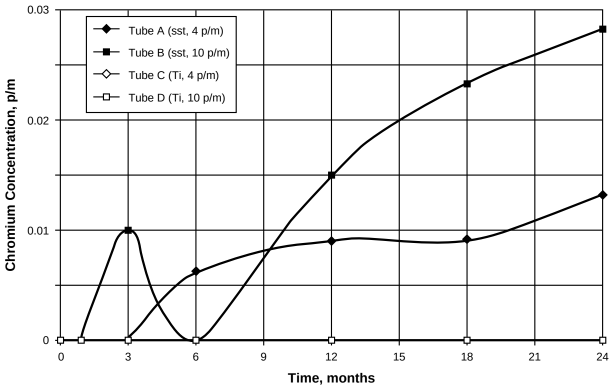

Figure 9. Graph of chromium concentration versus time.

## J. Conductivity

As shown in figure 10, conductivity has increased in all tubes. As would be expected, tubes containing higher initial iodine concentrations (tubes B and D) generally show the highest conductivity levels. Of the 28 conductivity readings collected, only two seem to violate this generalization. First, the 3-month sample for tube C had an unexpectedly high conductivity of 23.5 $\mu$mhos/cm. This conductivity measurement is difficult to explain since no ion concentrations were observed to be extraordinarily high. It was also unexpected that this high conductivity would occur in a titanium tube with a low initial iodine concentration (4 p/m). Later conductivity values for the low-iodine titanium tubes (i.e., tubes C) were lower, ranging from 8.12 to 11.3 $\mu$mhos/cm. The second point which violated the overall upward trend occurred in tube B at 18 months, with a low conductivity of 3.93 $\mu$mhos/cm. This measurement coincided with a marked increase in chromium and iron concentration, which would have been expected to increase the conductivity. Again, the next sample (i.e., the 24-month tube B sample) returned to previous levels. The cause of these variations are not readily apparent.

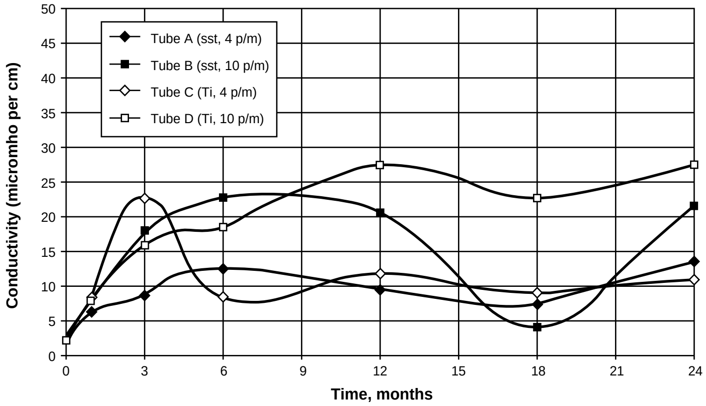

Figure 10. Graph of conductivity versus time.

## K. Turbidity

As shown in figure 11, turbidity decreased sharply during the first month of exposure and has remained at or below the detection limit (0.2 NTU) in later samples. This result is not unexplainable, since long-term, undisturbed stagnation in a gravitational field would allow additional settling of fine particles in the water. It does seem unlikely that this decrease in turbidity would occur in microgravity.

