Hot Water, Cold Reality: Experimental Analysis of Sorption Constraints in Iodine Filtration Media Under Heated-Water Conditions

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Iodine has been widely employed as a residual biocide in potable water applications during crewed missions. Unlike other biocides, it is essential to remove iodine from drinking water prior to consumption, as its biocidal concentration raises health concerns. Consequently, effectively removing iodine species from water is a critical step in potable water processing. Although the non-biocided heated leg has not violated microbial specifications on the International Space Station, any wetted volume lacking biocide presents potential risks for long-duration exploration missions and for systems that are sensitive to microbial growth/contamination. Recent assessments indicate, however, that iodine-removal performance may degrade under elevated temperature conditions, such as those required for dispensing hot water for food preparation. This reduction in efficacy appears to stem from both the potential physical degradation of filtration media and the temperature-dependent behavior of adsorption processes. To investigate the influence of water temperature on the efficacy of filtration media for iodine removal, a series of adsorption capacity tests were conducted at both room temperature and elevated temperatures (90 °C). These experiments aimed to benchmark the performance of the adsorbents that constitute the ACTEX filter in the ISS's potable water dispenser. The findings of this study provide critical insights into the iodine filtration process, verify the potential performance shortfall under elevated temperature conditions, and establish the basis for defining new absorbent requirements to ensure reliable iodine removal in future mission architectures.

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Acronyms and Nomenclature

ACTEX = Activated Carbon/Ion Exchange
GAC = Granular Activated Carbon
H^+ = *Proton*
I^- = *Iodide*
I_2 = *Molecular Iodine*
ISS = *International Space Station*
IX = *Ion Exchange*
LSS = *Life Support Systems*
N_{Pe} = *Péclet Number*
pH = *Hydrogen Potential*
PWD = *Potable Water Dispenser*
R^2 = *Coefficient of Determination*

I. Introduction

Iodinating water at a 1-4 ppm concentration has historically been a key method to effectively maintain microbial control in potable-water streams and reservoirs for various manned missions. The extensive use of iodine in water recovery and management systems has not only demonstrated consistent chemical potency against a broad spectrum of microbials but also fair compatibility with legacy metallic materials, simple integration with logistical and operational procedures, and stable water-quality monitoring [1]. Although the residual-biocide portfolio has been expanded with the development of new antimicrobial strategies for spacecraft potable water applications, iodine remains a highly-regarded option in trade-off analyses and feasibility assessments by the Life Support Systems (LSS) community [2], [3], [4], [5], [6], [7]. Nevertheless, iodine has a fundamental limitation that imposes pivotal engineering considerations on its integration into potable water systems: At biocidal levels, extended consumption of iodinated water poses human-health risks [8], [9]. Consequently, extra equipment must be installed in water systems at points of use to ensure the removal of iodine from drinking water. A case in point is the Activated Carbon/Ion Exchange (ACTEX) filter, an essential component for removing iodine from water distributed to the Potable Water Dispenser (PWD) aboard the International Space Station (ISS) United Sates on-orbit segment.

The ACTEX filter can remove iodine from up to 4,320 lbm of iodinated water supplied to the PWD; however, because it is not located at the terminal point of the PWD, a downstream section of the water line remains without biocide protection [10]. In the PWD, this section primarily consists of the water-heater lines, where the absence of dissolved biocide may be offset by the local thermal conditions experienced during the heating process, which could be sufficient to limit microbial growth and biofilm formation. In general, a configuration with sections lacking biocide is undesirable in idealized and redundant water-dispenser designs because the non-iodinated water volume can promote biofilm growth, particularly during long stagnant periods, yet it has not presented a significant issue during continuous on-orbit operation of the PWD. Despite this success, the absence of biocidal agents in certain sections of water distribution lines may present a more critical challenge for systems exposed to prolonged dormancy, which is an inherent operational condition anticipated in architectures for exploration missions. In this study, it is conjectured that the PWD design intentionally avoids positioning the ACTEX filter near the distribution end because the filtration media is not optimally designed to remove iodine from heated water (~90°C) supplied by the internal water heater which is located between the filter and the dispensing point. If temperature constraints are not the underlying technical limitation, no other substantive engineering consideration appears sufficient to preclude positioning the ACTEX filter as close as possible to the dispensing outlet in subsequent PWD designs. A comprehensive system-level evaluation of the PWD architecture, with particular emphasis on the implications of iodine removal from heated water, is presented in a concurrent investigation by Nadeau et al [11].

Given that the open-source literature within the LSS domain does not explicitly address the engineering rationale for the placement of the ACTEX filter within the PWD, this investigation aims to characterize the iodine-removal performance of the ACTEX filtration media under both ambient and elevated temperature conditions. However, this effort seeks to scientifically and systematically characterize the presumed material limitations, starting with an evaluation of their sorption characteristics, prior to constraining the study to strict flight operational conditions that, in some cases, preclude detailed scientific assessment of the phenomena and provide only pass/fail results lacking contextual information. By evaluating the activated carbon and ion-exchange materials across these thermal regimes, the influence of temperature on iodine adsorption capacity can be quantified. The experimental methodology comprises a series of batch adsorption tests designed to establish equilibrium metrics for determining global and bulk

performance parameters. Within this scientific framework, the objectives of the study are as follows: (1) assess whether a measurable difference in sorbent performance exists when treating iodinated water at ambient versus heated conditions; (2) derive theoretical parameters that represent the average performance of these materials using equilibrium data; and (3) formulate recommendations for higher-fidelity testing and design improvements for future water de-iodination units applicable to PWD-like systems design to use iodine as a residual biocide.

