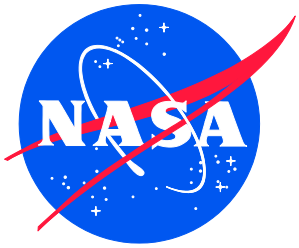
NASA/TM–20230007658
NESC-RP-22-01727



ISS Universal Waste Management System (UWMS) Optical Sensor

Phase 2

Upendra N. Singh/NESC
Langley Research Center, Hampton, Virginia

Christopher Biagi
Kennedy Space Center, Florida

Tracy L. Gibson
Engineering Research and Consulting LLC, Huntsville, Alabama

Robert C. Youngquist
Analytical Mechanics Associates, Hampton, Virginia

May 2023

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

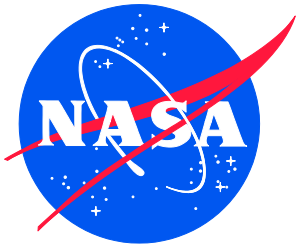
For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the "General" help request type.

NASA/TM–20230007658
NESC-RP-22-01727



ISS Universal Waste Management System (UWMS) Optical Sensor

Phase 2

Upendra N. Singh/NESC
Langley Research Center, Hampton, Virginia

Christopher Biagi
Kennedy Space Center, Florida

Tracy L. Gibson
Engineering Research and Consulting LLC, Huntsville, Alabama

Robert C. Youngquist
Analytical Mechanics Associates, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

May 2023

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

NASA Engineering and Safety Center
Technical Assessment Report

ISS Universal Waste Management System (UWMS) Optical Sensor: Phase 2

TI-22-01727

NESC Lead - Dr. Upendra N. Singh

Technical Lead – Dr. Christopher Biagi, Dr. Robert C. Youngquist

April 27, 2023

Report Approval and Revision History

NOTE: This document was approved at the April 27, 2023, NRB.

Approved: TIMMY WILSON Digitally signed by TIMMY WILSON Date: 2023.05.09 16:03:13 -04'00'

NESC Director

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Upendra N. Singh, NASA Technical Fellow for Sensors and Instrumentation, LaRC	04/27/2023

Table of Contents

List of Figures

List of Tables

Technical Assessment Report

1.0 Notification and Authorization

Collins Aerospace has delivered a new Universal Waste Management System (UWMS) to the International Space Station (ISS), which is not operational, partially due to a faulty urine pretreat concentration sensor. Collins Aerospace has suggested that an optical-based sensor might be a potential replacement for the existing sensor. The ISS Program has requested help from the NASA Engineering and Safety Center (NESC) in developing such a sensor. The first phase of this effort was to determine if an optical approach was feasible, which was completed in 2022. The second Phase, the topic of this report, was to determine the impact of ISS water contaminants and pretreat aging on the performance of the sensor and to design, construct, and test a prototype sensor.

Key stakeholders for this assessment include Melissa McKinley (Crew % Thermal Systems Division), the ISS Program, and the Orion Multipurpose Crew Vehicle (MPCV)

ISS/Collins Aerospace Technical Interchange Meeting (TIM) on the ISS UWMS	January 12, 2022
Phase 1. Request Submitted and Initial Evaluation Approved	January 21, 2022
Phase 1 status and Phase 2 request approved	April 14, 2022
Phase 1 NRB presentation and release of report	September 15, 2022
Phase 1 Stakeholder Update	September 30, 2022
Phase 2 NESC Review Board (NRB) presentation	April 27, 2023
Phase 2. Final Report Delivery and Stakeholder Update	TBD

2.0 Signatures

Submitted by: NESC Lead

Upendra Singh

Digitally signed by Upendra Singh
Date: 2023.05.05 13:51:33 -04'00'

Dr. Upendra N. Singh

Significant Contributors:

Christopher Biagi

Digitally signed by Christopher Biagi
Date: 2023.04.28 12:44:38 -04'00'

Dr. Christopher Biagi

Tracy Gibson (affiliate)

Digitally signed by Tracy Gibson (affiliate)
Date: 2023.04.28 14:36:17 -04'00'

Dr. Tracy L. Gibson

Robert C. Youngquist

Digitally signed by Robert C. Youngquist
Date: 2023.04.28 12:09:13 -04'00'

Dr. Robert C. Youngquist

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 Members

Name	Discipline	Organization
Core Team		
Upendra Singh	NESC Lead, and NASA Technical Fellow for Instruments and Sensors	LaRC/NESC
Christopher Biagi	Technical Lead after September 30, 2022	KSC
Robert C. Youngquist	Technical Lead to September 30, 2022	KSC, sub to AMA
Tracy Gibson	Chemist	KSC/LASSO (labs contract)
Consultants		
Morgan Abney	NASA Technical Fellow for Environment Control/Life Support	MSFC
Business Management		
Lorrie Hardin	Manager	LaRC/MTSO
Assessment Support		
Linda Burgess	Planning and Control Analyst	LaRC/AMA
Leanna S. Bullock	Technical Editor	LaRC/AMA
Betty Trebaol	Project Coordinator	LaRC/AMA

4.0 Executive Summary

On January 12, 2022, Collins Aerospace held a technical interchange meeting (TIM), entitled "ISS Toilet Discussion," to discuss problems with the new International Space Station (ISS) Universal Waste Management System (UWMS). One of the problems was the faulty operation of a conductivity sensor used to determine if pretreat was diluted to the proper concentration for use in processing urine (ideally the pretreat concentration should be 6.7 ± 1% (by volume)). Cory Kaufman, the Collins Aerospace UWMS design lead, suggested that it might need to be replaced with an optical sensor, but that this would require a design effort. Robert Youngquist, Kennedy Space Center (KSC), attended the TIM at the request of the NASA Engineering and Safety Center (NESC). He offered to help (contingent on NESC approval), indicating that KSC has access to the pretreat compound, optical spectroscopy equipment, and experience in the development of optical sensors. Cory Kaufman accepted this offer on January 20, 2022.

The NESC decided to separate the effort into phases, with Phase 1 determining if an optical-based sensor was feasible, Phase 2 developing a prototype sensor, and Phase 3 (if needed) helping with the developing a space-rated sensor version. The Phase 1 feasibility assessment was approved at the February 10, 2022, NESC Review Board (NRB). The work was completed at the end of March 2022 and a status was presented in April 2022, at which time the NRB approved a Phase 2 effort to develop a prototype sensor. The Phase 1 closeout was approved by the NRB in September of 2022 and a final report was released.

The first task performed under the Phase 2 effort was to determine if the presence of iodine in the ISS water would affect the optical sensor. This request came from Dana Weigel, the Deputy ISS Program Manager. Water samples were created with iodine levels matching the maximum reached on the ISS and spectroscopic measurements made. Data analysis was conducted showing less than a 0.05% error in the pretreat sensor concentration measurement. This is negligible and indicates that iodine in the ISS water does not significantly degrade the performance of the proposed pretreat concentration sensor. It has also been shown that aging of the pretreat is not an issue based on the replacement cycle used on the ISS to ensure the pretreat is viable.

At the start of the Phase 2 activity, ISS/Collins Aerospace requested that the NESC develop an optical pretreat sensor that monitored the pretreat concentration by looking through a transparent flow line. They felt that this was difficult, but, if successful, would greatly simplify the design versus installing windows to view the pretreat solution. A novel design involving bouncing light back and forth within the tube carrying the pretreat solution was proposed. Preliminary devices were constructed and tested, leading to a self-contained prototype where the optical head and supportive electronics were packaged in a single housing. Theoretical analysis led to a calibration curve for the device which was encoded into the microprocessor that processed the outputs from the sensor photodiodes. The pretreat concentration sensor met the accuracy requirements requested by the ISS Program and Collins Aerospace (see Appendix A). Flow testing was performed where the output from the sensor was used to determine the total amount of pretreat and compared to the inserted amount in the flow stream. The measured total was about 10% lower than expected, likely due to inadequate mixing and the presence of air bubbles in the flow stream. Given these considerations, the optical-based sensor is demonstrated for use in the UWMS design and can be offered to the ISS Program for further testing.

5.0 Assessment Plan

The Phase 2 assessment plan contained three topics:

1. Perform additional spectroscopy to:
   a. Examine the effect of water constituents. Of special concern is iodine in the ISS water.
   b. Ensure that degradation of the pretreat (which causes a color change) is not an issue.
2. Provide optical design consulting.
   a. Optimal light sources based on testing and analysis.
   b. Additional optics to monitor window clarity, light source variations, etc.
   c. Perform some testing of optical designs using pretreat.
3. Consultg on mechanical and electrical design issues.

The ISS Program/Collins Aerospace requested that the NESC design and construct an optical pretreat sensor that could measure concentration by looking through the walls of a transparent tube to minimize the need for fittings and windows. They stated that this might be a difficult task given the refractive issues of looking through a round tube. This task fulfills item 2 above in that it involves choosing an optimal light source, designing an optical system, and performing testing.

The ISS Program/Collins Aerospace originally requested that the Phase 2 assessment include some consulting on mechanical and electrical design issues, but NESC team members personnel were never asked to supply that capability. Therefore, item 3 in the assessment plan was not performed.

6.0 Problem Description and Background

The UWMS was delivered to the ISS in 2020 as shown in Figure 6.0-1. This system was designed to be smaller volume (i.e., 65%) and lower mass (i.e., 40%) than the existing ISS waste management system.

Note, a version of the UWMS was delivered to the MPCV Program and installed into the Artemis II Orion Spacecraft in March 2021. Potential modifications to the ISS UWMS would be considered for incorporation into the MPCV Program system.

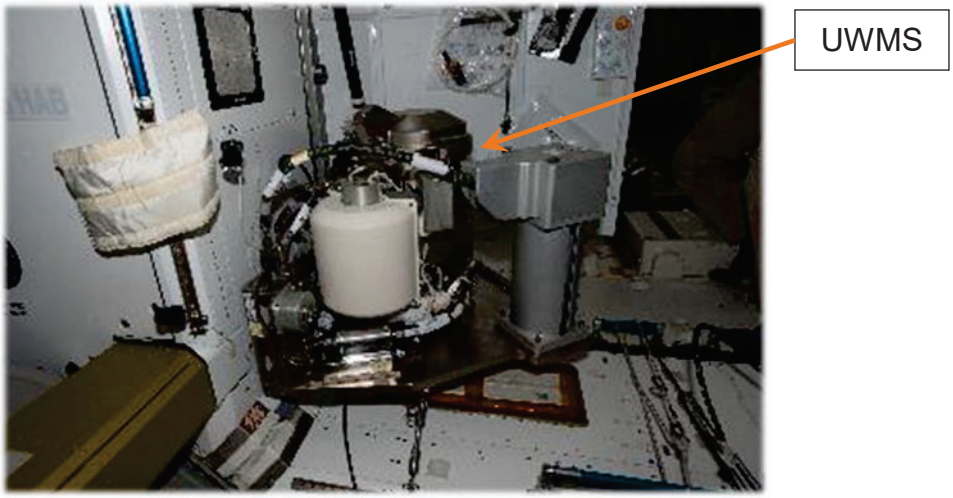


Figure 6.0-1. UWMS Installed in Node 3 on ISS

The ISS UWMS suffered from multiple operational problems. The first installation attempt in December 2020 failed due to issues with the conductivity sensor. A second attempt to validate operation occurred in May 2021, but the conductivity sensor was not operational, and a rotor was nonfunctional. The rotor was replaced, and the UWMS was used by the crew starting on October 18, 2021, without an operational conductivity sensor. The UWMS was operational for 15 days, but was shut down on November 3, 2021, due to pressure sensors showing out-of-range conditions. The UWMS was placed in dormancy pending resolution of the known technical issues [refs. 1 and 2].

The UWMS has a tank of concentrated pretreat solution used to stabilize urea (to prevent hydrolysis to NH3/NH4+, prevent increasing pH, and prevent salt precipitate formation) and to prevent microbial growth in the urine. A dose of this pretreat is drawn from the tank and mixed with ISS potable water, diluting the pretreat to 6.7±1% (by volume) concentration before using it to treat urine. If the mixed concentration is too low, then the urine will begin to hydrolyze and precipitate and biofilms may form that can cause hardware failures, and if the pretreat concentration is too high, then the concentrated pretreat solution will be consumed too quickly and poses an increased risk to hardware due to the lowered pH. To monitor the pretreat concentration, a conductivity sensor (SV1027587 Goodrich) was part of the design installed. Figure 6.0-2 shows the UWMS dose pump and conductivity sensor.

