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Large-Scale Electrochemical Degradation of Poly-and Perfluoroalkyl Substances (PFAS) by Magnéli Ti4O7 Electrodes

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**Large-scale electrochemical degradation of poly- and perfluoroalkyl
substances (PFAS) by Magnéli Ti₄O₇ electrodes**

A Masters Project Presented

By

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September 2021

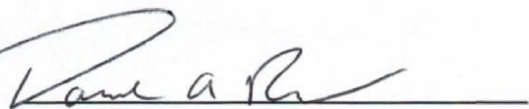
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Laura Siddon

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Abstract

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are a group of synthetic chemicals that are extremely persistent in the environment. They are classified as emerging contaminants and have been linked to impacts on the developmental, liver, immune, and thyroid systems, and are possible carcinogens. PFAS' resistance to biodegradation and conventional oxidation processes make them one of the hardest chemicals to remove from water. With the discovery of PFAS in public water supplies, existing technologies are not capable of removing these recalcitrant contaminants to levels expected for the health of the public. Even in cases when conventional technologies can remove PFAS compounds, removal is often the separation of the contaminants from water to another phase for further treatment. Electrochemical treatment has been shown to not just transfer PFAS to other phases, but to destroy these compounds. These electrochemical systems have emerged as a novel water treatment technology which has been performed at both bench-scale and pilot-scale. This study explored the degradation of six of the most commonly regulated PFAS compounds on a scale that could be used in industrial applications. Two designs of Magnéli phase Ti_4O_7 anodes, solid and microporous which differ in flow pattern, were tested. These reactors were evaluated for the ability to destroy individual PFAS compounds at two voltages, two amperages, and with the addition of sodium sulfate to the base conductivity of sodium chloride. Previous Aclarity research designated the settings that were tested. The reactors were not capable of removing shorter-chain compounds, such as PFOA, PFHpA, and PFHxS, likely due to the hydrophilic functional groups. While PFOS, PFNA, and PFDA were easily removed due to their hydrophobic functional groups. The reactors removed the most contaminants at higher voltages and amperages. Further investigation is required to remove short-chain compounds with this large-scale reactor and to make the system more energy efficient.

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1. Introduction

Poly- and perfluoroalkyl substances (PFAS) are commonly used in household and industrial products due to their amphiphilic properties. Their unique properties allow for numerous applications such as industrial detergents, fire-fighting foams, and water- and grease-repellent materials (Kotthoff et al., 2015). These make them resistant to biotic and abiotic breakdown which results in a persistent, bio-accumulative, and toxic compound in nature (Washington et al., 2010). Fluoropolymer manufacturers are one of the primary sources for the release of PFAS into the environment (Hoffman et al., 2011; Bach et al., 2017). Other sources of pollution are locations heavy with firefighting activities, including training sites, and oil and gas fields routine practices (Hu et al., 2016). PFAS enter the water cycle through industrial facilities and their atmospheric deposition, runoff, and groundwater infiltration (Hu et al., 2016; Lu et al., 2017). They have been detected around the world in drinking water (Takagi et al., 2011), wastewater (Eriksson et al., 2017), landfill leachate (Hamid et al., 2018), and groundwater (Xiao et al., 2015). Their highly stable carbon-fluorine bonds make them difficult to eliminate from aqueous media (Liu et al., 2013) and thus easily pass through conventional municipal and industrial water and wastewater treatment plants (Lu et al., 2017). Among these chemicals, perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) have received the greatest attention in literature due to their abundance, bioaccumulation, and persistence (Trojanowicz et al., 2018) and have regulatory limits established in several states below 70 ng/L. Other PFASs may be present in the environment, along with PFOA and PFOS, due to product manufacturing processes (Post et al., 2013). Many versions of aqueous film-forming foams (AFFF) were manufactured which complicates the different compounds and distribution of different PFAS chemicals in water affected by fire-fighting training areas (McGuire et al., 2014). With upwards of 4,700 types of PFAS substances tabulated by the Organisation for Economic Co-operation and Development (OECD, 2018), suggesting that a majority are not monitored or regulated in environmental testing.