II. Background: Iodine Sorption

In a heterogeneous system, dissolved iodine can be removed from the liquid phase by a solid substrate through coupled physical and chemical processes, the efficiency of which depends on solute speciation, concentration, temperature, chemical reactivity, hydrogen potential (pH), and available surface area. When molecular iodine (I_2) is dispersed in aqueous volume, the dissolution process is spontaneously followed by I_2 hydrolysis (see Equation 1) [12]. This phenomenon at equilibrium along with other intertwined lesser reactions produces iodide (I^-), protons (H^+), iodic-acid species which establish the simultaneous presence of iodine in both ionic and covalent forms at a given pressure and temperature. Nevertheless, the bulk speciation mechanism results in the dominant abundance of I^- *and* I_2 with a strong dependency on temperature that generally promotes more ionic iodine and pH increase as this parameter rises [13]. The influence of temperature can be quantitatively represented through thermodynamic frameworks, such as the electrolyte NRTL* model, with an illustrative example provided in Figure 1. Therefore, a heterogeneous iodine adsorbent must demonstrate sufficient removal capacity for I^- and molecular I_2 across the relevant operational temperature range.

$$I_2 + H_2O \rightleftharpoons HOI^- + I^- + H^+ \quad (1)$$

The typical mechanism involved in the sequestration of these solutes from an aqueous phase are ion exchange (IX), physisorption, and chemisorption [14]. Whereas physisorption interactions are predominantly governed by electrostatic forces, chemisorption and IX mechanisms proceed through the formation of chemical bonds or surface complexation and the substitution of superficial ions, respectively. Accordingly, filtration systems intended for the removal of both ionic and nonionic solutes typically employ distinct substrates optimized for ion exchange and physisorption, as most marketable sorbents are not engineered to deliver high-capacity performance for both mechanisms simultaneously [15]. With this consideration, iodine-sorption systems must accommodate increased ion-exchange capacity as iodine speciation shifts toward its ionic form with rising water temperature, a trend illustrated in Figure 1, which contrasts with the predominance of molecular iodine at ambient conditions.

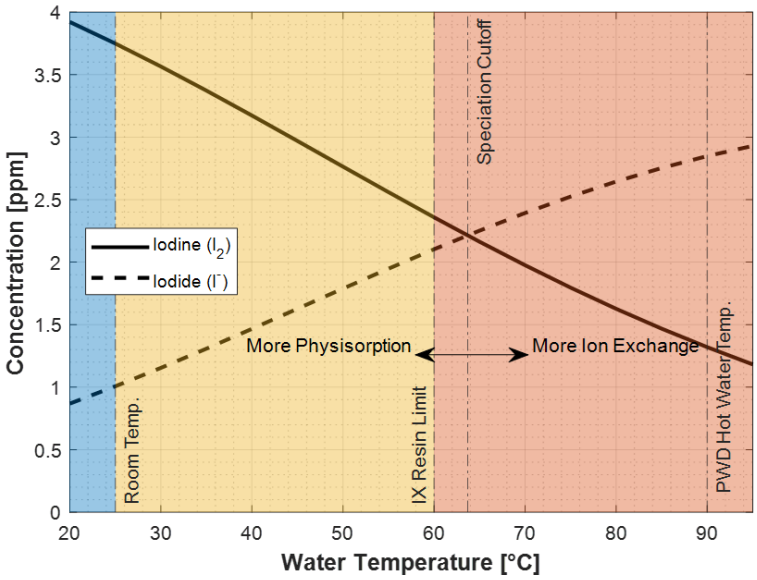

Figure 1. Temperature Effect on Speciation of 5 mg/L Iodine in Water. *Adapted from Nadeau et al. [11].*

The ACTEX unit is a small packed-bed system that contains two commercially-available sorbents: AmberSorb™ 4652 and UltraClean™ UCW3600 [16], [17], [18]. AmberSorb™ 4652† is a product based on engineered granular activated carbon (GAC) with high porosity/surface area, and UltraClean™ UCW3600‡ is a mixed IX resin based on a polymeric matrix loaded with anionic and cationic IX sites. The ACTEX bed has a total volume of 250 mL [17],

* Non-Random Two-Liquid (NRTL) model is a widely used activity coefficient model for predicting phase behavior in non-ideal liquid mixtures and provided by simulation tools such as Aspen Plus.

† www.dupont.com

‡ www.purolite.com

within which the filtration-media components are compartmentalized using disk spacers; however, the precise ratio of GAC to IX resin is not publicly disclosed in technical proceedings. Nevertheless, it can be reasonably inferred that the packed media contains a higher proportion of IX resin than GAC to ensure adequate removal of ionic iodine, given that engineered carbon-based materials typically exhibit greater bulk sorption capacity per unit mass compared to synthetic resins [19], [20]. If the system design necessitates a higher proportion of IX resin to ensure effective iodide removal at ambient temperature, an even greater quantity of UltraClean™ UCW3600 will be required as water temperature rises, given the increased transition of iodine to its ionic form at higher water temperatures.

Moreover, temperature not only influences iodine speciation, but also affects the fundamental mechanisms of ion exchange and physisorption, as these processes are inherently sensitive to thermal variations. In particular, the efficiency of physisorption decreases at elevated temperatures, as the increased kinetic energy of solute molecules surpasses the weak electrostatic forces governing their interaction with the sorbent surface [21]. Conversely, ion-exchange processes generally exhibit enhanced efficiency under elevated temperatures, as the associated thermokinetic effects facilitate interactions between dissolved solutes and ion-exchange functional groups, thereby promoting a greater frequency of exchange events [22]. Therefore, reconfiguring a system such as ACTEX to achieve the required performance demands rigorous scaling methodologies that account for iodine speciation dynamics and the influence of elevated thermal conditions on the sorption characteristics of commercially available products.