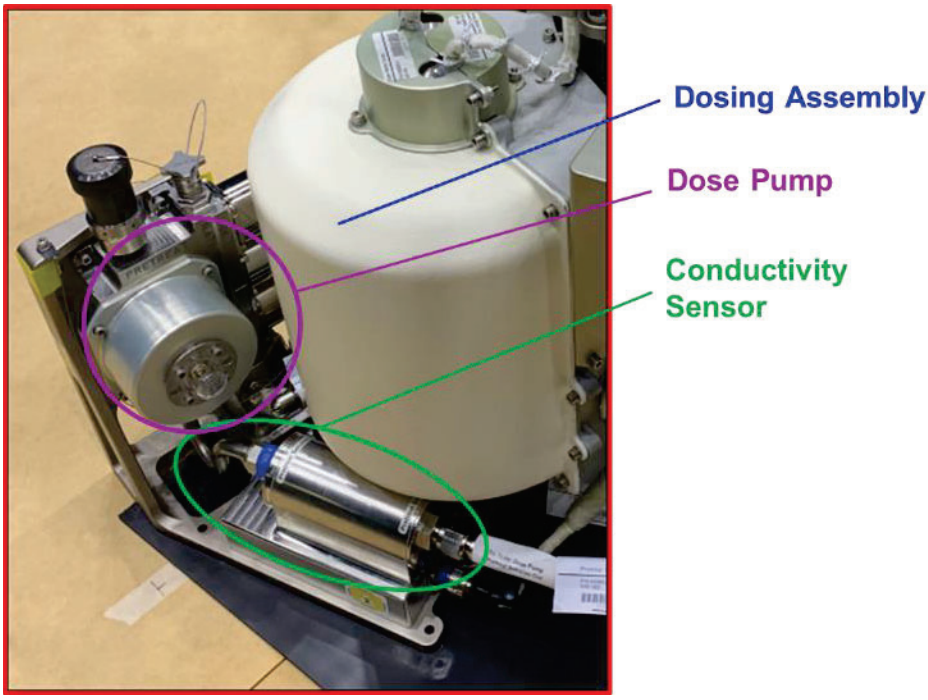


Figure 6.0-2. UWMS Showing Conductivity Sensor

The conductivity sensor operates by placing electrodes into the diluted pretreat mixture prior to addition to the urine and flowing current through the diluted pretreat to measure the conductivity. This reading is converted to a concentration. In operation, however, the output voltage from this sensor decays over time, yielding an unreliable measurement. Attempts to modify the sensor were made but did not solve the problem. The probable cause is an interaction between the electrodes and the diluted pretreat causing current flow decay [ref. 1]. Collins Aerospace stated

that “Sense electrode imperfections cause measurement instability, Crystals, foreign object debris, plating, ‘surface adsorption’ that changes one or both sense electrodes.”

On January 12, 2022, Cory Kaufman, the Collins Aerospace UWMS Design Lead, conducted a TIM to present and discuss the nonfunctional rotor, the conductivity sensor problems, and the pressure-sensor anomalies. During this presentation [ref. 1], Kaufman suggested that one solution for the conductivity sensor problem was to use a different sensing approach (e.g., an external toroidal conductivity sensor or an optical sensor). Robert Youngquist, attending as a member of the NESC Sensors and Instrumentation Technical Discipline Team, offered to help assess the feasibility of designing an optical sensor. To aid in this investigation, the NESC team had access to the pretreat compound and spectroscopy equipment, and experience in designing optical sensors [refs. 3–7]. Collins Aerospace/ISS Program accepted this offer of support.

The NRB approved the assessment to be approached in three phases:

1. Phase 1 would perform spectroscopy to determine if an optical based concentration sensor was feasible.
2. Phase 2 would generate a prototype sensor and test the impact of ISS water contaminants and aging of the pretreat.
3. Phase 3 would construct a space-rated sensor version for additional development and/or qualification testing.

The Phase 2 work is described in this report. The collected data and analysis are presented in the next section, and Appendix A provides the proposed sensor specifications.

7.0 Analysis

The primary goal was to demonstrate a prototype optical sensor that can monitor the concentration of pretreat in water from 2.7% to 10.7 % (by volume) to ±1% accuracy. The ideal concentration range is 6.7 ± 1%. During the Phase 1 effort six different concentrations of pretreat in pure water were prepared, as seen in Figure 7.0-1, corresponding to 3%, 5%, 7%, 9%, 11%, and 13% concentrations. Transmission spectra were taken of these using 5-mm and 10-mm cuvettes and the results were used to construct an absorption curve, shown in Figure 7.3-3. These measurements verified that the transmission through this material obeys Beer’s Law, allowing modeling of selected optical sources and path lengths. Beer’s law states that the transmission of material varies as:

$$T(\lambda) = 10\text{^}\{-\alpha(\lambda)\, x\, p\}$$

where λ is the wavelength, $\alpha(\lambda)$ is the absorbance with units of inverse centimeters (cm) and inverse %, x is the path length in cm, and p is the % pretreat concentration. It was determined that the ideal wavelength range to use for the sensor was between 500 and 600 nm, a region where there was sufficient absorption to measure the concentration of pretreat yet leave adequate light to ensure a reasonable signal to noise level.

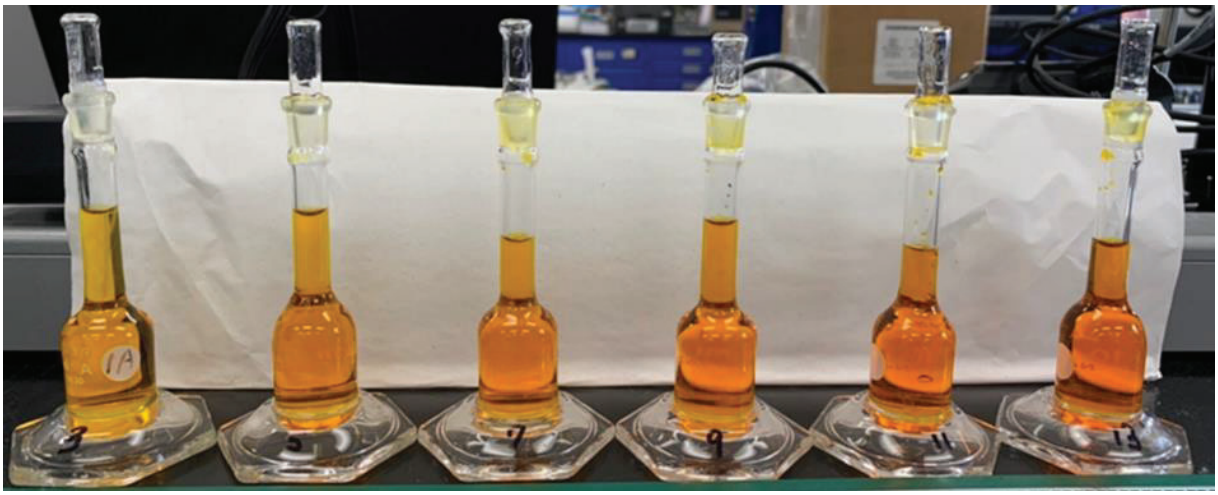


Figure 7.0-1. Six Different Concentrations of Pretreat in Water Prepared

The Phase 2 effort consists of two primary tasks:

1. Determine the impact of iodine in the ISS water and pretreat aging on the predicted performance of the sensor and
2. Design, construct, and evaluate a prototype pretreat concentration sensor that can monitor pretreat concentration through a transparent flow line.

7.1 Impact of ISS Water Contaminants on the Sensor Performance

The water on the ISS is not pure and has additional constituents as shown in Table 7.1-1. In this table, TC is total carbon, TOC is total organic carbon, and TIC is total inorganic carbon. Conductivity is measured in units of umho, micro inverse ohms or microSiemens. The most significant component that might affect the performance of the pretreat concentration sensor is iodine, which, according to Jill Williamson, the ISS Environmental Control and Life Support System (ECLS) Water/ Urine Processing Assembly (UPA) Subsystems Manager, can be as high as 4 ppm.

Table 7.1-1. ISS Water Composition

Sample Description		USL Potable
GMT Date		2020/265
Sample Barcode		
Bag Emptied		2/10/2021
Approximate Volume (mL)		1L
pH		5.3
Cond. (umho/cm)		2.25
TC (ppm)		1.25
TOC (ppm)		0.42
TIC (ppm)		0.83
Iodine (ppm)	Total	1.93
	I_2	1.49
	I^-	0.44

To test the impact of iodine on the sensor, iodine was dissolved in water to achieve a 4 ppm solution yielding a yellowish color as seen in Figure 7.1-1.

Figure 7.1-1. Container with 4 ppm of Iodine Dissolved in Pure Water

The transmission spectrum of this solution was measured from 300 nm to 1500 nm using a 1-cm path length cuvette. The spectral region from 400 nm to 700 nm (see Figure 7.1-2) showed some absorption, explaining the yellow color seen in the solution.

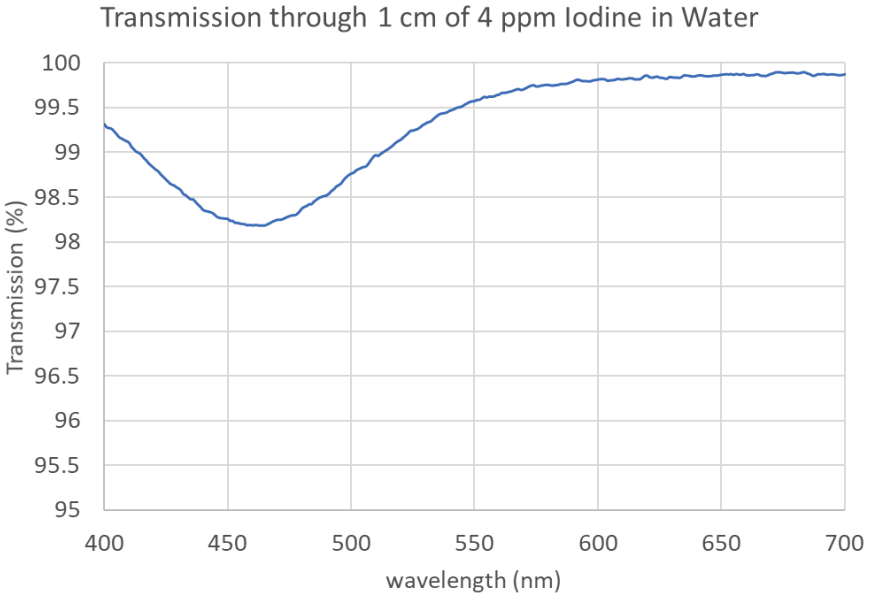


Figure 7.1-2. Transmission Spectrum of 4 ppm of Iodine in Pure Water

The pretreat concentration sensor will operate in the 500-nm to 550-nm range (see the Phase 1 report) and iodine has absorption in this spectral region, so the presence of iodine will affect the

performance of the sensor, but further analysis is required to determine to what extent. There are two ways to proceed:

1. Assume that iodine and pretreat are chemically independent and that the two transmission spectra can be combined. Using Beer's Law this yields a formula for the change in apparent concentration caused by the iodine.
2. Mix pretreat in 4-ppm iodine water, measure its transmission, and compare this to pretreat mixed in pure water to obtain a direct measurement of the error caused by the presence of iodine.

7.1.1 Independent Transmission of the Pretreat and the Iodine.

If the transmission of 4-ppm iodine and pretreat are independent, then the total transmission at each wavelength, $T(\lambda)$, of a mixture would be the product of the two transmissions. Mathematically

$$T(\lambda) = T(\lambda)_P T(\lambda)_I$$

where $T(\lambda)_P$ is the transmission of the pretreat and $T(\lambda)_I$ is the transmission of the 4-ppm iodine, both functions of wavelength, λ. From Beer's Law

$$T(\lambda)_P = 10\text{^}\{-\alpha(\lambda)\, x\, p\}$$

where λ is wavelength, $\alpha(\lambda)$ is the absorbance with units of inverse cm and inverse percent, x is the pathlength in centimeters, and p is the percent concentration of the pretreat (by volume). This can be written as a similar expression for the 4-ppm iodine in water as

$$T(\lambda)_I = 10\text{^}\{-\alpha_I(\lambda)\, x\}$$

where $\alpha_I(\lambda)$ is the absorptivity of 4 ppm of iodine in water with units of inverse cm. By using 4 ppm Iodine, the maximum amount expected in the ISS water, the worst case is analyzed.

The absorptivity of pretreat in pure water, $\alpha(\lambda)$, was previously measured (see the Phase 1 report). If the transmission of pretreat in 4-ppm iodine water is measured and the absorptivity for pretreat in pure water is used in the analysis (in other words, that the iodine is not present), the transmission equation would be

$$T(\lambda) = 10\text{^}\{-\alpha(\lambda)\, x\, p_T(\lambda)\}$$

where $p_T(\lambda)$ is the apparent, but incorrect, concentration, which is a function of wavelength. Combining the above formulae yields

$$\alpha(\lambda)\, x\, p_T(\lambda) = \alpha(\lambda)\, x\, p + \alpha_I(\lambda)\, x$$

and solving for $p_T(\lambda)$ the following expression is obtained

$$p_T(\lambda) = p + \frac{\alpha_I(\lambda)}{\alpha(\lambda)}$$

Assuming that the transmission spectra for 4 ppm of iodine in water can be multiplicatively combined with the transmission through pretreat in pure water, the error in measured concentration is given by the ratio of the absorptivity of the two solutions. The two absorptivities $\alpha_I(\lambda)$ and $\alpha(\lambda)$ have different units, so their ratio yields percentage.

A solution of 7% pretreat in water was mixed and its transmission measured. The absorption coefficient (in units of inverse cm and inverse percent concentration) for this diluted pretreat versus wavelength was measured as well as the absorption coefficient for 4 ppm of iodine in

water. These are shown on a log scale in Figure 7.1-3. The expected absorbance of iodine (red) is lower than the absorbance of the pretreat (blue).

Figure 7.1-4 shows the ratios of the absorbances, yielding the predicted concentration error, assuming independence of the iodine and the pretreat transmissions, of the sensor as a function of wavelength. Assuming the sensor operates in the 510-nm to 540-nm range the error is predicted to be less than 0.05%, which is negligible.

It should be noted that even though this analysis used 7% pretreat in water data, the final result is that the percent error is given by the ratio $\alpha_I(\lambda)/\alpha(\lambda)$ where the 7% factor has been factored out. In other words, this ratio reflects the error in the measurement regardless of the percentage pretreat present. It is the additive error to the actual pretreat concentration.