With their abundance and persistence in the environment, PFAS compounds pose a serious human health risk due to their toxic effects (Zhang et al., 2016). In the U.S. alone, over 95% of adolescents and adults have measurable serum levels of PFOS, PFOA, PFHxS, and PFNA (Kato et al., 2011). The EPA has now published national drinking water health advisories of 70ng/L for either PFOS, PFOA, or their sum (USEPA, 2016; USEPA, 2016a). Humans can be exposed to PFAS through consumption of food and water, and it can take several years for

the body to eliminate the compounds (Zhang et al., 2013). PFAS compounds have been linked to increased risk of cancer (IARC, 2004) specifically kidney and testicular cancers (Sunderland et al., 2018). Perfluorooctanoic acid (PFOA) has been linked to elevated cholesterol and liver enzymes, decreased vaccination response, thyroid disorders (USEPA, 2016b). The infiltration of PFAS substances into the human body is extensive and there is bioaccumulation within the placenta and fetuses are exposed to a mixture of PFAS through gestation (Mamsen et al. 2019).

The technologies used for water treatment, both drinking and wastewater, such as aeration, microbiological degradation (Takagi et al., 2011), filtration (sand or granular activated carbon), ozonation, and chlorination are not reliably sufficient to remove PFAS substances (Boiteux et al., 2017). GAC and ion exchange removal methods also simply transfer contaminants to another phase, requiring further treatment or management (Boiteux et al., 2017). More research into these adsorbents show new short-comings in their removal of short-chain PFAS and their precursors (Xiao et al.2017). Specific ion exchange resins can help to target PFAS removal, but it is unclear how effective these resins are across the broad spectrum of PFAS substances (Zaggia et al. 2016). Separation techniques such as reverse osmosis or nanofiltration are effective at removing PFAS but have other limitations such as high capital cost and low flow rates which would make these systems difficult to apply on a wide range of applications (Higgins and Dickenson 2016).

Emerging technologies for the treatment of PFAS include new adsorption separation, and destruction methods. Adsorption onto organically modified silica shows advantages in the removal of short-chain PFAS compounds, but this method only removes as much as other adsorption methods (Horst et al. 2018). Adsorption methods still present the issues of regeneration and disposal as well (Horst et al. 2018). Ozofractionation involves sparging ozone gas through tanks with PFAS contaminated waters to create a foam that can be collected. While promising as an addition to wastewater plants with heavily contaminated waters this method produces a waste stream with concentrated PFAS that will need further treatment (Dickson 2014). The newest and most promising of technologies are the destructive methods, including electrochemical treatment.

Electrochemical treatment involves the direct electron transfer from a molecule to the anode which oxidizes the molecule and the molecule is reduced at the cathode within an electrochemical cell. These cells consist of an anode, a cathode, and an electrolyte which can be divided or undivided and use various synthesized mixed metal oxide anodes (Schaefer et al 2015; Gomez-Riz et al. 2017). While PFAS is resistant to traditional advanced oxidation

processes (Moriwaki et al., 2005), electrochemical treatment has shown promise in treating PFAS with its high energy efficiency, ability to achieve complete mineralization, and operational simplicity (Zhuo et al., 2017). Boron-doped diamond (BDD) anodes appear to be very practical from an operational point of view (Urutiaga et al. 2015) but only demonstrated 65% effectiveness for removal of PFOS (Schaefer et al. 2017). Recent work showed that Ti_4O_7 is a promising electrode for the oxidation of organic compounds (You et al., 2016; Wang et al. 2017). Magnéli phase Ti_4O_7 ceramic anodes operated in batch mode achieved 99.9% removal of PFOA and 85% removal of PFOS (Lin et al., 2018).

