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Separation Science and Technology

Publication details, including instructions for authors and subscription information:

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To cite this Article Wilmarth, W. R. , Mills, J. T. and Dukes, V. H.(2005) 'Removal of Silicon from High-Level Waste Streams via Ferric Flocculation', *Separation Science and Technology*, 40: 1, 255 – 265

To link to this Article: DOI: 10.1081/SS-200042001

URL: <http://dx.doi.org/10.1081/SS-200042001>

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Removal of Silicon from High-Level Waste Streams via Ferric Flocculation

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Abstract: The presence of silicate from glass-forming frit in the recycle waste from the Defense Waste Processing Facility produces wastes that, when combined with the traditional aluminate-bearing wastes stored in Savannah River Site's tank farms, can produce insoluble sodium aluminosilicates. Currently, aluminum-bearing wastes and silicon-bearing wastes are processed in separate evaporators. This, however, limits operational flexibility. Therefore, treatment to remove silicon has been proposed to allow greater flexibility for processing these wastes in the site's evaporators. The use of a ferric precipitation (flocculation) to remove the silicon has been tested using waste simulants.

Ferric precipitation following ferric nitrate addition to two different alkaline DWPF recycle waste simulants was effective at removing silicon to levels below concern for processing in any of the Savannah River Site's evaporators. Removal of silicon was rapid with removal complete in 2 h. Elevated temperatures were tested and found to be not required. Capacities of the resultant iron flocculent were ~0.1 g of silicon per gram of iron at a final silicon concentration of 50 mg/L. Moreover, the silicon removal obeys a classical Freundlich adsorption isotherm.

INTRODUCTION

Approximately 130 million L of high-level waste are stored at the Savannah River Site. This liquid waste is made alkaline prior to discharge from

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the F- and H-Canyon facilities. During storage, the liquid waste is typically evaporated to concentrate the supernate and maintain storage volume. These operations have been performed for many decades during plutonium production. The high-level waste is typically several molar in sodium ion with large amounts of free hydroxide, nitrate, nitrite, and aluminate concentrations.

In the late 1990s, the Defense Waste Processing Facility (DWPF) was commissioned to begin transforming the sludge and supernate components of the high-level waste into a vitrified product that would be interned at the federal repository, currently slated for Yucca Mountain, NV. The DWPF returns a recycle water stream from condenser and other process operations to the tank farm. This stream is currently the largest volume source of influent to the tank farm (approximately 1–2 million gall produced per year). The DWPF recycle stream is very dilute (~1 M sodium ion concentration) as compared to concentrated supernate (10–12 M sodium ion concentration) and would be appropriate feed for evaporation. Unfortunately, the DWPF recycle stream contains silicon in the form of soluble silicates and insoluble glass-forming frit. The mixture of soluble aluminate in the historical canyon waste and the silicon from DWPF recycle led to the formation of insoluble sodium aluminosilicates in one of the Savannah River Site's evaporators (1).

Operation of the high-level waste evaporators is vital to maintain tank space to meet site mission requirements, as well as regulatory commitments for closing the high-level waste tanks. Since the aluminosilicate deposits were discovered and one evaporator was shut down for almost 2 yrs, research into understanding the reaction kinetics for formation and aluminosilicate product solubilities has been performed. The results have shown that the mixture of the two tank farm streams produced waste supersaturated in aluminosilicate. The aluminosilicate can readily form and precipitate under evaporator conditions (2).

Current waste handling processes in the tank farm segregate the high-aluminate streams from the silicon-containing streams to prevent aluminosilicate formation, sending each to different evaporators. However, operational flexibility is hampered by this segregation approach. Therefore, silicon treatments for use with existing stored DWPF recycle in the tank farm, along with the possible treatment inside DWPF at the point of origin of the silicon-containing waste, have been examined.

One identified treatment option is the use of the addition of ferric ion to the alkaline waste resulting in the formation of an iron hydroxide floc. This treatment technology (3) removes silicon by coprecipitation and/or silicon adsorption onto the iron precipitate. This treatment technology has been well established for municipal wastewater operations (4) but has not been tested to remove silicon from either simulated nuclear wastes or actual waste from the tank farm. Additionally, information on the ferric precipitate morphology and filtration performance are needed to assess the technology

for nuclear application. Therefore, initial testing for silicon removal by ferric flocculation was performed on simulated wastes from the tanks containing stored DWPF recycle (termed Tank 20 simulant) and from a projected composition of the alkaline contents of the recycle collection tank.