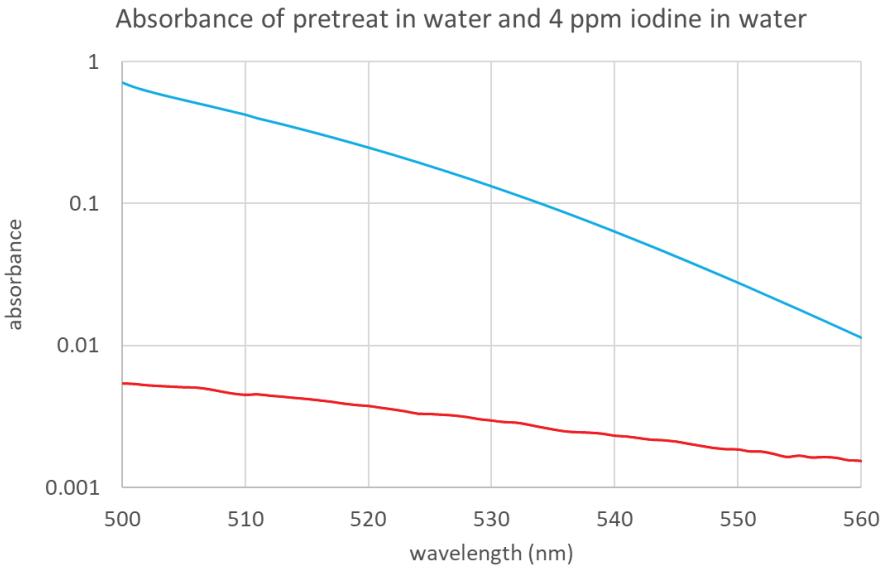


Figure 7.1-3. Absorbance of Pretreat (blue) and 4 ppm of Iodine in Water (red)

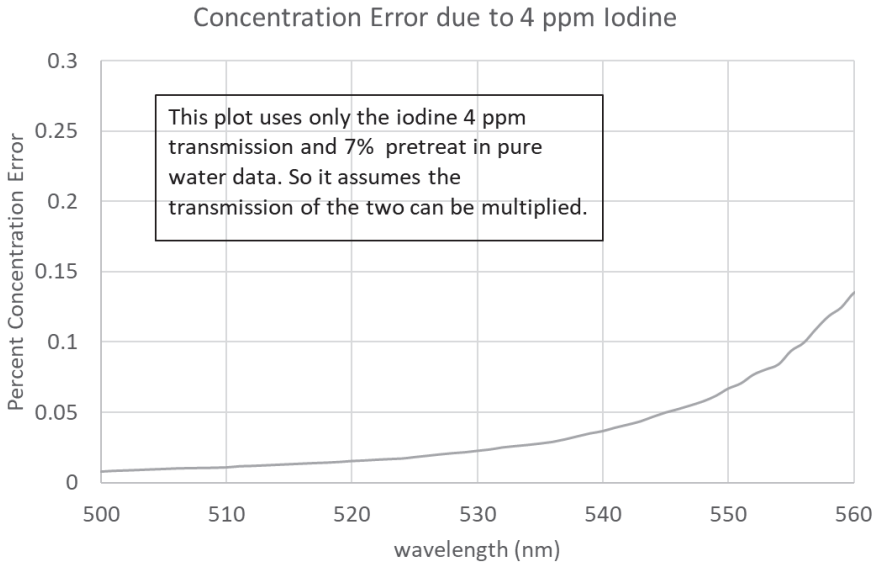


Figure 7.1-4. Percent Error in Sensor Performance Assuming Independent Transmission Spectra

7.1.2 Direct Measurement of the Error Caused by 4-ppm Iodine.

A more direct measurement of the pretreat concentration measurement error caused by the presence of 4 ppm of iodine can be obtained by preparing two solutions, one composed of 7% pretreat in pure water and one composed of 7% pretreat in water with 4 ppm of iodine added. Figure 7.1-5 plots the transmission from 500 nm to 600 nm of these solutions, showing that the effect of the iodine on the transmission is so small as to make the two curves nearly identical.

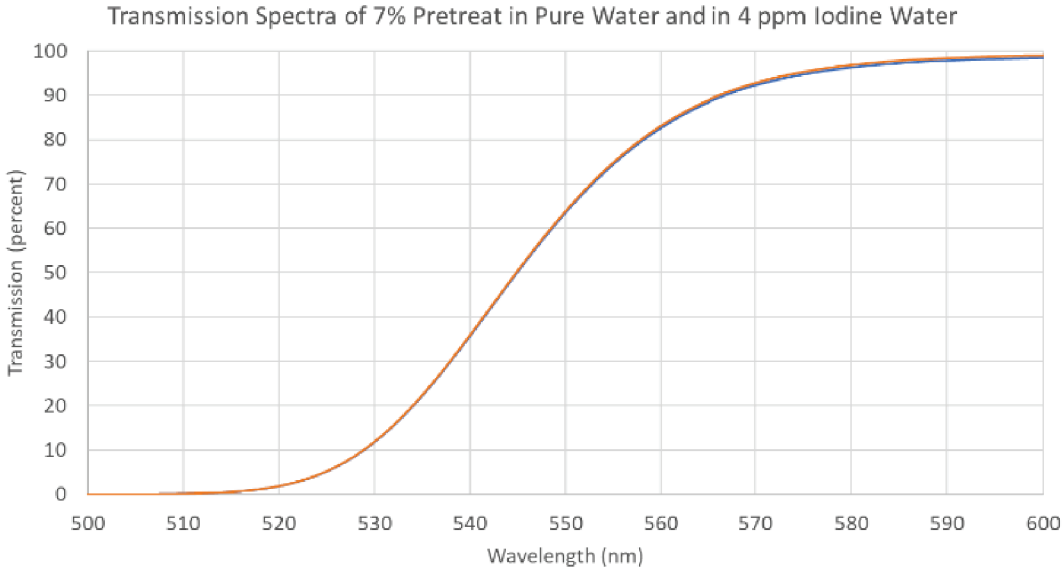


Figure 7.1-5. Transmission Spectra of 7% Pretreat in Pure Water (orange) and in 4-ppm Iodine Water (blue)

From Figure 7.1-5, it is difficult to assess the impact of the iodine on the concentration measurement. A better way to gauge the impact is to process the transmission curve for the 7% pretreat in water with 4 ppm of iodine using the absorptivity curve from the 7% pretreat in pure water (see Figure 7.1-6). In other words, act as if it is not known that the iodine is there, and calculate the percent pretreat.

If the iodine had no effect, then Figure 7.1-6 should show a flat line at 7%, so deviations from 7% indicate the error caused by the presence of the 4 ppm of iodine. Similar to the first approach, the concentration error in the band from 510 nm to 540 nm is less than 0.05%, indicating that modeling the iodine transmission as independent from the pretreat transmission was a reasonable assumption. The rise in the error below 510 nm is caused by the small signal reaching the spectrometer in this wavelength band and reflects offset or biasing errors in the spectrometer. The increase past 540 nm is in agreement with the rise in this region seen in Figure 7.1-4 and is caused by the absorptivity of the solutions both becoming small causing the impact of the iodine to grow.

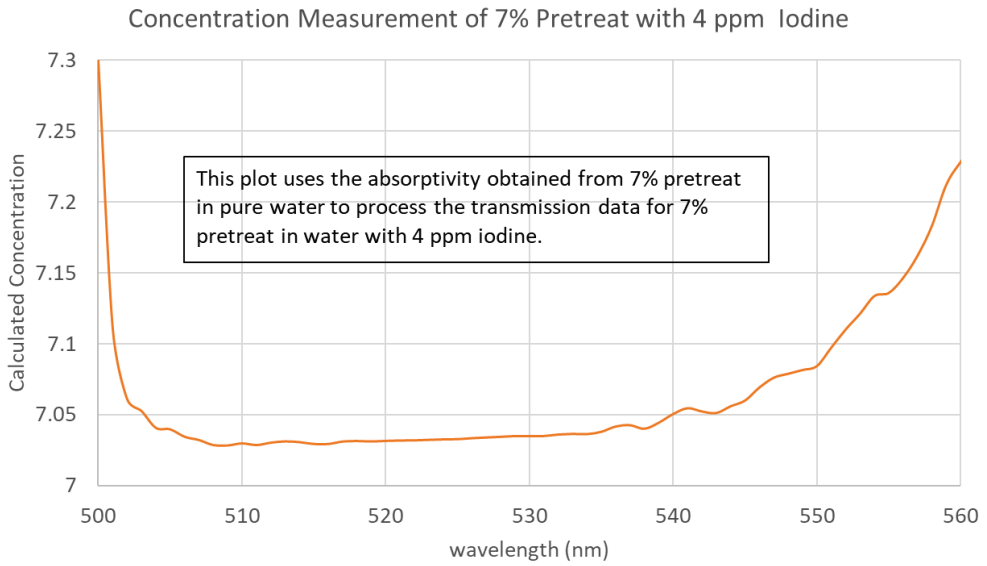


Figure 7.1-6. Calculated Pretreat Concentration of 7% Pretreat in Water with 4 ppm of Iodine Using absorptivity of 7% Pretreat in Pure Water

The specification for the pretreat concentration sensor is that it measures the concentration of pretreat in water to be 6.7 ± 1%. The error introduced by the presence of 4 ppm of iodine over the 510-nm to 540-nm range is less than 0.05%, verified through two different assessment approaches. So, the effect of 4 ppm of iodine on the optical pretreat concentration sensor is negligible (Finding #1).

It should be mentioned that a preferable light source to design the pretreat concentration sensor is a light-emitting diode (LED). In the Phase 1 effort, a 525-nm center wavelength LED was modelled. This device has about a 30-nm full width at half maximum wavelength range tailing off to almost 600 nm. However, the bulk of the energy is within the 510-nm to 540-nm window, indicating that it can be used as the basis for a pretreat concentration sensor and not suffer degradation in performance due to the presence of 4 ppm of iodine.

7.2 The Impact of Pretreat Aging

It is known that pretreat changes color as it ages or reacts. As it ages, the pretreat changes composition and is no longer effective at treating urine, so it was proposed that the optical sensor incorporate a capability of monitoring the pretreat for signs of aging.

A sample of pretreat was exposed to light for a period of weeks to months with no color change observed. To help clarify this issue the group at KSC that processes pretreat for the ISS (chemists with the Laboratory Support Services and Operations (LASSO), the lab support contract at KSC) was contacted. They pointed out that the pretreat on the ISS is replaced before aging is an issue, removing the need to monitor for this effect. So, it was decided that the additional complication of having the sensor monitor the aging of the pretreat was not needed. (Finding #2).

However, replacement of pretreat will not be possible for long-duration missions, so there may be a need for a sensor that can monitor its aging. When pretreat fully reacts it changes from a red color to a bright green color, so spectral analysis to determine its aging should be possible; however, no spectral transmission measurements were made of reacted pretreat. Even so,

development of an optical based pretreat reaction or aging sensor may be a feasible future project.

7.3 Development of an Optical Pretreat Sensor

This section presents the development of the optical pretreat sensor. It starts with the proposed concept to allow such a sensor to operate by looking at the pretreat through a transparent tube. Then, using the results from the Phase 1 study, the theory describing the operation of this sensor is presented. Section 7.4 describes the hardware and circuitry. Section 7.5 describes the testing performed on the sensor.

7.3.1 Transparent Tube Optical Pretreat Sensor

Making an optically based pretreat concentration sensor requires that light passes through the water/pretreat solution. This can be achieved by installing windows on opposing sides of a flow line, but this adds possible leak sites. Instead, the NESC and Cory Kaufman (Collins Aerospace lead engineer) discussed using perfluoroalkoxy (PFA) tubing, which is translucent, to develop a sensor that would look through the PFA walls at the pretreat. PFA is a tough, chemically resistant material that is approved for carrying pretreat solutions. Looking through the PFA at the pretreat would remove the need for windows, simplifying the sensor design. However, Cory Kaufman was not sure this was feasible, "given the lack of clarity of the PFA and the refraction of a cylindrical tube setup." However, with the advantages of not needing windows, it was requested the NESC team attempt to develop this version of a pretreat concentration sensor.

The NESC team decided to develop a PFA-based pretreat concentration sensor by using a "white cell" or integrating sphere approach. A white cell is an enclosed volume whose inner surface is coated with a highly scattering, minimally absorbing material, where light enters through an opening and is detected at a second opening, but where the two openings are not aligned. So, light enters the cell and scatters off the inner walls, reflecting until a portion reaches the detector. Doing this allows the light to propagate throughout the volume, filling the volume with light, and allowing spectroscopy to proceed without having to worry about refraction issues.

Modifying the white cell concept, an optical pretreat concentration sensor might be developed (see Figure 7.3-1) where the PFA tube is surrounded by a white scattering surface, in this case Teflon™. The Phase 1 work showed that a 525-nm center wavelength LED would work as an appropriate light source, but that some filtering might improve the response. So, the sketch shown in Figure 7.3-1 has a slot for an optional filter holder. The light, before entering the PFA, is partially scattered so that an LED/filter photodetector can monitor the LED output to account forvariations. Most of the light passes through an opening and enters the region containing the PFA tube and pretreat. This light bounces off of the Teflon™ walls, interacting with the pretreat from multiple directions, before a portion reaches the pretreat photodiode, whose output is an indication of the amount of pretreat in the tube. By scattering the light off of the Teflon™ walls, refraction by the curved PFA tubing is not an issue since the light is scattered in all directions. Also, this approach does not require external optics, (e.g., lenses) to collimate or collect light.