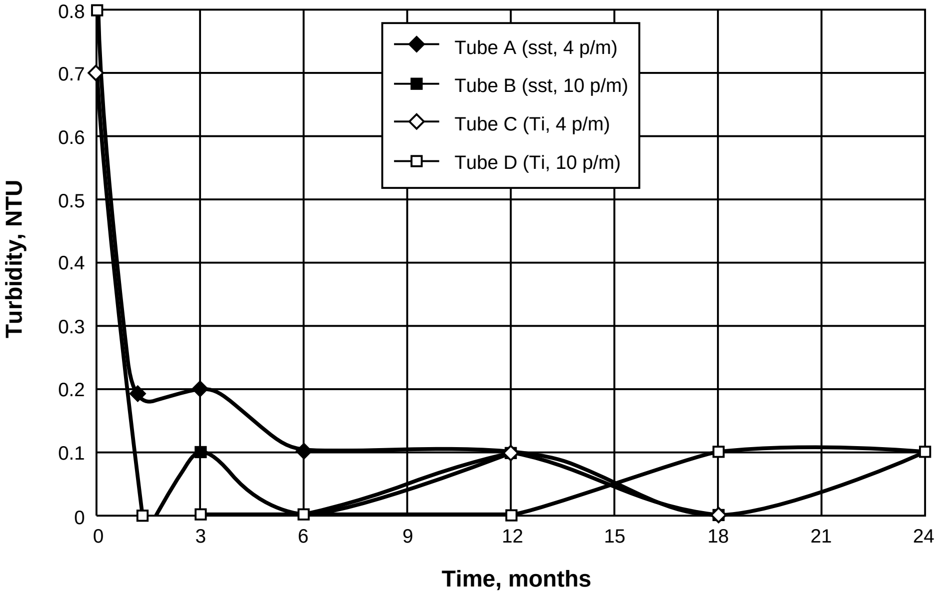

Figure 11. Graph of turbidity versus time.

## L. pH

The pH in all tubes has exhibited an overall downward trend. Although the initial pH values were slightly basic (7.5 and 8.2), the pH readings have ranged from 4.3 to 6.2 since the end of the first month (fig. 12). The increase in the iodide levels could be partially responsible for the lower pH.

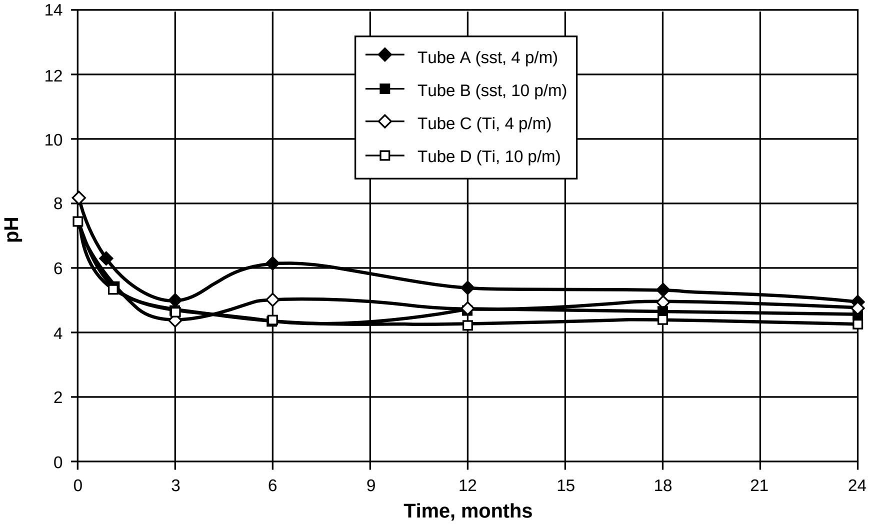

Figure 12. Graph of pH versus time.

## IV. CONCLUSIONS

Thus far, the WDS has clearly demonstrated that it is possible to store water in a stainless steel or titanium distribution system for up to 24 months without significant levels of microbial growth. The WDS has shown that the microbial integrity of the water can be maintained even after iodine depletion, if the quality of the water and tubes are carefully controlled during the filling. Although some parameters such as pH, conductivity, iodine, iron, nickel, and TOC have been shown to violate their specified limits during extended storage, the absence of biofilm growth would enable the lines to be ready for use following a simple flushing operation. Furthermore, the WDS suggests that the water flushed from the system would be easily reconditioned by the space station's water processor for use as potable water.

Data from the WDS suggests that there is an interaction between iodine and nickel that results in depletion of up to 10 p/m iodine within 3 to 6 months. Viewed another way, the WDS suggests that an initial iodine concentration of 10 p/m may be insufficient to maintain iodine levels above the specified 2 p/m minimum for any extended period of time. Of course, if iodine is indeed being consumed through some interaction with stainless steel or with a nickel-rich lubricant, avoiding these materials could increase the longevity of biocidal iodine in the distribution lines. Results from batch 2, expected in early 1996 and 1998, should provide insight into iodine longevity in an all-titanium system without the nickel-rich valve lubricant.