Beyond the thermokinetic effects associated with elevated temperatures, an increase in water temperature may also alter the physical structure of the adsorbent matrix, thereby influencing the overall iodine sorption performance. For GAC, it can be inferred that an increase in water temperature within the range considered in this study exerts minimal influence, as pure carbon is inherently resistant to extreme thermal conditions [23]. Consequently, AmberSorb™ 4652 is unlikely to undergo physical degradation when exposed to heated water. On the other hand, UltraClean™ UCW3600, a polymeric composite of polystyrene crosslinked with divinylbenzene, is expected to exhibit robust thermal stability under the expected heated-water temperatures as this material in its bulk form does not undergo thermal degradation below ~300°C [24]. According to Purolite®, this IX resin must not be operated at temperatures of 60°C or above. While this constraint may have been established for continuous, industrial-scale applications of UltraClean™ UCW3600, under the relatively mild and intermittent operating conditions anticipated in orbital or exploration water systems, the media might be unlikely to exhibit significant structural degradation when operated at this temperature under discrete duty cycles, such as those characteristics of ACTEX filter operation. Nevertheless, it is presumed that the manufacturer imposes this temperature limit because elevated thermal conditions can reduce crosslinking within the polystyrene–divinylbenzene matrix, and strongly basic anion exchangers (such as UltraClean™ UCW3600) are prone to elimination and deactivation of hydroxyl functional sites [25], [26]. These material considerations, together with temperature-driven iodine speciation and thermokinetic sorption effects, underscore the complex interplay of factors that may support the hypothesis proposed herein: the ACTEX filter is intentionally not positioned at an endpoint to avoid processing heated water. Table 1 compiles the temperature-related sorbent considerations discussed in this section.

Table 1. Potential Impact of Hot Water on ACTEX Filtration Media

Iodine Sorbent	*UltraClean™ UCW3600*	*AmberSorb™ 4652*
Matrix Material	*polystyrene–divinylbenzene*	*carbon*
Targeted Iodine Species	I^-	I_2
Speciation-Capacity Consideration	*more ionic iodine is present in water at 90°C*	*less molecular iodine is present in water at 90°C*
Sorption Effect	*IX is enhanced with temperature increase*	*physisorption diminish with temperature increase*
Thermal Effect	*matrix material and IX sites likely to degrade above 60*°C	*matrix is not impacted*

Moreover, the combined influence of these physicochemical factors on sorbent performance can be quantified through the equilibrium and maximum iodine adsorption capacity, which, in accordance with the proposed hypothesis, is expected to exhibit a reduction from its baseline value at ambient temperature. Purolite® marketing documentation reveals that UltraClean™ UCW3600 has an anionic total capacity of 1.1 eq/L (or ~127 mg/g for I^-). On the other hand, no publicly accessible specifications are available regarding the total iodine capacity of AmberSorb™ 4652.

Nonetheless, Schunk™ 4652*, a product marketed in Germany and considered by this study virtually identical to AmberSorb™ 4652, reports an iodine capacity of 1450 mg I_2/g, according to acquirable product documentation. Therefore, these two metrics will serve as reference values in this study, complemented by experimentally derived parameters obtained from iodine adsorption data under ambient and heated-water conditions within a controlled system. This approach should be sufficient to identify a clear performance decline, consistent with our hypothesis.

III. Materials and Methods

Given the preliminary nature of this study and its pioneering focus on dedicated iodine adsorption research, the proposed hypothesis will be evaluated through a series of controlled benchtop adsorption experiments designed to quantify iodine removal by the components of the ACTEX filtration media. This approach aims to establish a fundamental understanding of the underlying mechanisms before progressing to flow-through experimentation. The experimental apparatus utilized in this investigation is configured for batch-mode operation and devised to enable precise regulation and monitoring of water temperature, facilitate iodine adsorption within acceptable iodine volatilization, and maintain controlled hydrodynamic conditions to optimize adsorbate–sorbent interactions. Figure 2 provides schematics of the experimental apparatus used to carry out iodine adsorption capacity tests.

A critical consideration in configuring this experimental setup is the high volatility of iodine; when dissolved in water, it readily transitions to the vapor phase at elevated temperatures, with volatilization losses becoming more pronounced at low concentrations [27]. Hence, the experiments are conducted at an iodine concentration of 63 ppm, which is substantially higher than typical biocidal levels, to minimize volatilization losses. The selected iodine concentration may appear erroneous or inconsistent with established operational specifications for biocidal iodine. However, within the scope of the present material-characterization effort, the initial solute concentration is not a governing parameter, provided that the experimental temperature, volume, pressure, and adsorbent loading are consistently controlled. Under isothermal conditions, equilibrium sorption behavior is determined by thermodynamic state variables and sorbent characteristics; therefore, these specific sorption experiments do not require adherence to operational biocide concentrations to achieve its goals. Specifically, the estimation of maximum adsorption capacity is not strongly dependent on solute concentration, in accordance with adsorption isotherm theory [14]. In addition, this concentration independence enables efficient generation of meaningful equilibrium data within practical contact times. For example, conducting experiments at 4 ppm would result in rapid solute depletion by the adsorbent, preventing acquisition of measurable nonzero equilibrium data and necessitating more sophisticated thermal-control systems to mitigate iodine volatilization at such low concentrations.