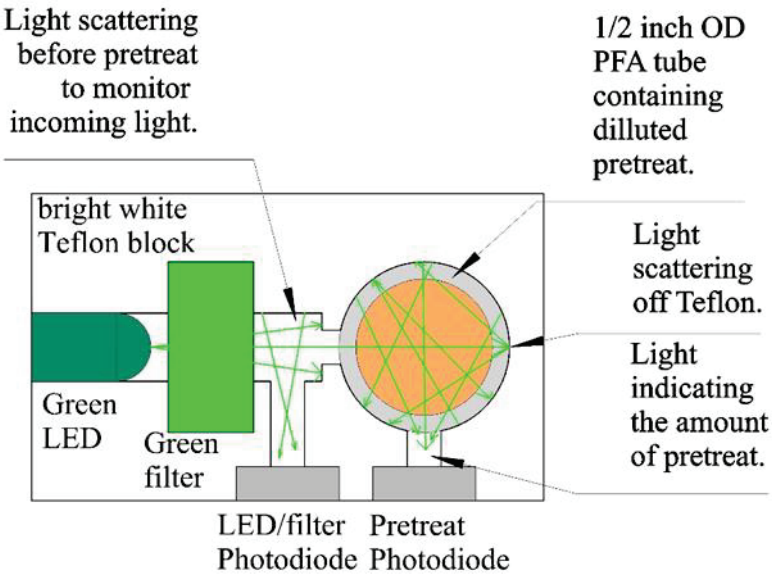


Figure 7.3-1. Proposed Optical Pretreat Concentration Sensor Using a White Cell Approach

Figure 7.3-2 shows the first attempt at making this sensor, with the LED turned on. The LED is part number LED528EHP from ThorLabs and is a 525-nm Epoxy-Encased LED that can run up to 7 mW. It is in a T-1 ¾ package. More detail is available at this link Thorlabs - LED528EHP 525 nm Epoxy-Encased LED, 7 mW, T-1 3/4, Qty. of 5. The two photodiodes seen in the figure are ThorLabs part number FDS 100, silicon photodiodes. They are low-noise, fast (1.e. 10-nsec rise time), and have area of 3.6 mm x 3.6 mm. Their responsivity in the green portion of the spectrum is about 0.25 A/W, with a Noise equivalent Power of 0.012 pW/$Hz^{1/2}$, yielding a current noise of 0.003 pA/ $Hz^{1/2}$.

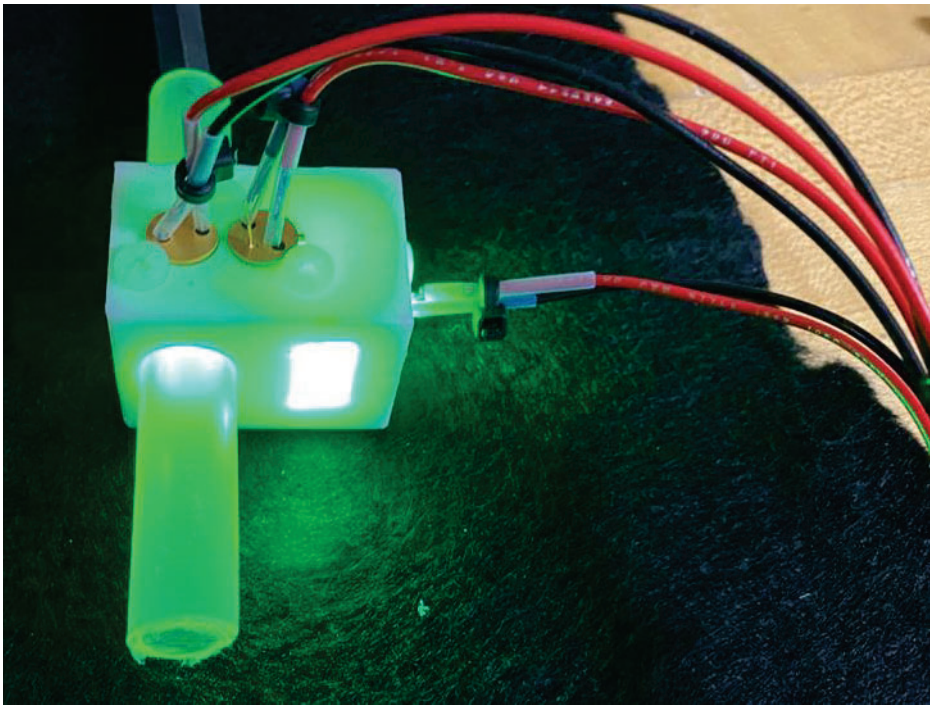


Figure 7.3-2. PFA Tube Optical Pretreat Concentration Sensor Using Teflon™ The filter slot is empty in this image.

The tubing is high-purity, hard PFA plastic, translucent tubing. It has a 0.9525-cm (3/8-inch) inner diameter (ID) and a 1.27-cm (½-inch) outer diameter. This tubing is used by the food industry and has excellent chemical resistance to a wide variety of acids. It is semi-flexible, accommodating gradual bends. It is flame retardant and contains extremely low levels of additives, so it will not contaminate the fluid. PFA tubing is approved for pretreat flow as listed in Appendix A.

Teflon™ was initially chosen for the housing because it is bright white, non-absorbing, and scatters light well. However, as can be seen in Figure 7.3-2, light is lost propagating through the Teflon™ and ambient light can get through the Teflon™ and reach the photodiodes. Neither of these is desirable. Any light lost traveling through the Teflon™ cannot reach the photodiode and light reaching the photodiodes from outside light sources can cause measurement issues. In addition, the transparency of the Teflon™ can cause cross talk between the two photodiodes, so that their measurements are skewed.

Alternative materials that had less transparency than Teflon™ were sought, but nothing appropriate was found. So, the decision was made to switch to sand-blasted aluminum. The filter holder was removed since early results indicated that the LED spectrum yielded an acceptable sensor response (the absorption versus percentage pretreat for the LED used was calculated and presented in the Phase 1 report), so its light does not need to be filtered. In addition, the opening between the cylindrical region and the photodiode was enlarged to increase the light reaching that detector. Figure 7.3-3 shows two images of the aluminum housing version of the sensor. This optical assembly is referred to as the optical head in the remainder of this report.

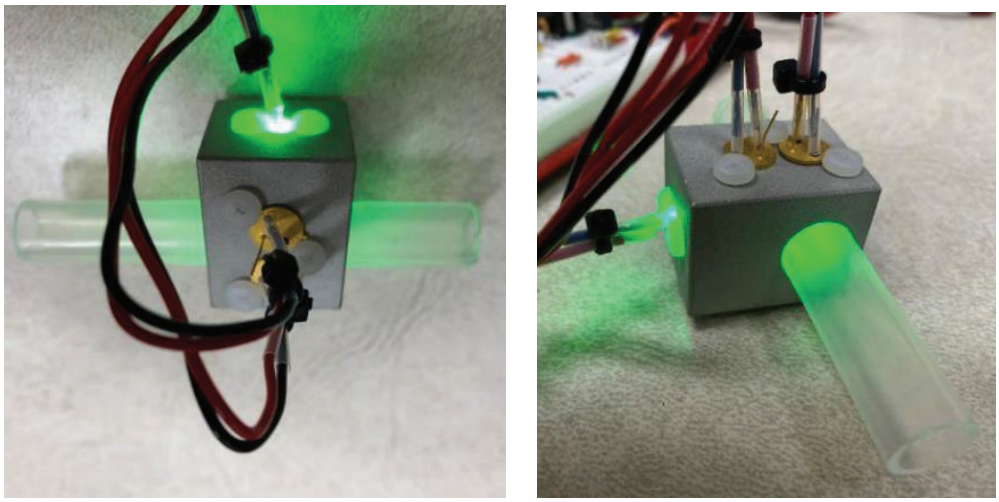


Figure 7.3-3. PFA Tube Optical Pretreat Concentration Sensor Using Aluminum

7.3.2 Transparent Tube Optical Pretreat Sensor Theory

Spectral transmission measurements of pretreat versus concentration were made in the Phase 1 effort, resulting in an absorbance function, $\alpha(\lambda)$, of wavelength, λ. This function is shown in Figure 7.3-4, displaying the absorbance of a 1% pretreat concentration over a 1-cm path length. Consequently, from Beer's Law, the transmission through the pretreat at any given wavelength is expressed as

$$T(\lambda, x, p) = 10\text{^}(-\alpha(\lambda)\, x\, p)$$

where x is the path length in cm, and p is the % pretreat concentration.

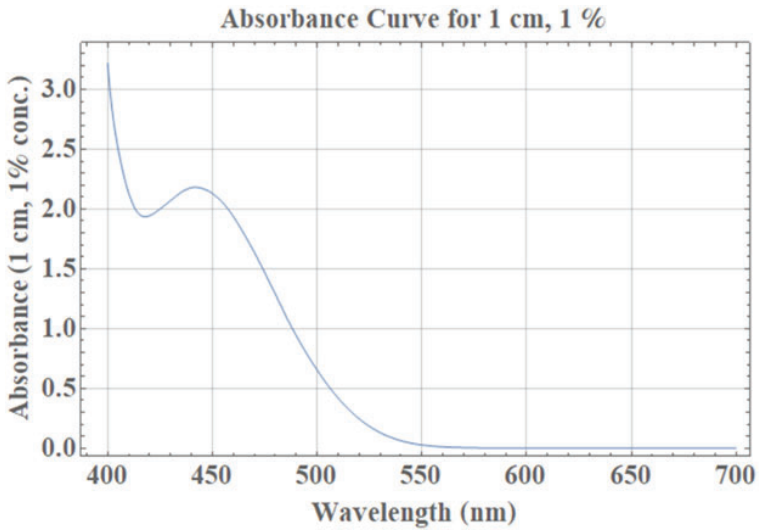


Figure 7.3-4. Absorbance Curve Used to Model Optical Pretreat Sensors

However, with the white cell approach for monitoring pretreat, there is no single path length, so a generalization of Beer's Law is needed. Assuming each time light impinges on the scattering surface that the same fraction of light is lost (i.e., is absorbed or scattered), indicates that the fractional amount of light, $S(x)$, that can reach the detector decreases exponentially with the distance it travels within the tube. In other words, the longer the light stays in the tube, the more likely it is that it has scattered within the tube or been absorbed and is no longer available for detection. Mathematically this is expressed as

$$S(x) = k\ \text{Ln}[10]10\text{^}(-b\ (x - x_1))$$

where k is the decay rate of the light versus distance, x_1 is the shortest distance traveled by the light, and the factor b Ln[10] normalizes the function (i.e., its integral from x_1 to infinity is 1, allowing this to be used as a distribution or density function). An example of this function is shown in Figure 7.3-5 when the decay rate, k, is 1.029 cm^{-1} and the minimal distance, x_1, is 1.235 cm. These two parameters will be determined by fitting to the experimental data taken from the sensor.

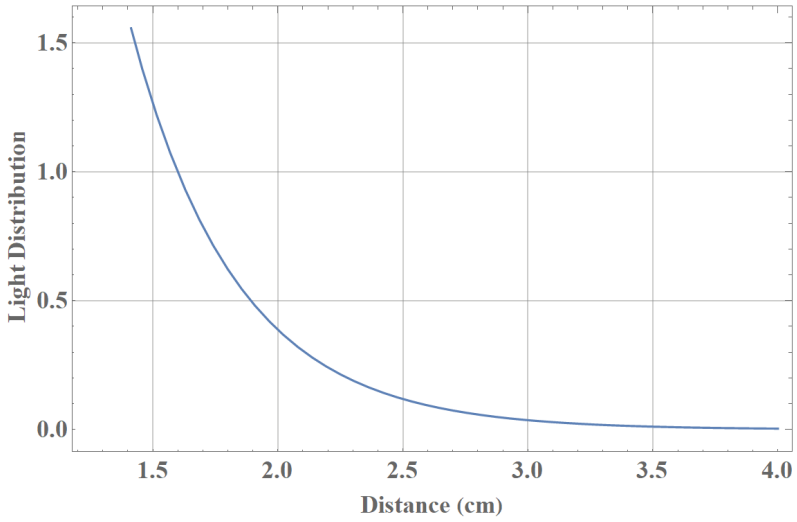


Figure 7.3-5. Example of Light versus Distance Travelled that Reaches Photodetector

If pretreat is present, then the proportional amount of light, $I(\lambda, x, p)$, that reaches the photodetector after having travelled a distance, x, is determined by scattering losses and absorption and is represented by the product of the distribution function, $S(x)$, and the Beer's Law transmission, $T(\lambda, x, p)$,

$$I(\lambda, x, p) = I_0 S(x) T(\lambda, x, p) = I_0 (k \text{ Ln}[10] 10\text{^}(-k\ (x - x_1)) 10\text{^}(-\alpha(\lambda)\ x\ p)$$

where I_0, is a proportionality constant. The total amount of light at any one wavelength that reaches the photodetector, $I(\lambda, p)$, is equal to the integral of this function over all path lengths from the minimal distance, x_1, to infinity. Integrating $I(\lambda, x)$, yields

$$I(\lambda, p) = I_0 \int_{x_1}^{\infty} I(\lambda, x) dx = I_0 \frac{10\text{^}(-\alpha(\lambda)\ x_1\ p)}{1 + \alpha(\lambda)\ p/b}$$

where Beer's Law has been recovered with an additional term in the denominator. This function is plotted in Figure 7.3-6 when the decay rate, k, is 1.029 cm^{-1}, the minimal distance, x_1, is 1.235 cm, and at three wavelengths, 515 nm, 525 nm, and 535 nm.