EXPERIMENTAL DETAILS

Laboratory tests were performed on the 50 mL scale using the simulated wastes with the compositions shown in Table 1. As generated, the DWPF recycle is slightly acidic. The stream is neutralized prior to discharge to be compatible with the carbon steel construction of the storage tanks, and its composition is shown in Table 1. Additionally, the DWPF Recycle has been stored and mixed with other waste heels. The composition of this stream, the Tank 20 simulant, is also in Table 1. The simulants were prepared from reagent grade chemicals. Silicon was added as the hydrated sodium metasilicate salt.

The ferric precipitation agent was prepared from reagent-grade ferric nitrate and dissolved in deionized water to a 1 M $\text{Fe}(\text{NO}_3)_3$ concentration. Following procedures used for other ferric flocculent applications (5), tests were conducted at ambient and elevated (50°C) temperatures. The silicon-bearing solutions were added to the 100 mL reaction vessel, heated to reaction temperature in a water bath, and stirred using a magnetic stir bar for at least 2 h. Afterward, the ferric slurry was filtered through a 0.45 μm cellulose nitrate filter. Mass measurements were performed initially and at the end of the experiment to correct measured concentrations for evaporation.

Table 1. DWPF recycle compositions

Analyte	Units	Acidic DWPF recycle	Neutralized DWPF recycle in RCT	DWPF recycle in TF
Na	M	0.35	1.25	1
Nitrate	M	0.08	0.05	0.06
Nitrite	M	0.24	0.2	0.25
Free OH	M	Slightly acidic	1	0.5
Carbonate	M	*	*	0.075
Al	mg/L	270	250	*
Si	mg/L	620	600	56
Fe	mg/L	590	*	*
Formate	mg/L	21	*	*

*None added.

The stock solution and resulting filtrate solutions were analyzed for silicon using an Inductively Coupled Plasma-Emission Spectrometer (ICP-ES) using a JY 170C, Instruments SA, Inc. Table 2 contains the silicon concentrations in the stock solutions and the treated wastes. The ferric flocculent was dried at ambient temperature and characterized using a International Scientific Instruments DS-103 Scanning Electron Microscopy (SEM) and a Noran A4105 Energy Dispersive Spectroscopy (EDS) for elemental profiling.

Table 2. Silicon data (mg/L) from ferric testing

Temp (°C)	Initial vol (mL)	Initial Si (mg/L)	Final Si (mg/L)	Amt Fe added (g)	Mass Si sorbed (mg)	Si capacity (mg Si/g Fe)
		51.8	51.8	0.000		
50	50	51.8	27.048	0.014	1.24	88.6
50	50	51.8	20.904	0.042	1.54	36.9
50	50	51.8	13.2	0.056	1.93	34.6
50	50	51.8	6.9696	0.084	2.24	26.8
50	50	51.8	3.9192	0.112	2.39	21.4
50	50	51.8	27.602	0.014	1.21	86.7
50	50	51.8	21.296	0.042	1.53	36.4
50	50	51.8	16.884	0.056	1.75	31.3
50	50	51.8	10.5	0.084	2.07	24.6
50	50	51.8	3.9512	0.112	2.39	21.4
Ambient	50	51.8	33.666	0.014	0.91	64.9
Ambient	50	51.8	22.08	0.028	1.49	53.2
Ambient	50	51.8	16.008	0.042	1.79	42.7
Ambient	50	51.8	10.974	0.056	2.04	36.5
Ambient	50	51.8	4.922	0.084	2.34	28.0
Ambient	50	51.8	2.585	0.112	2.46	22.0
Ambient	50	201.5	154.56	0.014	2.35	168.1
Ambient	50	201.5	124.08	0.028	3.87	138.6
Ambient	50	201.5	98.7	0.042	5.14	122.7
Ambient	50	201.5	72.404	0.056	6.45	115.6
Ambient	50	201.5	39.949	0.084	8.08	96.4
Ambient	50	201.5	21.344	0.112	9.01	80.6
Ambient	50	201.5	150.88	0.014	2.53	181.3
Ambient	50	201.5	117.18	0.028	4.22	151.0
Ambient	50	201.5	92.92	0.042	5.43	129.6
Ambient	50	201.5	67.05	0.056	6.72	120.4
Ambient	50	201.5	43.152	0.084	7.92	94.5
Ambient	50	201.5	21.712	0.112	8.99	80.5