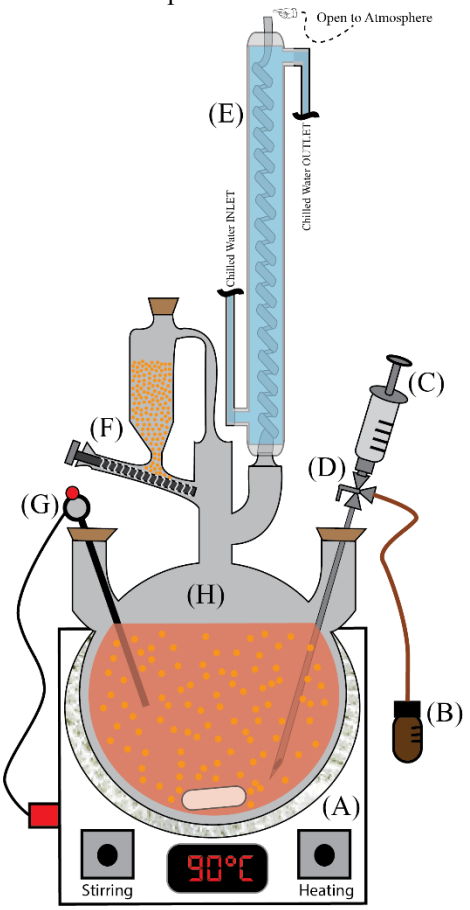

Figure 2. Iodine Adsorption Capacity Test, Experimental Apparatus. *(A) Heating Mantle; (B) Sample Vial; (C) Withdrawal Glass Syringe; (D) Three-way Stopcock Valve; (E) Graham Condenser; (F) Air-tight Solid-dispensing Funnel; (G) Thermocouple; (H) One-liter Glass Flask.*

The 63-ppm iodine solution was prepared by diluting a saturated stock solution, which was produced by dissolving high-purity crystalline iodine (Fisher Scientific, PN I35-100) until equilibrium saturation was reached. The target concentration of 63 ppm was selected because it aligned with the normalization approach used to account for the repeatable and unavoidable iodine losses from the heated trials. This concentration therefore provides a consistent baseline for comparison across experiments.

* www.schunk-group.com

Figure 2 illustrates an open system exposed to the atmosphere, equipped with reflux instrumentation (a vertical Graham condenser) purposed to recover vapors (primarily water) that naturally evolve from the aqueous phase as the iodine solution is maintained at 90 °C. The iodine solution is heated and maintained at the target temperature using an automated, feedback-controlled heating mantle equipped with a submersible thermocouple. The open configuration also reduces system complexity by ensuring consistent global ambient pressure for the liquid phase. Because the reflux process has some degree of condensation inefficiency, resulting in unavoidable iodine losses through minor vapor leakage and pronounced localized iodine recrystallization on surface of the condenser (see Figure A1), baseline water-heating experiments were conducted to quantify the innate iodine-loss rate of the system (see Figure A2). This baseline serves as a normalization parameter for subsequent experimental data analysis.

Moreover, the system incorporates an air-tight solid-dispensing funnel designed to introduce the adsorbent once the solution attains the target temperature. A notable limitation associated with this integration is the requirement for the operator to calibrate the dispensing rate prior to each test to ensure that the prescribed quantity of adsorbent is dispensed with a comfortable degree of precision into the liquid phase. The volume of iodine solution was one liter for all experiments. After the adsorbent is introduced, the solution and adsorbent are allowed to interact for a duration of one hour. This contact-time interval was established as sufficient for the system to reach equilibrium based on a preliminary transient experiment conducted using the maximum filtration-media loading evaluated in this study with the suspected most-robust adsorbent (see Figure A3). It should be noted that this study does not characterize kinetic behavior, as only a single data point is collected following the one-hour equilibration period for the main experimental matrix. As the reaction progresses, mixing is maintained through the magnetic stirring functionality integrated into the heating mantle. The stirrer operates at an estimated rotational speed of 250 rpm, a parameter subsequently employed to characterize the system by calculating the mass-transfer Péclet number (N_{Pe}, the dimensionless ratio between advective transport rate and diffusive transport rate) [28]. It should be noted that the room-temperature experiments are performed using the same apparatus and procedure as the heated trials, with the heating and refluxing functions disabled.

Upon reaching the one-hour mark, mixing is turned off, and the solids are allowed to settle at the bottom of the flask. The three-way stop valve is then set to the withdrawal position, and aliquots are extracted using the installed glass syringe to collect five 20-mL samples for subsequent analysis. Both Ultraclean™ UCW3600 and AmberSorb™ 4652 undergo this procedure independently five times, each with a distinct adsorbent loading. Consequently, each experimental run yields quintuplicate samples corresponding to separate material additions of 50 mg, 100 mg, 400 mg, 800 mg, and 1600 mg. The equilibrium iodine concentration (effectively the post-experiment concentration in the context of this analysis) is determined using a Hatch® DR6000 UV-Vis spectrophotometer. Although the experimental runs are conducted at elevated water temperatures, all sample analyses are performed at room temperature, as the instrument is calibrated for measurements under these conditions. Prior to analysis, aliquots undergo dilution to ensure compatibility with the detection range, given that the initial iodine concentration exceeds the upper limit (>7.0 ppm). Ultimately, iodine quantification is based on total molecular iodine metrics, as maintaining consistent control over solute speciation proves challenging due to temperature fluctuations throughout the testing cycle and the predominant abundance of I_2 in the source iodine solution (pH ≈ 5.17, conductivity ≈ 6.15 µS/cm).

A. Process Characterization and Data Analysis

As previously noted, the overall experimental process is characterized by computing the N_{Pe}. Although this dimensionless parameter does not directly convey mathematical information related to estimating the equilibrium or maximum adsorption capacities, it is chosen as the primary scaling parameter instead of other dimensionless groups for subsequent validation methods such as Multiphysics modeling and flow-through testing, because it reflects the combined influence of global convection and diffusion that govern the adsorption process. The characteristic N_{Pe} for the system is calculated using Equation 2, which translates the characteristic rotational speed of the fluid into its corresponding linear velocity [29]. Note that this number is not a function of iodine concentration nor adsorbent load.

$$N_{Pe} = \frac{uL}{D_{I_2}} = \frac{\pi N d^2}{D_{I_2}} [=] 1 \tag{2}$$

Where:
u: *fluid velocity, [m/s]*
L: *characteristic length (stirrer diameter), [m]*
D_{I_2}: *I_2 diffusion coefficient in water, [m^2/s]*
N: *stirrer rotational speed, [rev/s]*
d: *stirrer diameter, [m]*