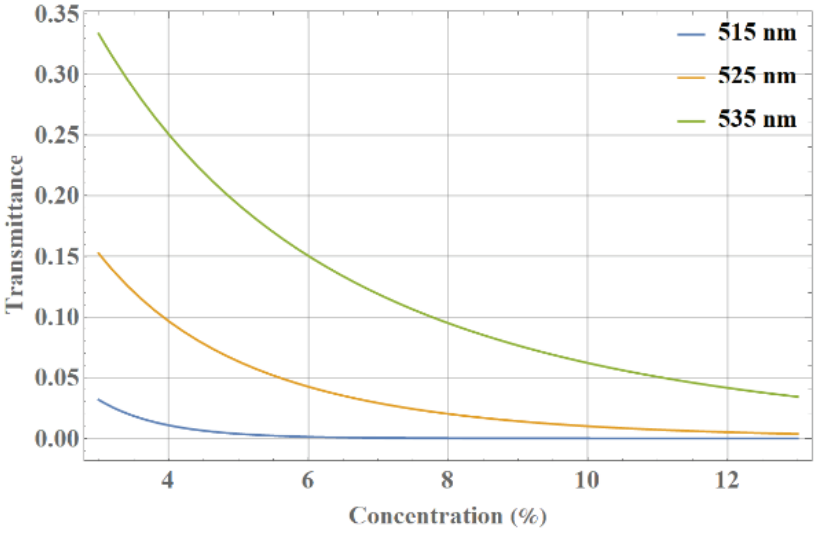


Figure 7.3-6. Transmittance versus Concentration for Three Different Wavelengths Passing Through Scattering Region

The light source being used in the sensor is a ThorLabs LED with a 525-nm center wavelength and a bandwidth of about 30 nm. Its normalized spectrum, $L(\lambda)$, is shown in Figure 7.3-7. The total light, $I(p)$, hitting the detector is then proportional to the integral of the LED spectrum, $L(\lambda)$, times the wavelength dependent transmission through the scattering region, $I(\lambda, p)$, over a band that includes the LED emission spectra, 400 nm to 650 nm.

$$I(p) = \int_{400}^{650} L(\lambda) I(\lambda, p) d\lambda$$

The function, $I(p)$, is not expressible in closed form, but can be numerically evaluated.

In practice, an inverted function is needed where concentration, p, can be found from the normalized, light intensity, I. Evaluating this numerically, a reasonably good fit can be achieved by using the function

$$p = a\frac{(I-1)}{(b + c\,I + d\,I^2)}$$

For the parameters used in the example plots shown in Figures 7.3-5 and 7.3-6, where the decay rate, k, is 1.029 cm^{-1}, and the minimal distance, x_1, is 1.235 cm, the following values yield an acceptable fit to the numerical function, $a = -6.93278$, $b = -0.0882987$, $c = 6.99981$, and $d = -1.85627$. The plot shown in Figure 7.3.8 shows the function (solid) line and the numerically determined values (red dots). This function is used by the microprocessor to find the pretreat concentration as a function of measured light intensity.

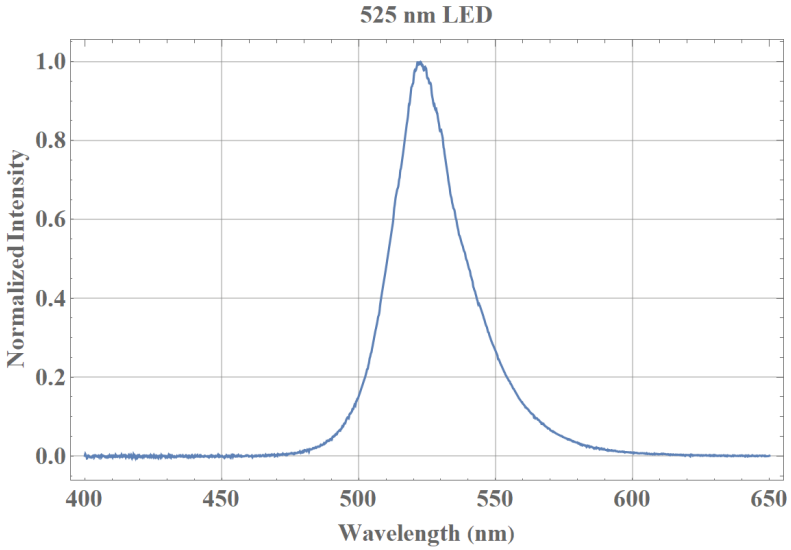


Figure 7.3.7. Normalized Intensity for ThorLabs 525-nm LED

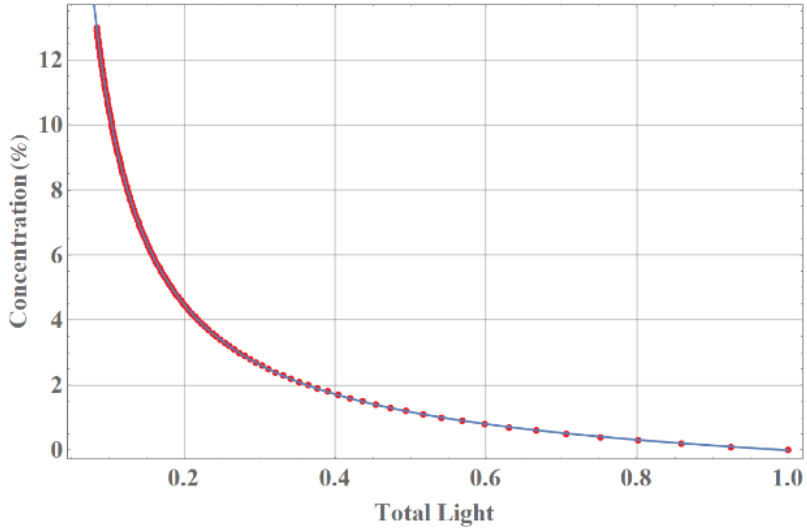


Figure 7.3-8. Functional Fit (solid line) and Numerical Values (red) Show Conversion from Light Measurement to Concentration

7.4 Transparent Tube Optical Pretreat Sensor Hardware

This section describes the hardware designed and constructed to make the optical pretreat sensor a stand-alone device, that only requires power and can generate an analog, 0-V to 10-V, output indicating the concentration of pretreat. The first subsection describes the circuitry, and the second subsection describes the packaging of the sensor.

7.4.1 Transparent Tube Optical Pretreat Sensor Circuitry

The relationship between light and concentration is sufficiently nonlinear (see Figure 7.3-8) that a microprocessor-based signal processing approach was chosen. This would allow digital conversion from the light measurements to an analog concentration voltage, calculating the correct amount of pretreat in the sensor. Figure 7.4-1 shows a block diagram of the analog and digital processing. The currents from the tube and reference photodiodes (PDs) are converted to voltages and sent to the microprocessor, where a normalized intensity is calculated by removing offset signals with the LED turned off and by dividing the tube/pretreat signal by the reference signal. The normalized intensity is used to calculate a pretreat concentration using the formula derived in Section 7.3.2. An analog output voltage is generated, which is scaled and buffered to provide the desired 0-V to 10-V output signal.

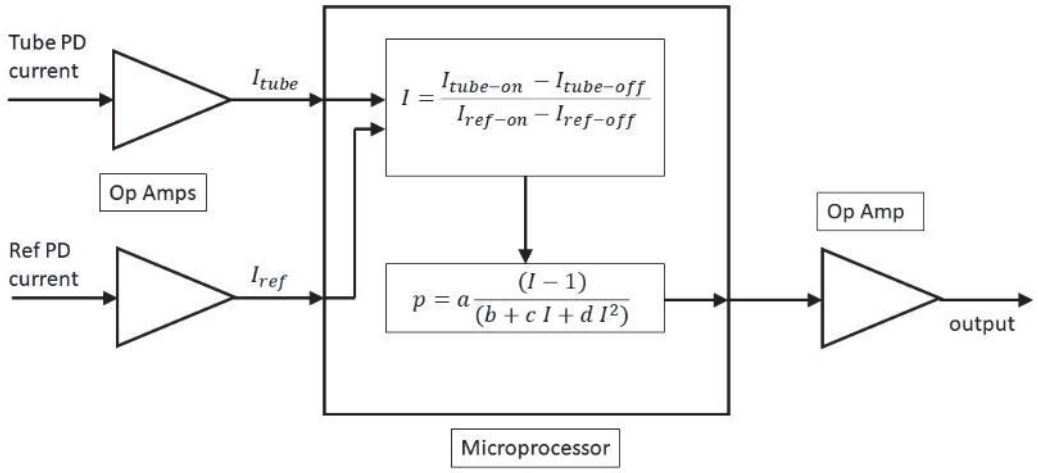


Figure 7.4-1. Block Diagram Showing Processing of Optical Signals

The photodiode circuits are shown Figure 7.4-2. Each photodiode is treated as a current source, and a Junction Field Effect Transistor (JFET) operational amplifier (a TLC2272) is used to convert this current to a voltage. The amount of light seen by the reference photodiode is greater than the amount seen by the tube photodiode, so the feedback resistor is lower to bring the two signals into an optimal range for the microprocessor analog-to-digital converter. In practice, the trim potentiometers are used to adjust the outputs of the two operational (op) amps to be 3 V when only water is present in the PFA tube. Clamping diodes are placed on the op amp outputs to protect the inputs to the microprocessor.

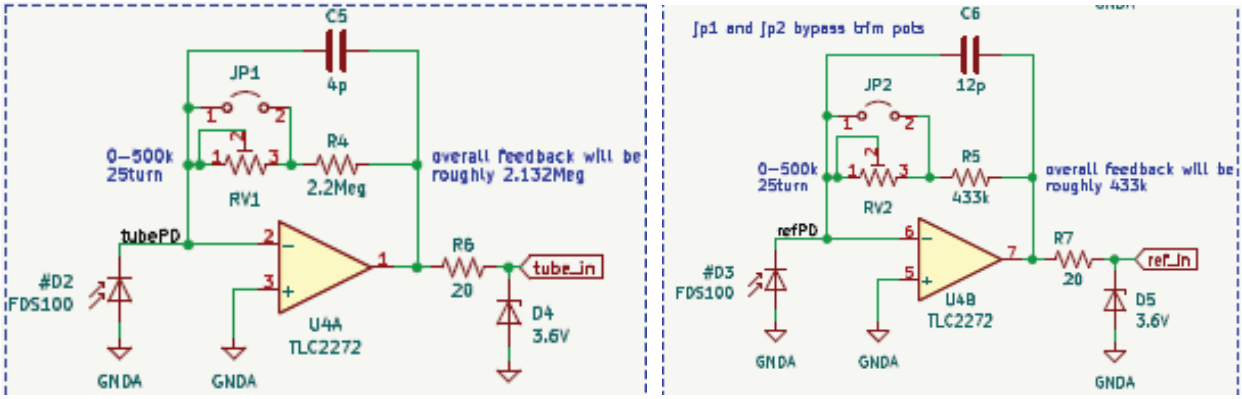


Figure 7.4-2. Sensor Photodiode Current-to-Voltage Converters
The tube circuit is on the left and the reference circuit is on the right.

The sensor is operated by cycling the LED at 1 kHz and then monitoring the photodiodes when dark and when lit and subtracting the two measurements. Doing this substantially reduces 1/f noise and minimizes interference ambient light sources. The microprocessor controls the LED using the circuit shown in Figure 7.4-3.

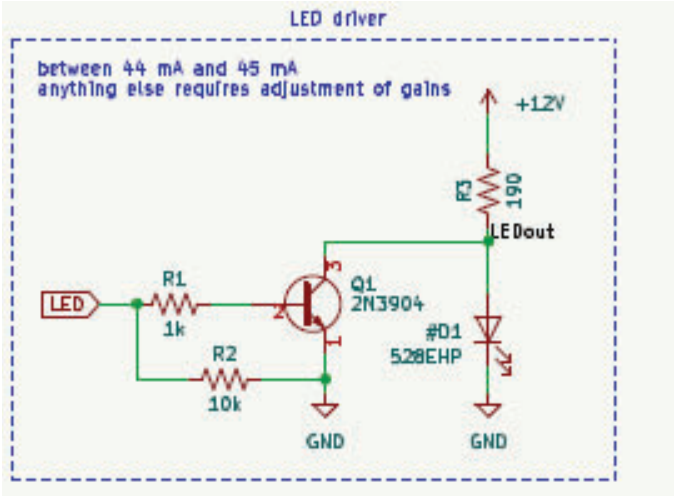


Figure 7.4-3. Circuit Used by Microprocessor to Turn LED Off and On

The microprocessor is a Teensy 3.2 with a 1-msec response time providing an updated signal once per LED cycle. This is a universal serial bus (USB) compatible processor that can sample the two photodiode channels to 16-bit resolution. It averages and then processes the signals to calculate the pretreat concentration and then generates a 0-V to 3.3-V analog output signal proportional to this concentration. A 3.0 times amplifier, shown in Figure 7.4-4 is used to amplify the processor output to the ISS Program specified 0-V to 10-V range.

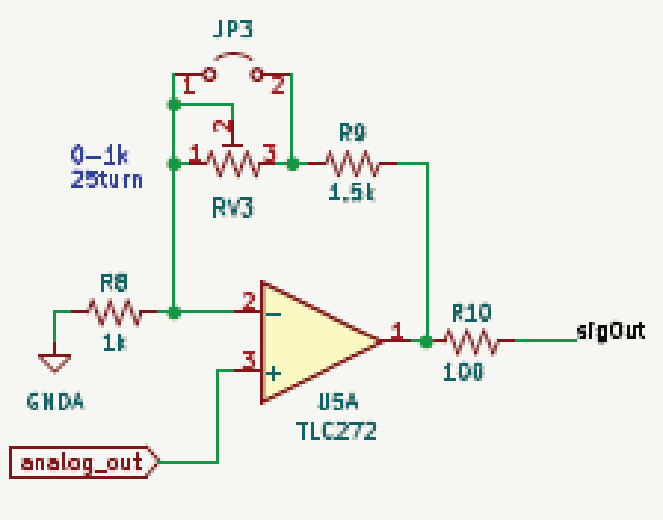


Figure 7.4-4. Circuit Used to Generate 0-V to 10-V Analog Output Range Representing Pretreat Concentration

7.4.2 Transparent Tube Optical Pretreat Sensor Packaging Development

The sensor requirements state that the packaged assembly be able to fit into a volume no larger than the existing conductivity sensor, which is about 11 cm high by 19 cm long by 9 cm wide (see Appendix A). Also, it should use specified PFA tube fittings and a specified electrical connector with the pin out shown in Appendix A. It was decided to construct a package smaller than the existing volume to showcase the sensor. The assembled device is shown in Figure 7.4-5 and is about 8 cm wide, 12 cm long, and 5 cm high. The left image shows the assembly without the electronics board where the PFA tube can be seen, and the right image shows it with the electronics board installed. The PFA tube passes under the electronics board and through the optical head. The LED is hidden from view, but the two photodiodes are visible. The enclosure is constructed from aluminum and has tapped holes on the corners to hold the cover in place, with the electrical connector bolted to the aluminum enclosure. A temporary USB connector is shown. Grommets are used to hold the PFA tube rigidly to the enclosure and fittings (not shown) are placed on the PFA tubing.