RESULTS AND DISCUSSION

Tank 20 Simulant (DWPF Recycle in Tank Farm)

As previously mentioned, the DWPF recycle that was generated during the period when evaporator operation was curtailed is stored in the tank farm. The volume, nearly 3-million gall, will eventually be concentrated in the evaporator dedicated to silicon processing. However, the recycle that is currently being generated represents ~70–80% of that evaporator's utility. Therefore, it is potentially desirable to remove the silicon and concentrate with the other site evaporators. A simulant with the composition previously discussed was tested for silicon removal by ferric flocculation. Shown in Fig. 1 is a dosage curve for the addition of iron and the subsequent removal of silicon for a Tank 20 simulant. The starting silicon concentration was 200 mg/L. The curve appears linear until ~70% of the silicon is removed and then flattens out with higher addition of iron.

Figure 2 shows the measured capacity of the ferric flocculent for silicon removal as a function of the measured final silicon concentration. Tests were initially conducted at ambient laboratory temperature and 50°C. The targeted silicon concentration that would allow the treated Tank 20 material to be processed in other site evaporators is less than 50 mg/L. The data shown in Fig. 2 at a final silicon concentration below 50 mg/L did not indicate a difference between performing the tests at ambient or elevated temperature. Therefore, additional testing was conducted at ambient temperature.

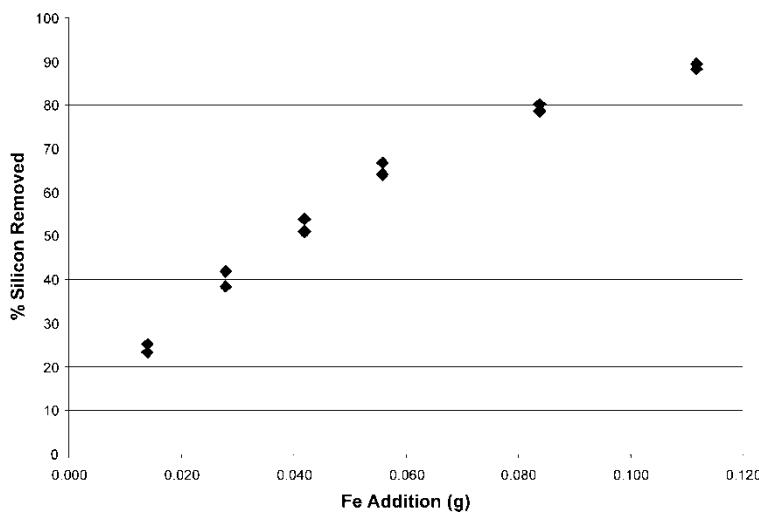


Figure 1. Silicon removal via iron addition at ambient temperature (25°C).

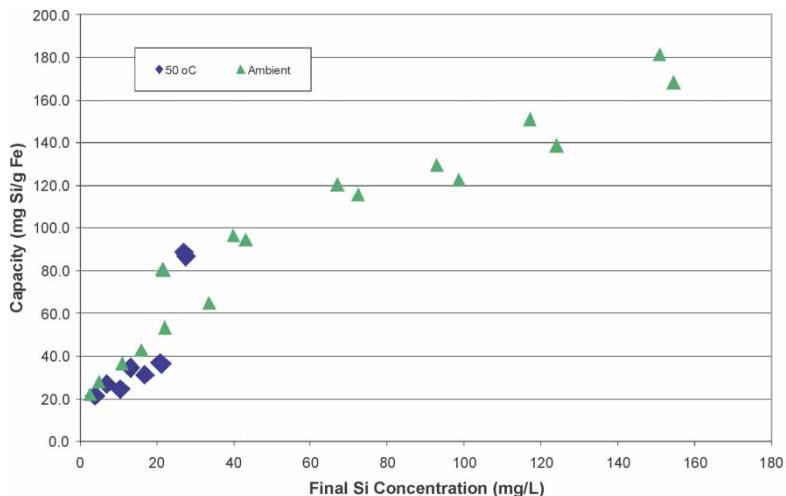


Figure 2. Silicon adsorption isotherm for Tank 20 simulant.