Other studies have indicated that oxidation of PFAS compounds in electrochemical treatment might occur through indirect oxidation of the non-fluorinated head groups along with direct electrode oxidation mechanism (Gomez-Ruiz et al. 2017; Schaefer et al. 2020). The indirect oxidation could occur through generated radicals from different species such as chlorine, sulfate, or carbonate present in the water (Pica et al. 2019; Velazquez-Pena et al. 2013; Azizi et al. 2011). Sulfate radicals have been shown to oxidize perfluoroalkylether compounds which would conclude that PFAS compounds could be susceptible to carbonate and hydroxyl radicals (Pica et al. 2019). These radicals likely do not have the capacity to break down PFAS on their own and a large contribution for degrading PFAS is the direct oxidation on the electrode surface (Hanshuang et al. 2011). A theory proposed is that the degradation begins with a direct one electron transfer from the carboxyl or sulfonate group of PFASs to the electrode surface. Consequently, a PFAS radical is formed after being stripped of its' functional group. This is proceeded by reactions with hydroxyl radicals which ultimately break the carbon-fluorine bond (Zhuo et al. 2012).

The objective of this study was to evaluate industrial-scale Ti_4O_7 electrochemical anodes on the degradation of the six most regulated PFAS compounds: perfluorooctane sulfonic acid (PFOS); perfluorooctanoic acid (PFOA); perfluorohexane sulfonic acid (PFHxS); perfluorononanoic acid (PFNA); perfluoroheptanoic acid (PFHpA); and perfluorodecanoic acid (PFDA). Two anode types, solid and microporous, which differ in flow pattern and in composition of precious metal coatings were tested to determine economic feasibility in treating PFAS. These reactors were evaluated for the degradation of individual PFAS compounds at two voltages, two amperages, and with the addition of sodium sulfate to the base conductivity of sodium chloride. These key variables have the most significant effect on the reactor and were used to find the balance most economical and highest removal for commercialization.

2. Experimental

2.1 Materials:

Perfluorooctanoic acid (95%), perfluorononanoic acid (97%), perfluorodecanoic acid (98%), perfluoroheptanoic acid (99%), heptadecafluorooctanesulfonic acid potassium salt ($\geq 98\%$), and tridecafluorohexane-1-sulfonic acid potassium salt ($\geq 98\%$) were purchased from Sigma-Aldrich. Granular, USP-grade sodium chloride was purchased from Spectrum Chemical. 99% purity, anhydrous sodium sulfate was purchased from Sigma-Aldrich. The electrochemical reactors were provided by Aclarity, LLC. Deionized water was produced onsite at the Aclarity laboratory.

2.2 Experimental Methods:

Experiments were conducted in two types of flow-through reactors. Both of the reactors have Ti_4O_7 anodes and stainless steel cathodes with 0.0943 m^2 of anodic surface area. The first reactor has a microporous surface in which water flows through the reactor body with a 3-millimeter gap between the electrodes. The second reactor has a solid surface in which water flows around the working electrodes in the chamber also with a 3-millimeter gap between the electrodes. Four gallons of deionized water was dosed with 100 micrograms per liter of PFOS, PFOA, PFNA, PFDA, PFHpA, and PFHxS. The experimental setup is shown in Figure 1 but the filter was not utilized.

The experiments were conducted in either constant voltage or constant current through a variable switching DC benchtop power supply. For the voltage experiments, which were conducted at 12 and 15 volts in each reactor type, the voltage was set constant and the amperage allowed to vary throughout the experiment. 100 milligrams per liter of sodium chloride was added to the system for each voltage test. Sodium sulfate, 100 milligrams per liter, was added to the system along with sodium chloride and tested at 12 and 15 volts. For constant current testing the amperage was set constant, at either 60 or 80 amps, and sodium chloride was added to achieve the target voltage of 12 or 15 volts. While the power supply was able to achieve the voltage level in the beginning of the tests, the voltage dropped throughout the test. Samples were taken every hour over a four hour testing period. Voltage, amperage, conductivity, ORP, pH, temperature, and oxidants were measured for every sample.