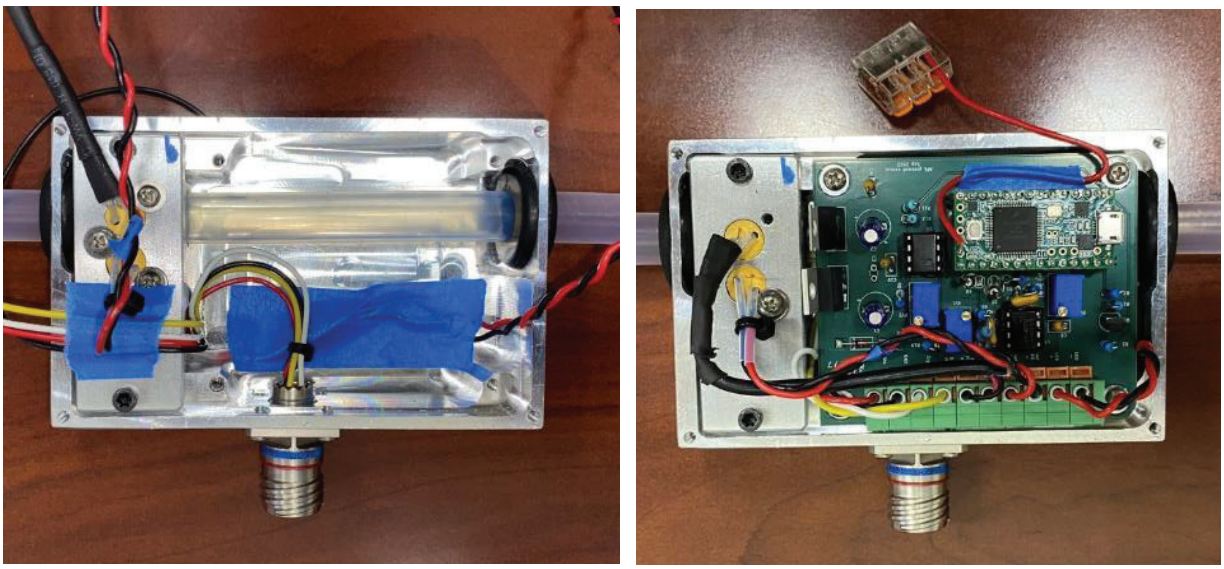


Figure 7.4-5. First Packaged, Transparent Tube, Pretreat Concentration Sensor (without and with electronics)

This first device was calibrated and used in flow testing but experienced issues. The PFA tube was not held rigidly in the optical head causing calibration drift and it was found that the grommets used to hold the tubing in place were distorting its cross section (see Figure 7.4-6). So, it was decided to construct a modified version of the assembled sensor in a larger box to provide more access, a better fit of the PFA tubing to the optical head, and a less damaging support for the PFA tubing (see Figure 7.4-7). The enclosure is a commercial off-the-shelf project box which is about 13 cm by 18 cm by 5 cm, a little larger than allowed by the specifications, but acceptable for a prototype unit. This version of the assembled sensor provided more consistent operation.

Figure 7.4-6. Damage Caused to PFA Tubing by Grommets

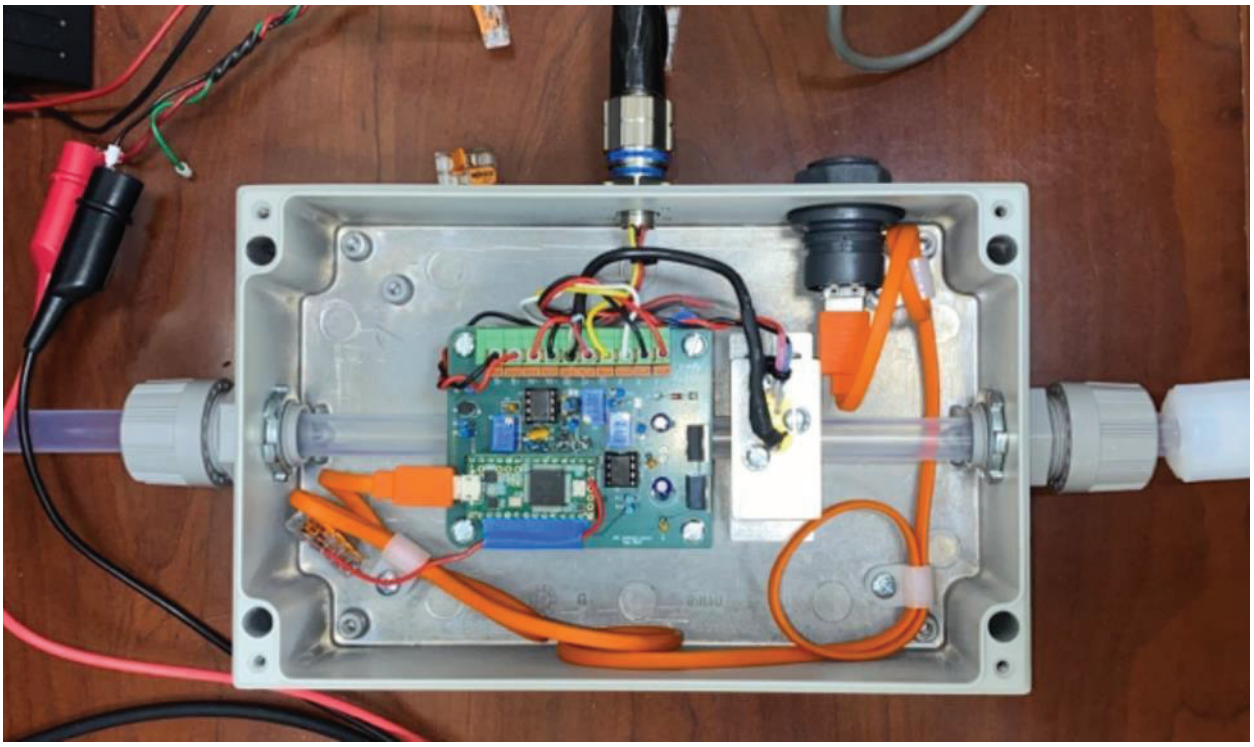


Figure 7.4-7. Second Assembled Pretreat Concentration Sensor

7.5 Transparent Tube Optical Pretreat Sensor Testing

The primary goal of this work is to demonstrate that the sensor can be used in the ISS UWMS as a replacement for the existing concentration sensor. To accomplish that the prototype sensor must not only monitor pretreat concentration in static testing, where the pretreat solution is poured into the sensor, it must monitor pretreat concentration levels as it flows through the sensor. The two following sections describe the static, or calibration, testing of the sensor and the flow testing.

7.5.1 Static Testing

As described in the Phase 1 report, quantities of pretreat solutions in pure water were created at concentrations of 3%, 5%, 7%, 9%, and 11% as seen in Figure 7.0-1. A 13% pretreat concentration solution was prepared and analyzed (see the Phase 1 report), but that concentration is well outside of the ISS Program requested operating range (maximum is 10%), so it was not used in the sensor calibration. The PFA tube in the first sensor (see Figure 7.4-5) was filled with each of these solutions, as well as with pure water corresponding to a 0% pretreat concentration, and the light intensity measured, yielding the data shown in Figure 7.5-1. These data were used to determine the best values for the decay rate, k, and the minimal distance, x_1, where the theoretical curve most closely matched the data, resulting in values of 1.029 cm^{-1} and 1.235 cm, respectively. This theoretical curve, based on the results of Section 7.3.2, matches the data, supporting the theory.

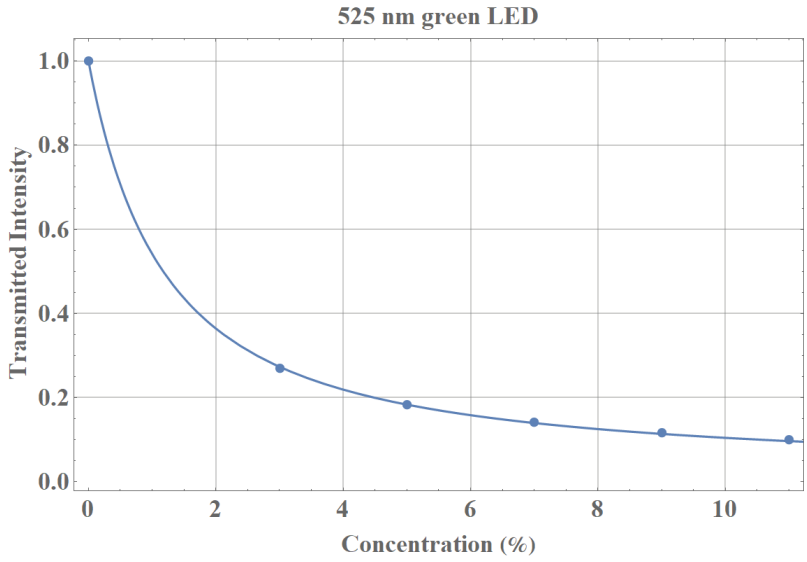


Figure 7.5-1. Light Intensity from Sensor versus Pretreat Concentration with Fitted Theoretical Curve

The theoretical curve can be inverted, yielding an equation that can be programmed into the microprocessor to convert normalized light to pretreat concentration. This curve and the measured data are shown in Figure 7.5-2 for the first assembled sensor.

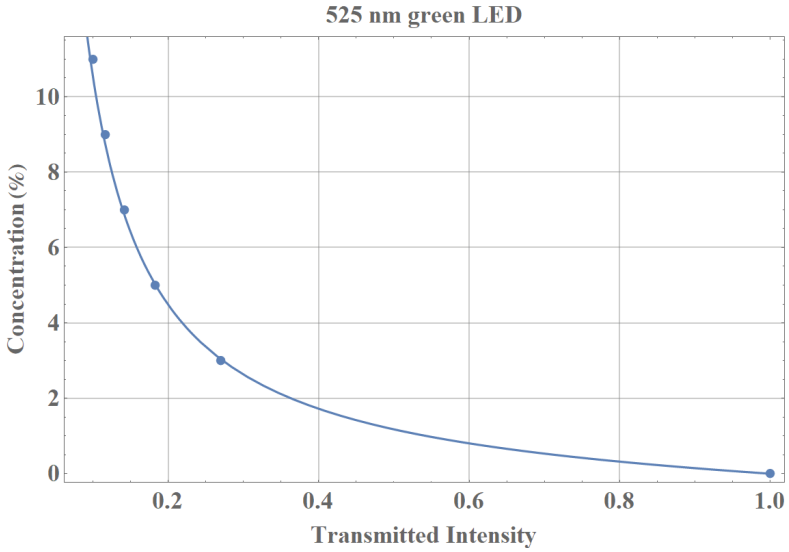


Figure 7.5-2. Pretreat Concentration as a Function of Light Intensity with Fitted Theoretical Curve for First Assembled Sensor

However, as mentioned, the first sensor was not stable, resulting in the design and construction of a second assembled sensor, as shown in Figure 7.4-7. This second sensor was calibrated, resulting in values indicative of improved light reflection within the optical head. The conversion algorithm from normalized light to pretreat concentration was programmed into the microprocessor and then the sensor was retested about a week later. The results are shown in Figure 7.5-3 where a shift is seen. The source of this shift is not known, possibly thermal, and corresponds to about a 3% offset, which is within the specifications, (e.g., reading 7.2% when it the correct concentration is 7%). There was a suggestion that the PFA may be affected by the

pretreat; however, a sample of PFA was exposed to pretreat for an extended time and no change in the PFA was seen.

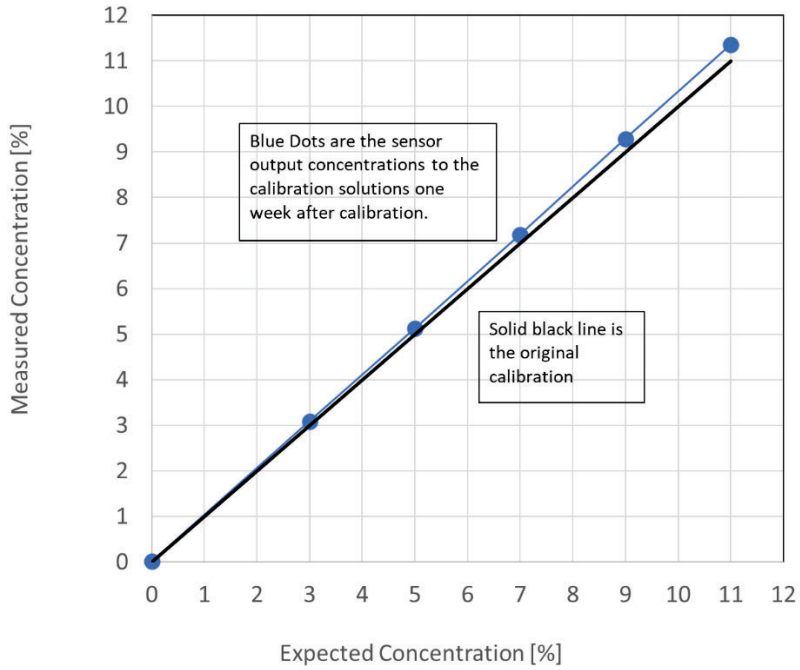


Figure 7.5-3. Second Sensor Operation After Calibration

7.5.2 Flow Testing

In the ISS UWMS, a dose pump injects concentrated pretreat into a line with flowing water to achieve the net desired concentration of pretreat to water. So, depending on mixing and the pretreat injection rate, the flow reaching the sensor will have variations in concentration. The sensor will need to monitor these variations, providing an analog output with the proper response time and accuracy that the UWMS data acquisition system can process the data and calculate the average concentration.