Despite the rapid decrease in iodine concentrations, the WDS has not exhibited rampant microbial growth. Extremely low levels of bacteria were isolated on only four occasions with no correlation between the occurrences. The early depletion of iodine suggests that optimization of the initial iodine levels may be needed to maintain an active biocide concentration in a "launch-wet-and-wait" scenario.

## V. FUTURE WORK

Due to the number of unanswered questions surrounding the interaction of various materials with diatomic iodine ($I_2$), the WDS investigators believe that a test program should be undertaken to quantify the iodine depletion rates to be expected in the space station WRM system. This effort should seek to determine the initial iodine dose required to satisfy the system's "appetite" for iodine and should also determine whether the system can be effectively passivated to the extent that iodine levels can be maintained above the specified minimum levels during extended periods of stagnation.

# REFERENCES

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3. Traweek, M.S., and Tartara, J.D.: “Analytical Control Test Plan and Microbiological Methods for the Water Recovery Test.” NASA TM 108473, 1994.

4. Mudgett, P.D., Flanagan, D.T., Schultz, J.R., and Sauer, R.L.: “Depletion of Biocidal Iodine in a Stainless Steel Water System.” SAE Paper 941391, 1994.

# APPENDIX

## Water Degradation Study Raw Data

**Tube A (Port 003:  4 mg/L I2 Batch Stainless Steel)**

| | Specifications | Initial Jan-93 | 30 Day Feb-93 | 91 Day Apr-93 | 183 Day Jul-93 | 371 Day Jan-94 | 547 Day Jul-94 | 730 Days Jan-95 |
|---|---|---|---|---|---|---|---|---|
| **pH** | 6.0-8.0 | 8.2 | 6.2 | 5.1 | 6.2 | 5.5 | 5.4 | 5 |
| **Conductivity** | 3.3 umhos/cm | 2.69 | 5.88 | 8.53 | 12.4 | 8.95 | 7.27 | 13.9 |
| **turbidity** | 11 NTU | 0.7 | 0.2 | 0.2 | 0.1 | 0.1 | <0.1 | 0.1 |
| **Iodine, res** | 4 +/- | 3.31 | 1.96 | <0.10 | <0.10 | <0.10 | <0.1 | <0.1 |
| **Iodide** | | 2.43 | 3.34 | 5.48 | 4.78 | 4.45 | 4.6 | 2.46 |
| **Total Iodine** | | 5.74 | 5.3 | 5.48 | 4.78 | 4.45 | 4.6 | 2.46 |
| **Chloride** | | n/a | 0.08 | <0.04 | <0.04 | <0.04 | <0.04 | 0.053 |
| **Flouride** | | n/a | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 |
| **Nitrate** | | n/a | <0.01 | <0.01 | <0.10 | <0.10 | <0.01 | <0.1 |
| **Sulfate** | | n/a | 2.1 | 0.18 | 0.015 | 0.19 | <0.15 | <0.15 |
| **Chromium** | 0.05 mg/L | <0.010 | <0.005 | <0.005 | 0.006 | 0.009 | 0.009 | 0.013 |
| **Iron** | 0.3 mg/L | <0.005 | <0.005 | <0.010 | 0.132 | 0.099 | 0.098 | 0.187 |
| **Nickel** | 0.05 mg/L | 0.009 | 0.138 | 0.19 | 0.237 | 0.177 | 0.609 | 0.321 |
| **Molybdenum** | | <0.020 | <0.020 | <0.020 | <0.02 | <0.02 | <0.02 | <0.02 |
| **Titanium** | | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | NR | <0.005 |
| **TOC** | 1 mg/L | <1.0 | 1.15 | <1.0 | 1.31 | 2.64 | 2.89 | 5.03 |
| **TIC** | | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1 |
| **Total Carbon** | | <1.0 | 1 | <1.0 | 1 | 3 | 3 | 5 |
| **R2A (7 Day)** | <1 CFU/100mL | <1 | 32 | <1 | <1.0 | <1.0 | <1.0 | <1 |