After the experimental aliquots are analyzed and the total equilibrium iodine concentration is determined for each trial, these values are used to calculate the equilibrium adsorption capacity using Equation 3. This parameter, together with the equilibrium concentration, serves as a key input for the adsorption model that estimates the theoretical experiment-specific maximum adsorption capacity. The model applied in this investigation is the Langmuir isotherm expressed in one of its linearized forms, as shown in Equation 4, to simplify the determination of theoretical values [30]. By plotting the reciprocals of the equilibrium capacities versus equilibrium concentrations, the y-intercept representing the theoretical maximum adsorption capacity is obtained through standard linear regression techniques.

$$q_{eq,I_2} = \frac{(c_{0,I_2} - c_{eq,I_2})V_0}{m_{abs}} [=] \, {}^{mg}/_{g} \tag{3}$$

Where:
c_{0,I_2}*: total I2 concentration, [mg/L]*
c_{eq,I_2}*: total I2 equilibrium concentration, [mg/L]*
V_0*: batch volume, [L]*
m_{abs}*: added adsorbent amount, [g]*

$$q_{e,I_2} = \frac{k_L q_{max,I_2} c_{e,I_2}}{1 + k_L c_{e,I_2}} \overrightarrow{\overrightarrow{\overrightarrow{Linearization}}} \frac{1}{q_{e,I_2}} = \left(\frac{1}{k_L q_{max,I_2}}\right)\left(\frac{1}{c_{e,I_2}}\right) + \frac{1}{q_{max,I_2}} \tag{4}$$

Where:
q_{e,I_2}*: equilibrium iodine adsorption capacity, [mg/g]*
c_{e,I_2}*: equilibrium iodine concentration, [mg/L]*
k_L*: Langmuir constant, [L/mg]*
q_{max,I_2}*: maximum iodine adsorption capacity*

IV. Results and Discussion

Table 2 shows the N_{Pe} computation of this system in a spreadsheet format and reveals that system is characterized by dominant advective transport rate as $N_{Pe} >> 1$. Therefore, this global parameter must be maintained when comparing the results from this experiment with flowthrough experimental apparatus for validation studies. For instance, if a subsequent flow-through experiment is to be compared with the present results, Equation 2 can used to determine the appropriate linear fluid velocity by maintaining a constant N_{Pe} and substituting the corresponding bed length. This approach ensures a physically consistent comparison with the batch-derived results.

Table 2. N_{Pe} System Characterization

Parameter, [unit]	Units	Parameter	Value	Equation/Notes/Reference
		Batch Process		
I_2 diffusion coefficient in water	[m^2/s]	D_I2	1.00E-09	[31]
stirrer rotational speed	[rpm]	N_rpm	250	
stirrer rotational speed	[rev/s]	N_rps	4	=N_rpm/60
stirrer diameter	[m]	d_st	0.03	
batch Péclet number	[1]	Nb_Pe	1.18E+07	=(PI()*N_rps*d_st^2)/D_I2
		Assumed Flowthrough Process		
bed diameter	[in]	Dь_in	1.62	[17]
bed diameter	[m]	Dь_m	0.041	=Dь_in/39.3701
nominal bed flow rate	[mL/min]	Qь_mlpmin	1059	[32]
nominal bed flow rate	[m3/s]	Qь	1.77E-05	=Qь_mlpmin/60000000
bed nominal fluid velocity	[m/s]	vь	1.33E-02	=Qь/(PI()*(Dь_m/2)^2)
bed length	[in]	Lь_in	10.5	[17]
bed length	[m]	Lь_m	0.267	=Lь_in/39.3701
media void fraction	[1]	ε	0.3	educated guess
plug flow Péclet Number	[1]	Nf_Pe	1.18E+07	=(vь*Lь_m)/(ε*D_I2)

The charts below illustrate the comparative performance of UltraClean™ UCW 3600 and AmberSorb™ 4652 in removing iodine from solution under both ambient conditions and at 90°C. An additional experimental set incorporating the combined ACTEX mixture is included in the results. For this study, the ACTEX mixture was approximated using a working composition consisting of 70 percent IX material and 30 percent GAC by weight. This provisional composition was entirely selected based on the rational expectation that an effective ACTEX-type medium requires a higher proportion of IX resin relative to GAC due to the difference in bulk removal capacities between adsorbent type. Figure 3 presents the equilibrium iodine adsorption capacity as a function of adsorbent dosages.