The sensor response time (or speed) must be sufficient to track changes in the pretreat concentration. To find this time, note that the maximum flow through the water/pretreat line on the ISS UWMS is about 8 ml/sec. The 0.95-cm ID PFA tube has an area of about 0.71 cm^2, so an 8 ml/sec flow rate results in a velocity of 11.3 cm/sec. The photodiode is 3.6 mm by 3.6 mm square, where the opening through which light can reach the photodiode is about 3.8 mm in diameter, so the entire photodiode is exposed. Therefore, at a velocity of 11.3 cm/sec, the sensor must provide an independent reading every 34 milliseconds (i.e., an update rate of at least 30 readings per second). In the present design, the response time of the system has been set at about 1 kHz, which is greater than what is needed to provide tracking of the changes in the pretreat concentration.

The flow system, shown in Figure 7.5-4, was constructed to test the sensor operation when monitoring the injection of pretreat into a flowing water stream. A peristaltic pump is used to pump water from a container through the PFA tubing. An injection port, where undiluted pretreat is injected manually using a syringe, is located upstream of the sensor as shown, where the flow is from right to left. The mixed solution is then deposited in a glass container (not shown) for disposal. The water stream is flowing at 9.3 ml/sec, which is faster than that used in the UWMS.

Several flow tests were performed corresponding to different rates of pretreat injection. Figure 7.5-5 shows the measured pretreat concentration for one of these flow tests where approximately 3.7 ml of pretreat was manually injected into the flow stream over about a 3-second period. The injection rate was roughly uniform for over 2 seconds.

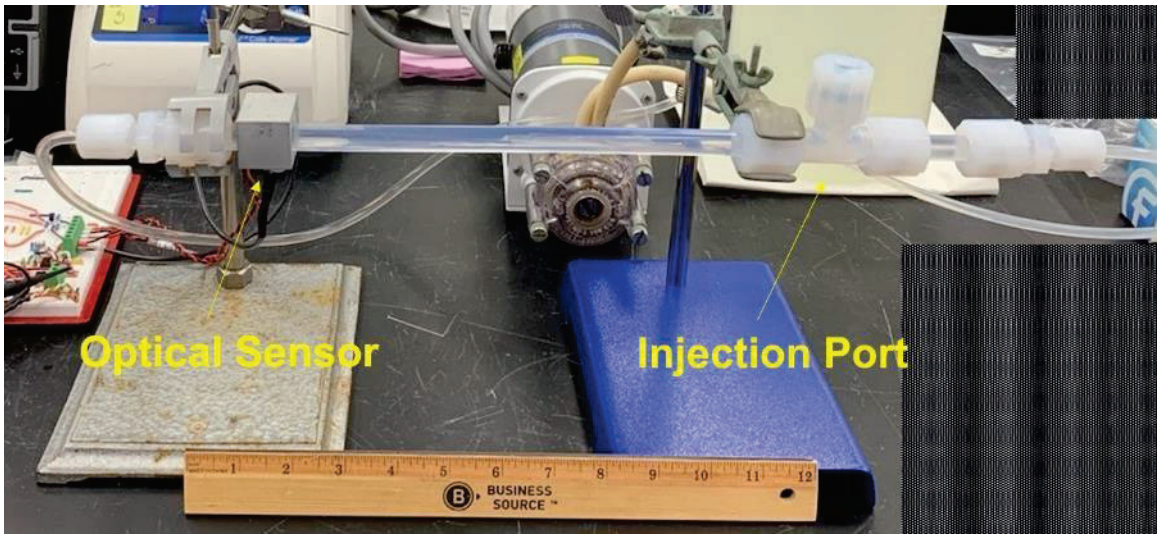


Figure 7.5-4. Flow Test System Using Just Sensor Head

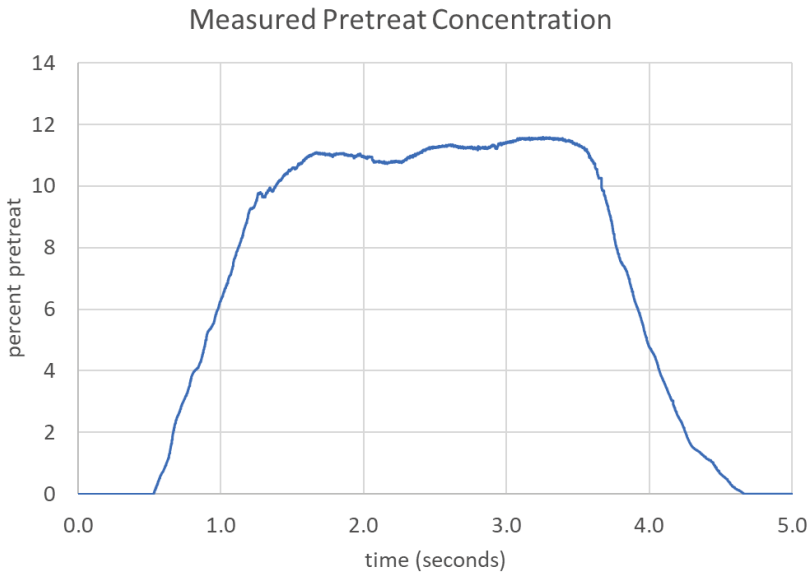


Figure 7.5-5. Measured Concentration During Flow Test

To convert from measured concentration to total pretreat, recall that the pretreat concentration is given by the ratio of the pretreat flow rate divided by the total flow rate. Letting p equal the fractional pretreat concentration, f_p equal the pretreat flow rate (or pretreat injection rate), and f_w be the water flow rate, the pretreat fractional concentration is given by

$$p = f_p/(f_p + f_w)$$

Solving for the pretreat flow rate yields

$$f_p = pf_w/(1 + p)$$

Integrating the pretreat flow rate, f_p, over time yields the total amount of pretreat injected into the water flow.

Recall that the volumetric water flow in the tube was preset at 9.3 ml/sec. Using this and the data shown in Figure 7.3-2 yields a total injected amount of pretreat of 3.5 ml, which is lower than the measured amount of 3.7 ml, but within 6% of the correct value. Figure 7.5-6 shows the integrated result versus time where the total amount of pretreat has plateaued at 5 seconds into the test.

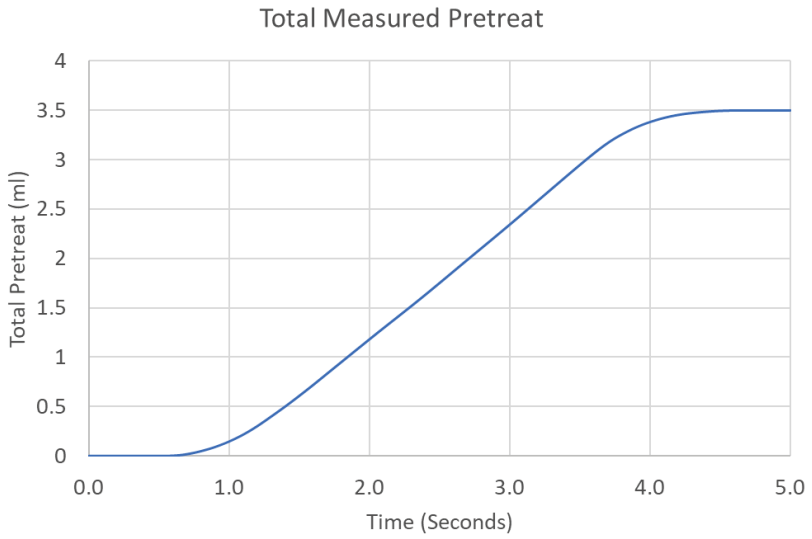


Figure 7.5-6. Total Measured Pretreat versus Time

The most likely reason for the low reading is lack of mixing between the pretreat and the water. Beer's Law is nonlinear, and it can be shown that if the concentration of pretreat varies spatially in the water solution that the net light through this unmixed solution will he higher than through a well mixed solution. In other words, an optical sensor monitoring an unmixed solution will indicate less pretreat than is present. Discussions with Collins Aerospace indicate that there may be insufficient mixing of the pretreat on the UWMS. This may result in inaccurate performance by the sensor.

After construction of the second packaged sensor, shown in Figure 7.4-7, flow testing was performed again with modifications as seen in Figure 7.5-7. Immediately after the injection point a mixer was installed (see the yellow component in Figure 7.5-7) and the sensor was positioned vertically to help minimize stratification of the pretreat.

Figure 7.5-7. Flow Testing with Second Packaged Sensor

As before, pretreat was injected manually into the flowing water stream as shown in Figure 7.5-8. Care was taken to determine the amount of pretreat being injected into the water stream. Using a scale and the known density of pretreat it was determined that 3.74 ml of pretreat was injected during the test. In addition, the flow rate of the water was more accurately determined to be 9.33 ml/sec.

Figure 7.5-9 shows the sensor output during the flow test, providing the percentage of pretreat in the water stream as a function of time. Using the equation derived above for the pretreat flow rate, f_p, the total amount of pretreat injected into the line versus time can be found and is shown in Figure 7.5-10. The total amount of pretreat, as measured by the sensor, is 3.36 ml.

This is smaller than the amount injected (about 11% low) and caused a careful reconsideration of the test and associated parameters. After discussions it was recalled that the water system has recently had its filter replaced, resulting in air bubbles in the flow stream. The test conductor recalled that the water stream contained so many microbubbles that it was cloudy. The appearance of these bubbles will scatter light and alter the flow rates, likely explaining the under-determination of the total amount of pretreat injected into the line.

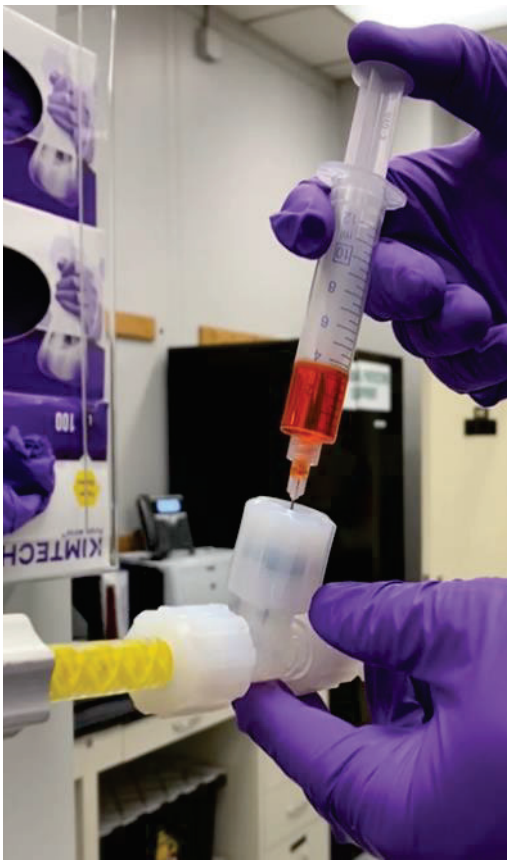


Figure 7.5-8. Manually Injecting Pretreat into Water Stream

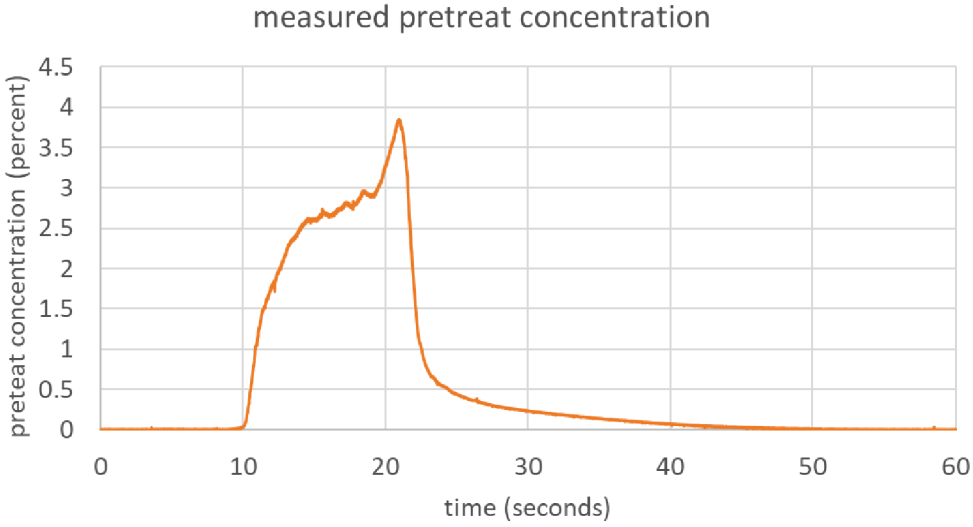


Figure 7.5-9. Measured Pretreat Concentration During Flow Test

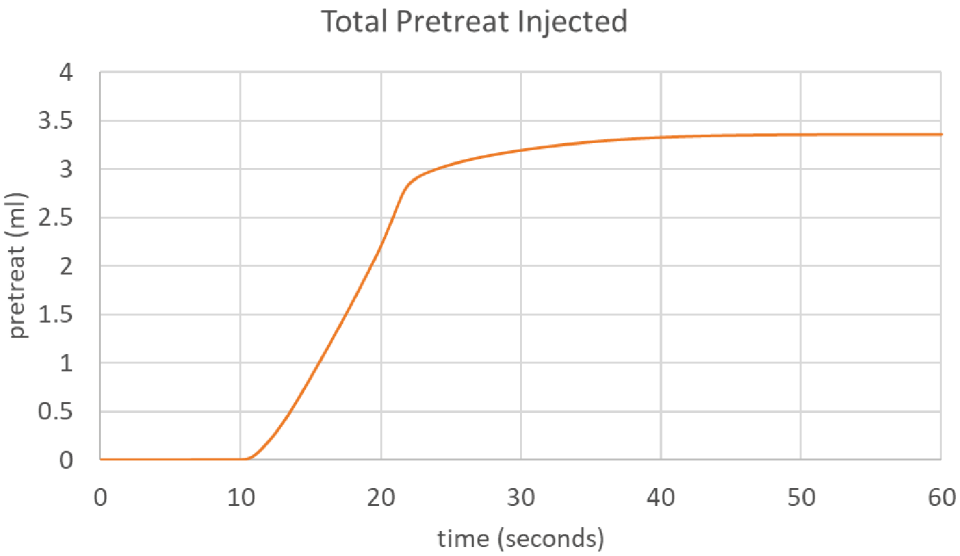


Figure 7.5-10. Calculated Total Pretreat versus Time

In addition, the sensor was only calibrated for pretreat concentrations between 3% and 11% and that the flow system shown above, with the manual injection, generated pretreat concentrations outside of the calibration range of the sensor. This is a limitation of manual injection with a syringe rather than using a dose pump (e.g., ISS UMWS).