The plot in Fig. 2 shows silicon capacities on the order of 0.1 g of silicon/g of iron added to reach a final silicon concentration of 50 mg/L and 0.15 g Si/g Fe at 150 mg/L final silicon concentration. These capacities are higher than ferric flocculent capacity report in wastewater treatment (4). This is most likely due to silicon being in the form of silicate ions in the caustic solution as compared to the species in pH 7 waters. At the capacities measured in the Tank 20 simulant, ferric flocculation will remove silicon to levels allowing processing in either of the aluminum-processing evaporators.

Adsorption onto solids has been studied for decades. There are two adsorption models that are traditionally used to describe the process. The Freundlich isotherm model was one of the first proposed to correlate the amount of a substance absorbed to the concentration of material in solution. Equation (1) shows the Freundlich expression, where m is the number of grams absorbed per gram of absorbent and c is the sorbate concentration with k and n as constants.

$$M = kc^{1/n} \quad (1)$$

The other adsorption model is the Langmuir isotherm and is very useful if only a monolayer of adsorption occurs. The data from the ambient temperature tests performed using the Tank 20 simulant were plotted using the Freundlich and Langmuir expressions. The regression of the data revealed that the adsorption of silicon on ferric flocculent did not obey the Langmuir model ($R^2 < 0.6$) but did obey the Freundlich model as shown in Fig. 3. The fit of the data to the Freundlich isotherm was very good with a correlation

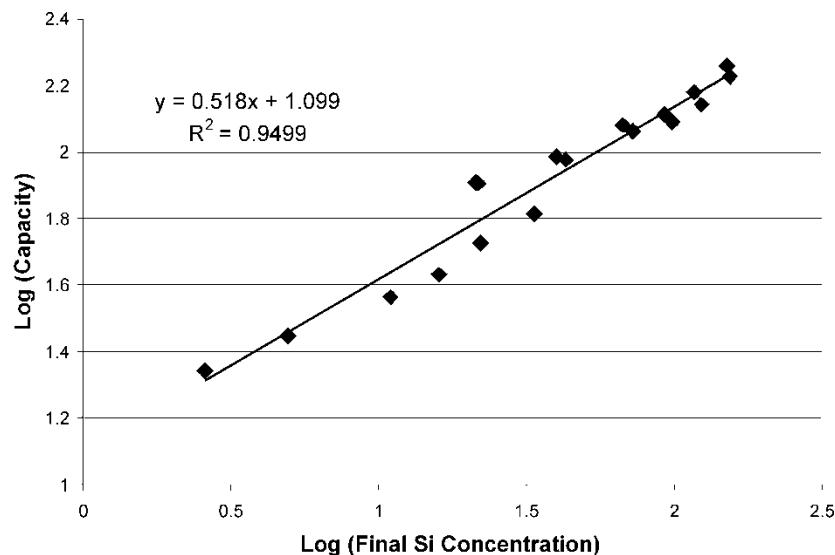


Figure 3. Freundlich plot of silicon adsorption.

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 coefficient of 0.95. There does appear to be some aspects to a sinusoidal curve to the lower final silicon concentrations. Potentially, other adsorption models would better explain this portion of the data.

Neutralized DWPF Recycle Stored Inside DWPF

Recycled water is accumulated in the recycle collection tank and neutralized prior to discharge to the tank farm. Though no samples of the water have been analyzed due to the difficulty in retrieving a sample, the estimated composition is provided in Table 1. The silicon concentration in the neutralized recycle is high (~600 mg/L); therefore, a wider silicon concentration range was used in ferric flocculation testing. Figure 4 shows the measured silicon isotherm for the ferric flocculent produced in the tests with neutralized DWPF recycle.

The capacity for silicon removal at a targeted 50 mg/L final concentration is approximately the same (0.1 g Si/g Fe) for the neutralized recycle as the capacity measured in the Tank 20 simulant. The data were analyzed using the Freundlich isotherm model, and the results are shown in Fig. 5. The fit for the Freundlich model is very good ($R^2 = 0.93$). The silicon removal efficiency using the ferric flocculation technique appears to not vary much with small changes in solution composition. This implies that the same silicon species is being removed.