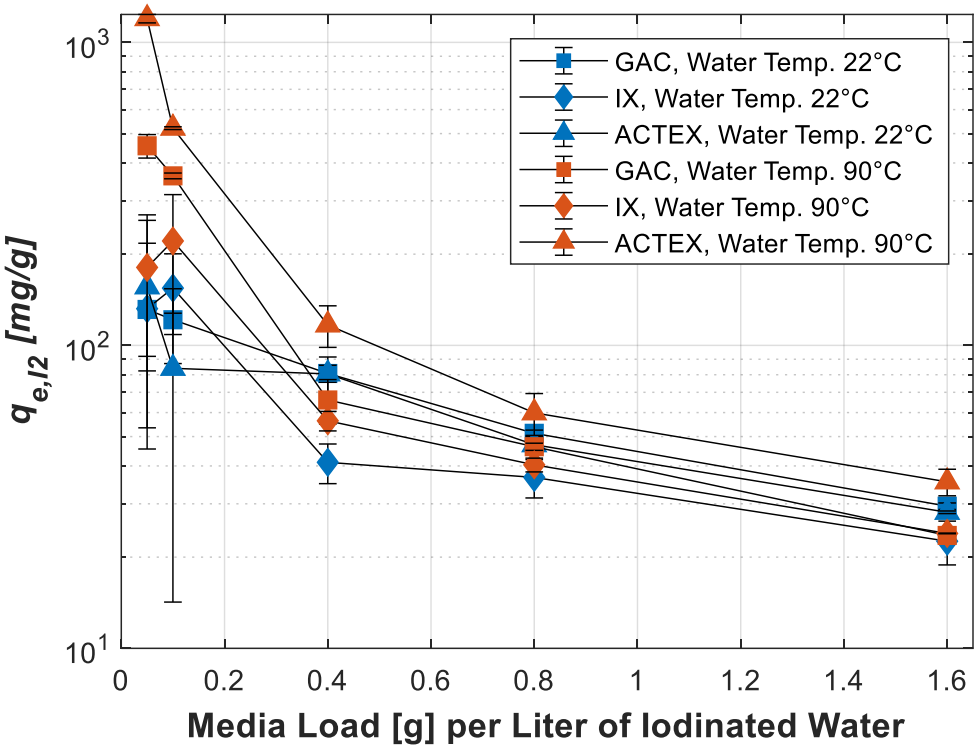

Figure 3. Iodine Equilibrium Removal Capacity at Ambient and 90 °C for ACTEX Sorbent.

The observed trend in Figure 3 shows a decrease in capacity with increasing media load, which is expected since the initial iodine concentration remains constant; consequently, as the adsorbent quantity increases, the available iodine for adsorption is proportionally reduced. These results indicate that the IX resin exhibits slightly higher iodine removal at 90°C compared to 22°C, suggesting that elevated temperature enhances the IX process, consistent with some thermokinetic principles. Furthermore, the equilibrium-capacity data imply that maintaining the resin at a temperature above its maximum operating limit for one hour does not appear to induce material degradation that would adversely affect adsorption performance. Moreover, Figure 3 reveals a modest thermal effect for AmberSorb™ 4652 on the sorption performance. As expected, the GAC material exhibits reduced performance at 90°C relative to 22°C, particularly at the higher media loadings. This reduction is likely due to increased thermal energy weakening local solute–substrate electrostatic interactions. Although the two lowest media loadings appear to show the opposite trend with acceptable point-to-point variability, the data obtained at higher loadings are more internally consistent. It is therefore presumed that the normalization procedure was less effective for the low-GAC-content experiments, leading to greater overall variability in the identified trend and yielding artificially elevated removal capacities at 90°C compared with 22°C. Moreover, the substantial differences observed at 90°C for the 50-mg and 100-mg loadings appear disproportionately large given the small mass of adsorbent relative to the fixed one-liter solution volume. This suggests that the heated experiments may have experienced additional iodine losses not fully captured by the physical or mathematical corrections applied. This feature of the results at 90°C persists in the metrics for the combined formulation; however, the overall trend favors a consistent slightly improved performance over the metrics at 22°C. Figures 4-8 effectively show the equilibrium capacity metrics from each media-load test configuration.

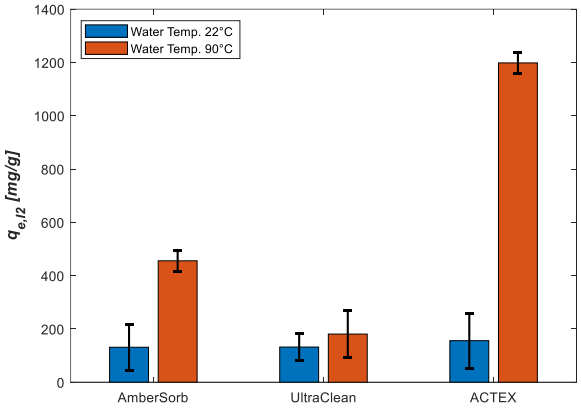

Figure 4. Iodine Equilibrium Removal Capacities with 50-mg/L Media Load and 1-hr Contact Time.

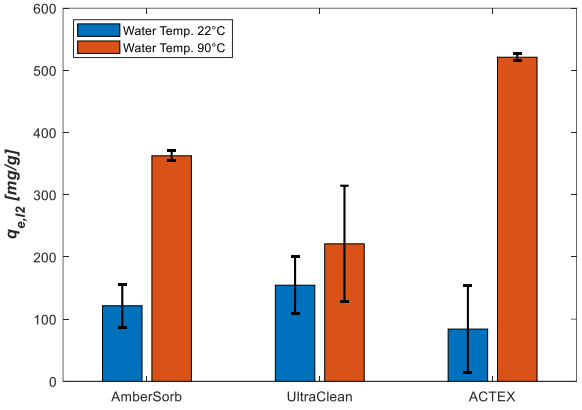

Figure 5. Iodine Equilibrium Removal Capacities with 100-mg/L Media Load and 1-hr Contact Time.

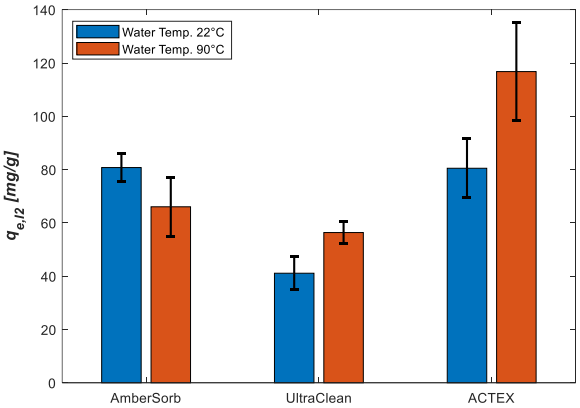

Figure 6. Iodine Equilibrium Removal Capacities with 400-mg/L Media Load and 1-hr Contact Time.