Figure 1: Experimental setup in the Aclarity laboratory with 10-gallon tank, pump, power supply, and electrochemical reactor

2.3 Analytical Methods:

Samples were analyzed via Liquid Chromatography LC/MC/MC with isotope dilution according to the Department of Defense (DOD) Quality Systems Manual (QSM) for Environmental Laboratories for aqueous matrices (Department Of Defense, 2019). This analysis was completed by Pace Analytical Laboratories in South Carolina.

The samples for the tests analyzing the effects of amperage were processed at a 100 times dilution due to matrix interference. All other samples were undiluted.

3. Results and Discussion

Both electrochemical reactors were successfully able to remove PFDA, PFNA, and PFOS under every tested condition. These three compounds have the highest number of carbons tested, with 10, 9, and 8 respectively. PFOS with a sulfonic acid group was easily removed but PFOA that has a carboxylic acid group was among the half of compounds that was not removed. The short-chain compounds PFHpA, with 7 carbons, and PFHxS, with 6 carbons, were removed significantly less than the long-chain compounds. PFHpA and PFHxS were removed less than 20% in both types of reactors. Figure 2 shows the difference of chain lengths and their removal in the microporous reactor.

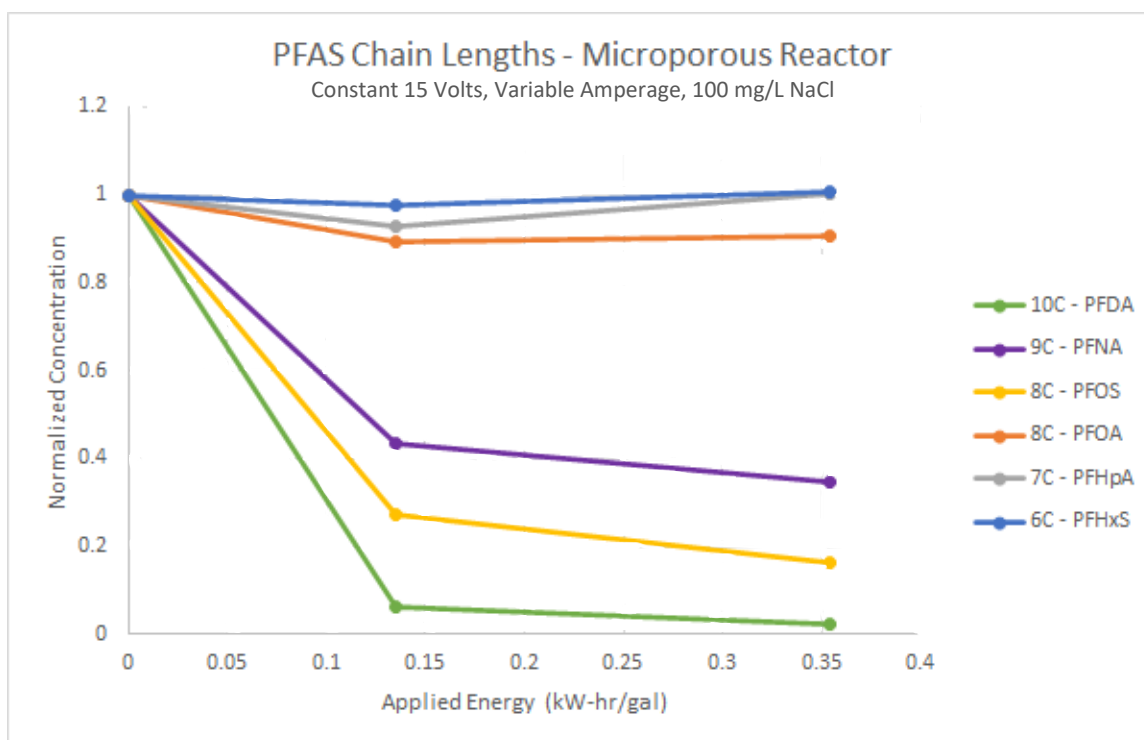


Figure 2: Microporous Reactor PFAS Chain Length Comparison