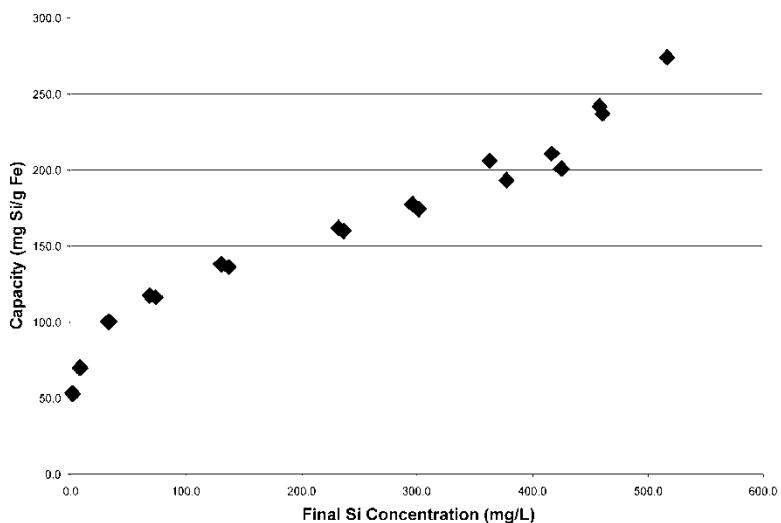


Figure 4. Silicon removal from neutralized DWPF recycle.

Samples from a previous scoping test in which the mother solution was spiked with very high silicon concentrations (8 g/L) were submitted for analysis by X-ray diffraction and scanning electron microscopy. The samples were rinsed once with inhibited water (0.01 M NaOH). The X-ray diffraction data did not show diffraction peaks from crystalline iron

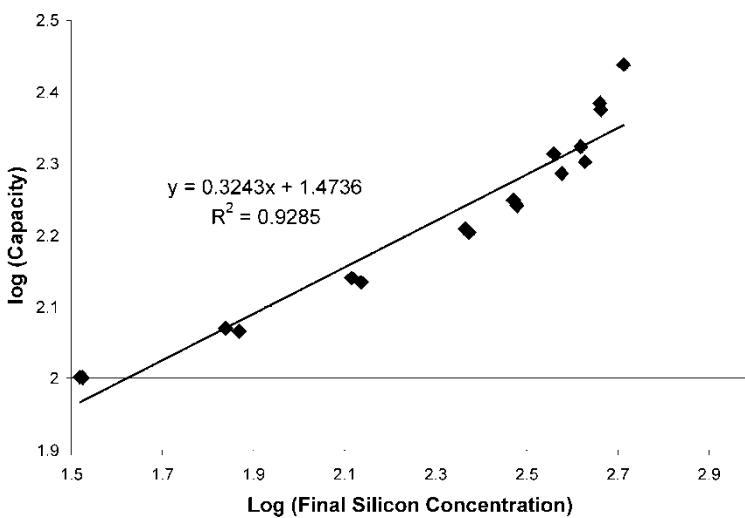


Figure 5. Freundlich isotherm for neutralized DWPF recycle.

oxides/oxyhydroxide. Only the broad band from the amorphous component of the precipitate was observed. The energy dispersive spectra obtained during the scanning electron imaging are shown in Fig. 6. The spectra contain peaks for iron and silicon as expected along with sodium from the salt solution.

Potential Silicon Removal in DWPF

The treatment of DWPF recycle for removing silicon has received substantial review. Initially, an acid-side evaporator was proposed to return the silicon-containing frit within DWPF and send only a small fraction of the volume and silicon to the tank farm. However, a review (6) of the possible options showed the cost, and schedule considerations would suggest that a more promising treatment would include acid-side filtration. Figure 7 shows the potentially viable process involving treating recycle water inside DWPF. The proposed process would involve the collection of the recycle constituents followed by filtering the insoluble frit using cross-flow filtration. The soluble component of silicon would be minimal due to the low solubility of silicon under these acidic pH ranges. The filtered frit would be returned to the slurry mix evaporator. The acidic filtrate would be neutralized to an optimum pH. Ferric nitrate would then be added to remove the soluble silicon to concentrations below concern. The caustic slurry containing the iron flocculent would be transferred to the tank farm and incorporated into the sludge