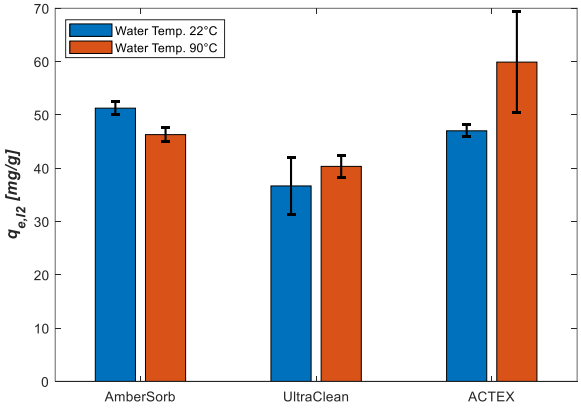

Figure 7. Iodine Equilibrium Removal Capacities with 800-mg/L Media Load and 1-hr Contact Time.

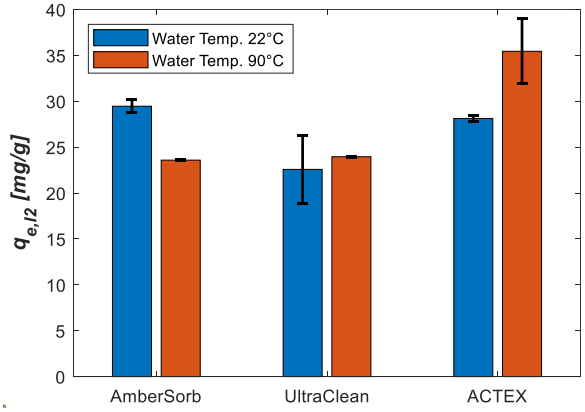

Figure 8. Iodine Equilibrium Removal Capacities with 1600-mg/L Media Load and 1-hr Contact Time.

The equilibrium data presented in Figures 4–8 were used to estimate bulk adsorption characteristics by applying linearized Langmuir isotherm approximations (Equation 4). The model was evaluated using both individual data points and averaged values derived from each set of quintuplicate measurements. Model performance was assessed primarily through the coefficient of determination (R^2) obtained from the corresponding regression analysis. In addition, the physical plausibility of the estimated maximum adsorption capacity and the Langmuir constant was examined to further evaluate the quality of the model fit. Table 3 summarizes all metrics relevant to the Langmuir-based characterization of the data.

Table 3. Summary of Estimated Langmuir Adsorption Parameters and Associated Regression Statistics

Media	Data-point Input	Temp. [°C]	Max. Capacity [mg/g]	Langmuir Constant [L/mg]	R^2
AmberSorb™ 4652	single	22	77.406	0.2785	0.3043
AmberSorb™ 4652	averaged	22	135.418	0.0927	0.9661
AmberSorb™ 4652	single	90	279.852	0.1318	0.5911
AmberSorb™ 4652	averaged	90	549.366	0.0549	0.7216
UltraClean™ UCW3600	single	22	-573.320	-0.0021	0.4170
UltraClean™ UCW3600	averaged	22	-51.559	-0.0133	0.8432
UltraClean™ UCW3600	single	90	72.261	1.8475	0.6041
UltraClean™ UCW3600	averaged	90	81.584	1.2243	0.7207
ACTEX	single	22	35.982	4.0593	0.0001
ACTEX	averaged	22	147.635	0.0545	0.9357
ACTEX	single	90	86.652	-8.0488	0.0001
ACTEX	averaged	90	65.427	-0.3170	0.0294

A notable feature across all regressions is the relatively low R^2, indicating generally weak model performance. Although the R^2 values improve when averaged data are used as input, the resulting sorption constants must be interpreted with caution. For example, when the equilibrium data for AmberSorb™ 4652 are analyzed as individual data points, the regression suggests that the maximum adsorption capacity increases while the adsorbate affinity decreases with increasing temperature, despite the accompanying R^2 indicating poor reliability. A similar trend appears when averaged data are used, although the R^2 improves slightly. This outcome is counterintuitive, given that the isolated equilibrium data (Figures 4–8) exhibit the opposite behavior, particularly at higher media loadings. These inconsistencies suggest that inaccuracies associated with the low-mass GAC experiments propagated through the normalization process and introduced artifacts into the model-fitting results.

The results for UltraClean™ UCW3600 show modest agreement with the overall trends observed in the equilibrium data, which indicate that the ion-exchange resin exhibits slightly improved performance at elevated temperatures. Specifically, the derived sorption parameters suggest a shift toward enhanced iodine uptake, as both the maximum adsorption capacity and the Langmuir constant increase with rising water temperature. However, these metrics are associated with underperforming regression statistics, which improve somewhat when averaged data are used as input. Despite this improvement, the parameter estimates for the ambient-temperature data set are not physically meaningful due to the appearance of negative values. Although these results are not strongly reliable from a regression standpoint, the relative trend indicating improved performance under heated-water conditions remains consistent with the experimental observations.

The isothermal adsorption analysis also attempted to fit the equilibrium data from the combined ACTEX formulation using the linearized Langmuir model. However, the data for both temperature conditions exhibited poor agreement with the model, yielding the lowest R^2 values among all materials tested. The most credible results were obtained from the averaged room-temperature data at room temperature; nevertheless, even this set indicates a combined maximum adsorption capacity substantially lower than excepted for the combined filtration-media recipe.

The major outcome of this isotherm analysis is insufficient to reliably assess material performance under the specific test conditions and with the experimental apparatus used. Consequently, the primary conclusions are drawn from the individual equilibrium-capacity values rather than from the isotherm-based model fits. Future work will extend this analysis using more robust adsorption models, including modified Langmuir formulations, the Brunauer–Emmett–Teller model, and the Toth isotherm. In addition, the study will attempt to collect additional equilibrium data

points with higher media loadings and longer contact times before transitioning to a dedicated flowthrough experiment.

The key trend identified in this investigation is that AmberSorb™ 4652 appears to exhibit reduced performance under heated-water conditions, whereas UltraClean™ UCW3600 shows a slight performance enhancement. These findings run counter to the initial theoretical hypothesis but may be specific to the selected contact time. The ion-exchange resin may ultimately exhibit decreased performance under prolonged exposure to hot iodinated water, an effect that will be evaluated in subsequent phases of the study.