8.0 Findings, Observations, and NESC Recommendations

8.1 Findings

The findings from this Phase 2 prototype sensor development are:

F-1. Sensor performance is not significantly affected by up to 4 ppm of iodine that may be present in the ISS potable water system.

F-2. An optical pretreat concentration sensor has been demonstrated that meets the specifications provided by the ISS Program.

F-3. The performance of the optical pretreat concentration sensor is affected by inadequate mixing of the pretreat and the water, as well as the presence of bubbles in the flow. It is speculated that the conductivity sensor in the UWMS will also be affected by these flow issues.

8.2 Observations

O-1. The sensor does not need to monitor pretreat aging on the ISS UWMS, since the replacement cycle ensures the pretreat is viable, however this capability may be needed for long duration missions.

9.0 Alternate Technical Opinion(s)

No alternate technical opinions were identified during the course of this assessment by the NESC assessment team or the NRB.

10.0 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 is not 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.
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.

11.0 Acronyms and Nomenclature List

A/D	Analog to Digital
APTS	Alternate Pretreat Solution
CrO_3	Chromium Trioxide
ECLS	Environmental Control and Life Support System
H_2O	Water
H_3PO_4	Orthophosphoric Acid
ID	Inner Diameter
ISS	International Space Station
JFET	Junction Field Effect Transistor
KSC	Kennedy Space Center
LASSO	Laboratory Support Services and Operations Contract
LED	Light emitting Diode
MPCV	Multipurpose Crew Vehicle
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
op	operational
PD	Photodiode
PFA	Perfluoroalkoxy
PPE	Personal Protective Equipment
PWQ	Process Waste Questionnaire
TC	Total Carbon
TIC	Total Inorganic Carbon
TIM	Technical Interchange Meeting
TOC	Total Organic Carbon
UPA	Urine Processing Assembly
USB	Universal Serial Bus
UV/Vis	Ultraviolet Visible
UWMS	Universal Waste Management System
V/V%	volume per volume percent

12.0 References

1. "ISS Toilet Discussion," Technical Interchange Meeting, January 12, 2022, held by Collins Aerospace.
2. "Universal Waste Management System (UWMS)—Toilet Status," December 15, 2021, Melissa McKinley, UWMS Project Manager.
3. Youngquist, Robert C.; Skow, Miles; and Nurge, Mark A.: "Optical Distortion Evaluation in Large Area Windows Using Interferometry", *14th International Symposium on Nondestructive Characterization of Materials*, Marina del Rey, California, June 2015, published on-line in NDT.net Vol. 20, No. 9 Sept. 2015.
4. Arens, Ellen E.; Youngquist, Robert C.; and Starr, Stanley O.: "Intensity calibrated hydrogen flame spectrum," *Int. J. of Hydrogen Energy*, Vol. 39, Issue 17, June 5, 2014, pp. 9545-9551.
5. Youngquist, Robert C.; Simmons, Stephen M.; and Belanger, Andrea: "Spectrometer wavelength calibration using spectrally resolved white light interferometry," *Optics Letters*, Vol. 35, 2257-2259 (June 2010).
6. Collins, J. D.; Youngquist, R. C.; Moerk, J. S.; Gleman, S. M.: "Infrared Multispectral Imaging for the Detection of Hydrogen Fires," *JANNAF Meeting*, Livermore, Ca. Editor, C.T. Hudson, pp. 73-79, 1990.
7. Youngquist, Robert C.; Carr, Sally; and Davies, D. E. N.: "Optical coherence-domain reflectometry: a new optical evaluation technique," *Optics Letters*, vol. 12, March 1987, pp. 158-160. Reprinted in "Selected Papers on Optical Low-Coherence Reflectometry & Tomography", Ed. Barry R. Masters, *SPIE Milestone Series*, Volume MS 165. Pp. 119-121. Bellingham, Washington, USA 2001.

Appendix A: Urine Pretreat Solution Sensor Specifications

1. The ideal concentration of pretreat to water is 6.7 ± 1% (by volume). Pretreat is composed (by mass) of
    a. 6.8 ± 0.7% CrO_3 (>98% purity)
    b. 15.9 ± 2.6% water
    c. 77.3 ± 2.4% concentrated phosphoric acids (85% H_3PO_4 by mass)

    The contractual requirement for the UWMS is
    a. The item shall deliver a solution of 5.67% to 7.85% of pretreatment concentrate volume by total solution volume to the UWMS Fluid Interface when the Actuation Human Interface is actuated.
    b. The item shall deliver a solution of 3.3 mL to 3.75 mL of pretreatment concentrate and 44 mL to 56 mL of dilute water to the UWMS Fluid Interface when the Actuation Human Interface is actuated.
2. The sensor should generate a voltage output between 0 V and 10 V that corresponds to a pretreat concentration (in percent) by the following formula:

    Voltage = 1.254 * concentration-3.4

    A 0-V output corresponds to a concentration of 2.7%,
    A 5-V output corresponds to a concentration of 6.7%,
    A 10-V output corresponds to a concentration of 10.7%.

    This relationship is shown graphically in Figure A-1.
3. The sensor will operate over the temperature range of the ISS, 17 °C to 31 °C.
4. The sensor will provide a correct reading when using the water on board the ISS. The primary concern is iodine which may be as high as 4 ppm.
5. The sensor needs to have an adequate response time to track changes in the pretreat concentration. The flow can vary from 0 ml/sec to 8 ml/sec.
6. The following materials have been approved for contact with the pretreat:
    a. Metallics: Hastelloy C-276, commercially pure titanium, Titanium 6AI-4V, Titanium 3Al-2.5V, Inconel 625, Elgiloy
    b. Non-Metallics: Teflon™ - PTFE, FEP, PFA (DuPont Supplied), PCTFE, Parker V747-75, Braycote 601EF

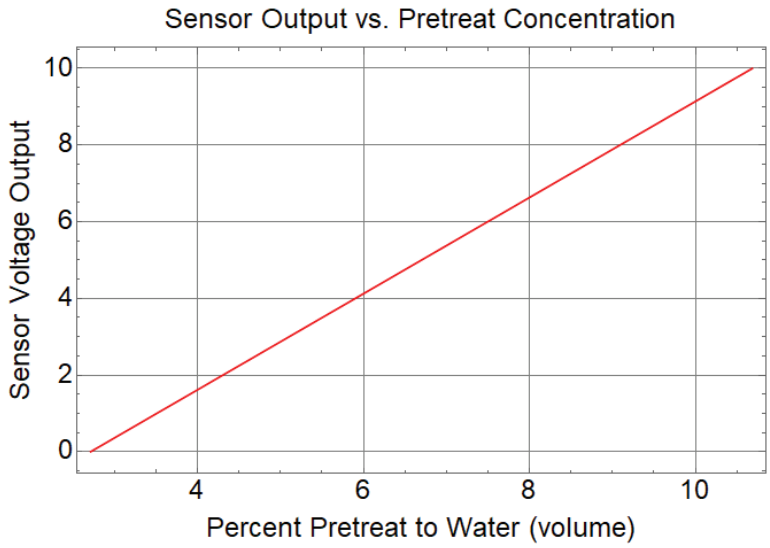


Figure A-1. Sensor Output Voltage versus Percent Pretreat in Water

7. Volume

   The existing conductivity sensor volume is about 11 cm high by 19 cm long by 9 cm wide. The new sensor should fit into that volume. Fittings are aligned with the length dimension.

8. Fittings

   The existing sensor has male AS1098-08 fittings, but for testing AS4395 is acceptable. If tubing or hoses are being added to the sensor, then the existing sensor has an 20 cm hose on the inlet and a 25 cm hose on the outlet. The hose ends are AS4395-08/AS1098-08 with floating nuts.

9. Connector

   The electrical connector is D38999/20LA35PB, but direct wires are acceptable for testing. The pinout is

   - Pin 1 – Open
   - Pin 2 – 15 VDC excite
   - Pin 3 – 15 VDC return
   - Pin 4 – Signal return
   - Pin 5 – Signal (0 VDC to 10 VDC)
   - Pin 6 – Open

Appendix B: Pretreat Handling Procedure Submitted for Kennedy Space Center (KSC) Safety and Health Review Board Review

Spectroscopy of ISS Pre-Treat Solution

There is a desire by the International Space Station (ISS) Program for a better, more reliable method of determining the 'quality' of the alternate pre-treat solution (i.e., alternate pre-treat solution (APTS)) that is utilized by the ISS Universal Waste Management System (UWMS). The current method for determining the 'quality' of the APTS is to measure its conductivity, after dilution, using a conductivity probe. The KSC Applied Physics Laboratory has proposed that optical spectroscopy could be used to measure the 'quality' of the APTS and has submitted a request to the NASA Engineering and Safety Center (NESC) for preliminary funding to investigate the concept. The NESC has given a preliminary approval for the funding and final approval is expected in the next several weeks.

As part of the effort, Laboratory Support Services and Operations (LASSO) Chemists in the Applied Chemistry Laboratory will prepare diluted ATPSs in M7-0355, Room 2214 and perform the spectroscopy using the JASCO V770 UV/Vis/NIR instrument in M7-0355, Room 2223. The work falls within the scope of KSC-PLN-2322_ACL-ALC-003 and KSC-PLN-2322_ACL-ALC-004. Details of the procedure follows.

- Obtain 25 ml of APTS from Jason Fischer (LASSO) from the supply located in M7-0360. The APTS is composed of the following:
  - CrO_3 – 6.8%
  - H_2O – 15.9%
  - H_3PO_4 – 77.3%
- In a chemical fume hood, wearing the appropriate personal protective equipment (PPE) (e.g., chemical-resistant laboratory coat, nitrile gloves, splash resistant goggles, and a face shield) pipette the appropriate volumes of APTS into 10-ml volumetric flasks needed to produce solutions with concentrations of 1, 3, 5, 7, 9, 11, and 13% APTS (volume per volume percent (V/V%)). Add the appropriate volume of nanopure water to each volumetric flask to complete the solution preparation. Stir/shake each volumetric flask carefully to mix the solutions. The volumetric flasks and APTS will be placed in a secondary container to minimize the risk of spilling the solutions onto the hood surface.
- Pipette the appropriate volume of diluted APTS into a quartz cuvette for spectroscopy. Nanopure water is pipetted into a second quartz cuvette to serve as the reference material. The cuvettes have caps, and they will be hand carried to M7-0355, Room 2223 for analysis.
- Carefully transport the filled cuvettes to M7-0355, Room 2223, and collect the ultraviolet visible (UV/Vis) spectrum for the diluted APTS. Once completed, return the solution to M7-0355, Room 2214, and empty the contents into a labeled waste container. A Process Waste Questionnaire (PWQ) has been submitted for this waste stream. Rinse the cuvette containing the solution three times with nanopure water, emptying the rinses into the labeled waste container. Repeat this process until all diluted APTSs have been analyzed.
- Contact LASSO Safety for waste pickup.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
05/16/2023	Technical Memorandum	

4. TITLE AND SUBTITLE
ISS Universal Waste Management System (UWMS) Optical Sensor

Phase 2

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Singh, Upendra N.; Biagi, Christopher; Gibson, Tracy L.;
Youngquist, Robert C.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
869021.01.23.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
NESC-RP-22-01727

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-20230007658

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category Spacecraft Design, Testing and Performance
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Collins Aerospace has delivered a new Universal Waste Management System (UWMS) to the International Space Station (ISS), which is not operational, partially due to a faulty urine pretreat concentration sensor. The ISS Program requested help from the NASA Engineering and Safety Center (NESC) in developing such a sensor. The first phase of this effort was to determine if an optical approach was feasible. The second Phase, the topic of this report, was to determine the impact of ISS water contaminants and pretreat aging on the performance of the sensor and to design, construct, and test a prototype sensor.

15. SUBJECT TERMS
International Space Station; NASA Engineering and Safety Center; Universal Waste Management System; Sensor

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	45	(443) 757-5802