*Biofilm analysis performed at 2 years (730 days), result <1 colony/25cm2

**Tube B (Port 004:  10 mg/L I2 Batch Stainless Steel)**

| | Specifications | Initial Jan-93 | 30 Day Feb-93 | 91 Day Apr-93 | 183 Day Jul-93 | 371 Day Jan-94 | 547 Day Jul-94 | 730 Days Jan-95 |
|---|---|---|---|---|---|---|---|---|
| **pH** | 6.0-8.0 | 7.5 | 5.6 | 4.8 | 4.4 | 4.7 | 4.7 | 4.6 |
| **Conductivity** | 3.3 umhos/cm | 2.14 | 8.55 | 17.6 | 22.5 | 20.5 | 3.93 | 21.6 |
| **turbidity** | 11 NTU | 0.8 | <0.1 | 0.1 | <0.1 | 0.1 | <0.1 | 0.1 |
| **Iodine, res** | 10 +/- | 9.75 | 6.15 | 1.35 | 0.24 | <0.1 | 0.16 | <0.1 |
| **Iodide** | | 2.35 | 6.25 | 10.9 | 12.6 | 10.5 | 10.4 | <0.1 |
| **Total Iodine** | | 12.1 | 12.4 | 12.2 | 12.8 | 10.5 | 10.6 | <0.1 |
| **Chloride** | | n/a | 0.05 | <0.04 | 0.17 | 0.04 | <0.04 | <0.04 |
| **Flouride** | | n/a | <0.02 | <0.02 | 0.12 | <0.02 | <0.02 | <0.02 |
| **Nitrate** | | n/a | 0.16 | <0.1 | <0.10 | <0.10 | <0.10 | <0.1 |
| **Sulfate** | | n/a | 0.26 | 0.18 | 0.18 | 0.25 | 0.15 | <0.15 |
| **Chromium** | 0.05 mg/L | <0.005 | <0.005 | 0.01 | <0.005 | 0.015 | 0.023 | 0.028 |
| **Iron** | 0.3 mg/L | <0.005 | 0.007 | <0.010 | 0.007 | 0.26 | 0.37 | 0.472 |
| **Nickel** | 0.05 mg/L | 0.039 | 0.399 | 0.641 | 0.316 | 0.319 | 0.295 | 0.454 |
| **Molybdenum** | | <0.020 | <0.020 | <0.020 | <0.02 | <0.02 | <0.02 | <0.02 |
| **Titanium** | | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | NR | <0.005 |
| **TOC** | 1 mg/L | <1.0 | 1.19 | <1.0 | 1.05 | 1.65 | 1.27 | 1.57 |
| **TIC** | | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 |
| **Total Carbon** | | <1.0 | 1 | <1.0 | 1 | 2 | 1 | 2 |
| **R2A (7 Day)** | <1 CFU/100mL | <1 | <1 | <1 | <1.0 | <1.0 | <1.0 | <1.0 |

*Biofilm analysis performed at 2 years (730 days), result <1 colony/25cm2

**Tube C (Port 005: 4 mg/L I2 Batch Titanium)**

| | Specifications | Initial<br>Jan-93 | 30 Day<br>Feb-93 | 91 Day<br>Apr-93 | 183 Day<br>Jul-93 | 371 Day<br>Jan-94 | 547 Day<br>Jul-94 | 730 Days<br>Jan-95 |
|---|---|---|---|---|---|---|---|---|
| **pH** | 6.0-8.0 | 8.2 | 5.6 | 4.5 | 5.1 | 4.8 | 5 | 4.8 |
| **Conductivity** | 3.3 umhos/cm | 2.69 | 8.96 | 23.5 | 8.12 | 11.3 | 8.74 | 11 |
| **turbidity** | 11 NTU | 0.7 | <0.1 | <0.1 | <0.10 | 0.1 | <0.1 | 0.1 |
| **Iodine, res** | 4 +/- | 3.31 | <0.10 | <0.10 | <0.10 | <0.10 | 0.12 | <0.1 |
| **Iodide** | | 2.43 | 5.6 | 5.6 | 5.69 | 5.9 | 5.48 | 5.26 |
| **Total Iodine** | | 5.74 | 5.6 | 5.6 | 5.75 | 5.9 | 5.6 | 5.26 |
| **Chloride** | | n/a | 0.06 | <0.04 | <0.04 | <0.04 | <0.04 | <0.04 |
| **Flouride** | | n/a | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 |
| **Nitrate** | | n/a | 0.14 | <0.1 | <0.10 | < 0.10 | < 0.10 | <0.10 |
| **Sulfate** | | n/a | 0.24 | 0.18 | 0.15 | 0.22 | <0.15 | <0.15 |
| **Chromium** | 0.05 mg/L | <0.010 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| **Iron** | 0.3 mg/L | <0.005 | <0.005 | <0.010 | 0.007 | <0.005 | <0.005 | <0.005 |
| **Nickel** | 0.05 mg/L | 0.009 | 0.114 | 0.11 | 0.122 | 0.172 | 0.175 | 0.241 |
| **Molybdenum** | | <0.020 | <0.020 | <0.020 | <0.020 | <0.020 | <0.02 | <0.02 |
| **Titanium** | | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | NR | <0.005 |
| **TOC** | 1 mg/L | <1.0 | <1.0 | <1.0 | 1.17 | 1.39 | 1.44 | 1.84 |
| **TIC** | | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1 |
| **Total Carbon** | | <1.0 | <1.0 | <1.0 | 1 | 1 | 1 | 2 |
| **R2A (7 Day)** | <1 CFU/100mL | <1 | <1 | <1 | <1 | <1 | <1.0 | 2 |