In addition, the results from the combined ACTEX media suggest that the overall adsorption behavior is dominated by the ion-exchange resin, as indicated by the similar improvement observed at elevated temperature. In other words, although the GAC component is expected to diminish iodine uptake, the 70 percent IX content continues to govern the overall removal behavior.

In summary, the insights gained in this investigation are essential for refining and maturing the experimental framework, enabling future studies to transition toward higher-fidelity, scientifically rigorous, and flight-representative testing.

V. Conclusion and Forward Work

This investigation confirms that elevated water temperatures influence the iodine-removal performance of ACTEX filtration media. Experimental results demonstrate that UltraClean™ UCW3600 resin exhibits a slight improvement in adsorption capacity at 90°C, consistent with thermokinetic principles, while AmberSorb™ 4652 granular activated carbon experiences a notable decline in performance under the same conditions. These findings validate the hypothesis that thermal effects, coupled with iodine speciation dynamics, impose critical constraints on the design and placement of iodine-removal units in potable water systems. The observed reduction in adsorption capacity for GAC at elevated temperatures underscores the need for careful consideration of sorbent selection and system architecture when accommodating heated-water dispensing requirements in future mission designs. An unintended outcome of this investigation was the recognition of the significant difficulty in maintaining a consistent iodine concentration in heated water, even when starting from a saturated solution. Although this challenge may partly reflect limitations of the experimental apparatus used in this study, the observation that dissolved iodine concentrations can significantly decrease under elevated thermal conditions, potentially due to vapor losses or enhanced depletion by wetted surfaces, highlights an important consideration for future work. Careful monitoring and control of iodine mass balance will therefore be essential in subsequent experiments.

Overall, the study establishes a foundational understanding of the interplay between temperature, iodine speciation, and sorbent performance. While the ACTEX filter remains effective under ambient conditions, its performance under heated-water scenarios suggests that current configurations may not fully satisfy reliability requirements for long-duration exploration missions. These insights provide a scientific basis for revisiting design strategies and scaling methodologies to ensure robust iodine removal across diverse operational environments.

Future research should expand beyond batch-mode experiments to include flow-through testing under representative operational conditions, enabling validation of adsorption trends observed in this study. Additionally, high-fidelity modeling of iodine speciation and sorption kinetics across varying thermal regimes will be essential to predict system behavior under dynamic mission profiles. Investigations into alternative sorbent formulations or hybrid media configurations could further enhance performance, particularly for heated-water applications. This investigation has preliminarily identified emerging materials with potentially improved thermal robustness, which will be evaluated in future work and presented in subsequent installments of this research effort. In addition, long-duration thermal exposure studies are recommended to assess potential material degradation and functional-site deactivation in ion-exchange resins, ensuring that design improvements align with the durability requirements of next-generation potable water systems. Although this initial investigation did not definitively demonstrate an alarming decline in filtration performance of the ACTEX media constituents at 90 °C, the observed reduction in GAC performance signals a cold reality that must be confronted when deploying these materials in hot-water conditions.

Appendix

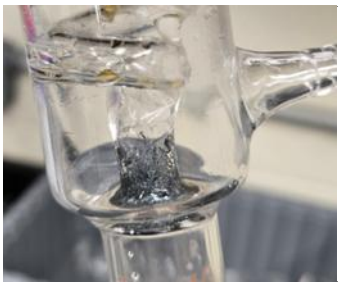

Figure A1. Crystalized Iodine at the Inlet of The Reflux Condenser.

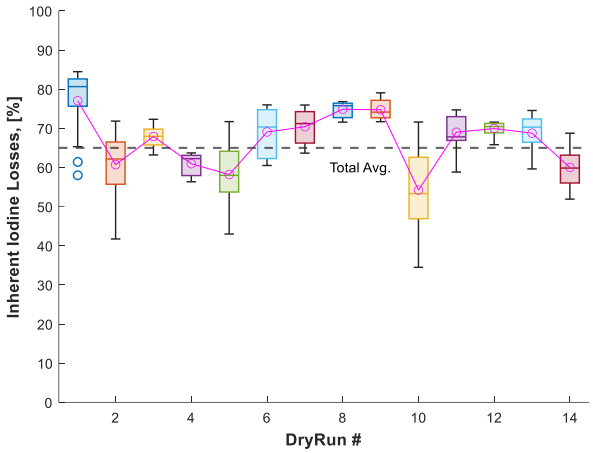

Figure A2. Iodine Losses in Experimental Apparatus in the Absent of Adsorbent. *The series of experiments demonstrated that iodine loss is primarily due to crystallization of iodine vapor on the cold surface of the condenser. The characterized iodine lost by the system is used to normalize the results from the main experiments.*

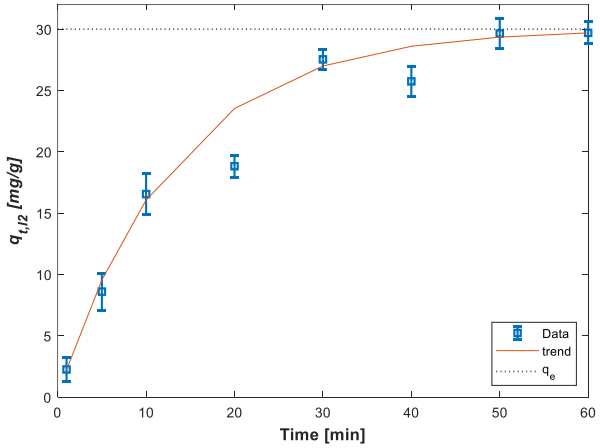

Figure A3. Transient Adsorption Experiment at 90°C with 1600 mg of AmberSorb™ 4652. *The trend indicates that a contact time of one hour is sufficient to reach equilibrium.*

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