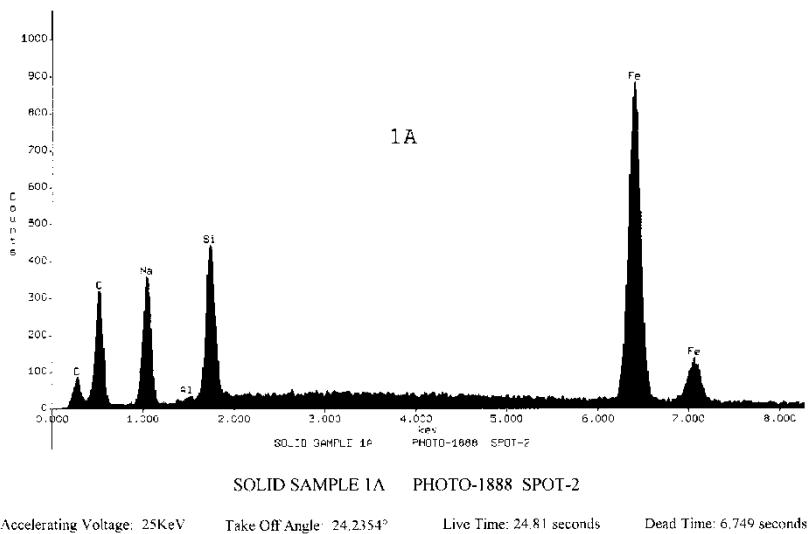


Figure 6. Energy dispersive spectra of silicon-bearing iron precipitate.

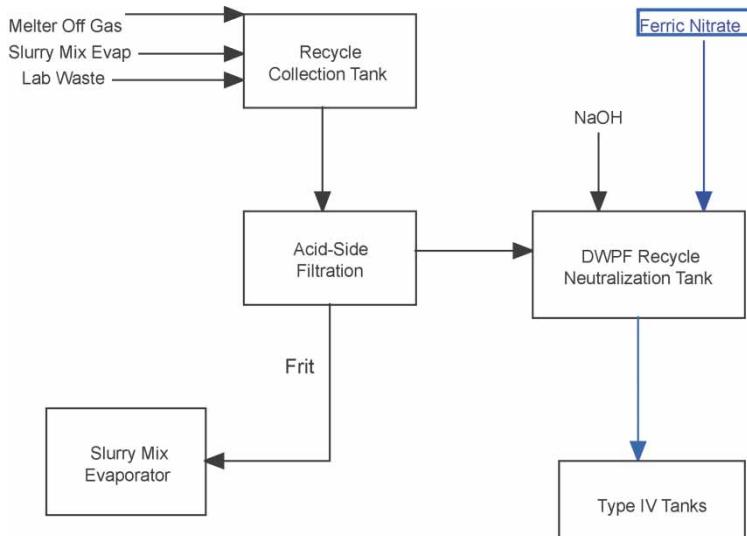


Figure 7. Potential process for treating DWPF recycle.

for processing in the DWPF or recycled into the slurry adjustment and receipt tank.

CONCLUSIONS

Silicon in the DWPF Recycle stream represents a waste instability when mixed with the more traditional aluminum-bearing waste produced in the separation canyons. This instability eventually fouled one of the Savannah River Site's operating evaporators and curtailed operation for an extended duration. The results of these tests aimed at removing silicon from wastes currently stored in the tank farm and for newly generated wastes in the DWPF have shown that ferric flocculation will produce a ferric precipitate, not unlike sludge, that removes soluble silicon.

The adsorption of silicon onto the ferric precipitates is a classical waste treatment operation and follows a Freundlich isotherm. The capacity of the ferric precipitate is higher than anticipated based on the use of ferric flocculation in municipal wastewater treatment and is ~ 0.1 g of silicon per gram of iron added when targeting a final silicon concentration of 50 mg/L. Optimization of the process for implementation would need to determine the target silicon concentration and the impact of the added iron. The process was effective at removing silicon from both simulant compositions tested. Additionally, ambient and elevated temperature tests indicated that heating the reaction vessel was not necessary.

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