Microbial ID: 730 Days- Sphingomonas paucimobilis, unidentified GNR
Biofilm results: 730 days- 2 colonies/25 cm2 (Bacillus cereus group, Unidentified GNR)

**Tube D (Port 006: 10 mg/L I2 Batch Titanium)**

| | Specifications | Initial<br>Jan-93 | 30 Day<br>Feb-93 | 91 Day<br>Apr-93 | 183 Day<br>Jul-93 | 371 Day<br>Jan-94 | 547 Day<br>Jul-94 | 730 Days<br>Jan-95 |
|---|---|---|---|---|---|---|---|---|
| **pH** | 6.0-8.0 | 7.5 | 5.5 | 4.7 | 4.5 | 4.3 | 4.5 | 4.3 |
| **Conductivity** | 3.3 umhos/cm | 2.14 | 8.31 | 16.6 | 18.5 | 27.3 | 22.4 | 27.3 |
| **turbidity** | 11 NTU | 0.8 | <0.1 | <0.1 | <0.1 | <0.1 | 0.1 | 0.1 |
| **Iodine, res** | 10 +/- | 9.75 | 6.6 | 2.85 | <0.1 | <0.1 | 0.14 | <0.1 |
| **Iodide** | | 2.35 | 6.7 | 10.4 | 13 | 12.2 | 11.9 | 12.5 |
| **Total Iodine** | | 12.1 | 13.3 | 13.2 | 13 | 12.2 | 12 | 12.5 |
| **Chloride** | | n/a | 0.07 | <0.04 | 0.07 | <0.04 | 0.1 | 0.12 |
| **Flouride** | | n/a | <0.02 | <0.02 | 0.06 | <0.02 | <0.02 | <0.02 |
| **Nitrate** | | n/a | <0.10 | <0.1 | <0.1 | <0.10 | <0.10 | <0.1 |
| **Sulfate** | | n/a | 0.27 | 0.2 | 0.17 | 0.31 | <0.15 | <0.15 |
| **Chromium** | 0.05 mg/L | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| **Iron** | 0.3 mg/L | <0.005 | <0.005 | <0.010 | 0.03 | 0.021 | 0.03 | 0.016 |
| **Nickel** | 0.05 mg/L | 0.039 | 0.245 | 0.385 | 0.26 | 0.29 | 0.731 | 0.541 |
| **Molybdenum** | | <0.020 | <0.020 | <0.020 | <0.02 | <0.02 | 0.088 | <0.02 |
| **Titanium** | | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | NR | <0.005 |
| **TOC** | 1 mg/L | <1.0 | 1.04 | <1.0 | 1.03 | 1.76 | 1.85 | 1.76 |
| **TIC** | | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1 |
| **Total Carbon** | | <1.0 | <1.0 | <1.0 | 1 | 2 | 2 | 2 |
| **R2A (7 Day)** | <1 CFU/100mL | <1 | <1 | <1 | 1 | <1 | <1.0 | 1 |

Micro ID: 183 days- ; 730 Days- Moraxella osloensis
Biofilm results: 730 Days- <1 colony/25 cm2