The solid reactor was able to achieve some level of removal for the short-chain compounds as well as almost half of PFOA, as shown in Figure 3. In both types of reactors, PFDA was removed over 96% but the solid reactor was able to remove 20% more PFNA and 10% more PFOS than the microporous reactor. There was no removal of the short-chain compounds in the microporous reactor but the solid achieved 11%, 16%, and 44% removal of PFHpA, PFHxS, and PFOA respectively. This separation of how the reactors remove the compounds may be due to the compounds' hydrophobic functional groups. The hydrophobic

ends will gravitate towards the electrode and be removed via direct electron transfer faster than the other compounds. With the flow configuration of the solid reactor, there is more time for interactions between the contaminants and electrode.

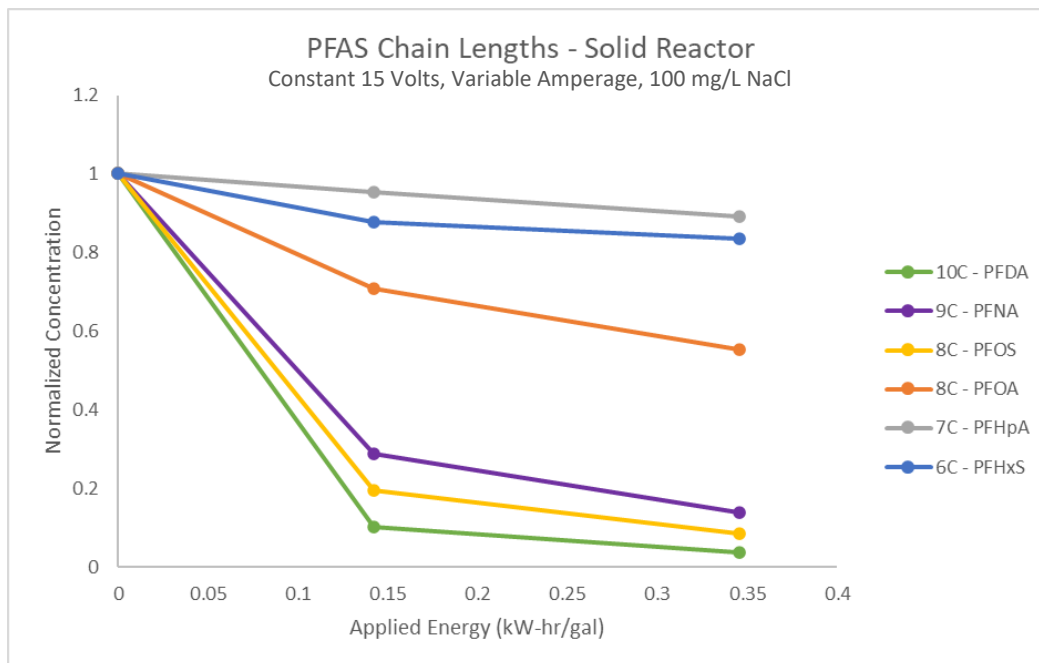


Figure 3: Solid Reactor PFAS Chain Length Comparison

As the removal of all six species can be categorized into long and short chain compounds, PFOS and PFOA can be used as representative species. While both reactors remove PFOS, the solid removes 8% more under the same conditions of 15 volts and varying current as seen in Figure 4. The solid reactor the short-chain compounds by at least 10% while the microporous reactor does not remove the compounds by more than 5%. The other variables studied also show this trend between reactors.

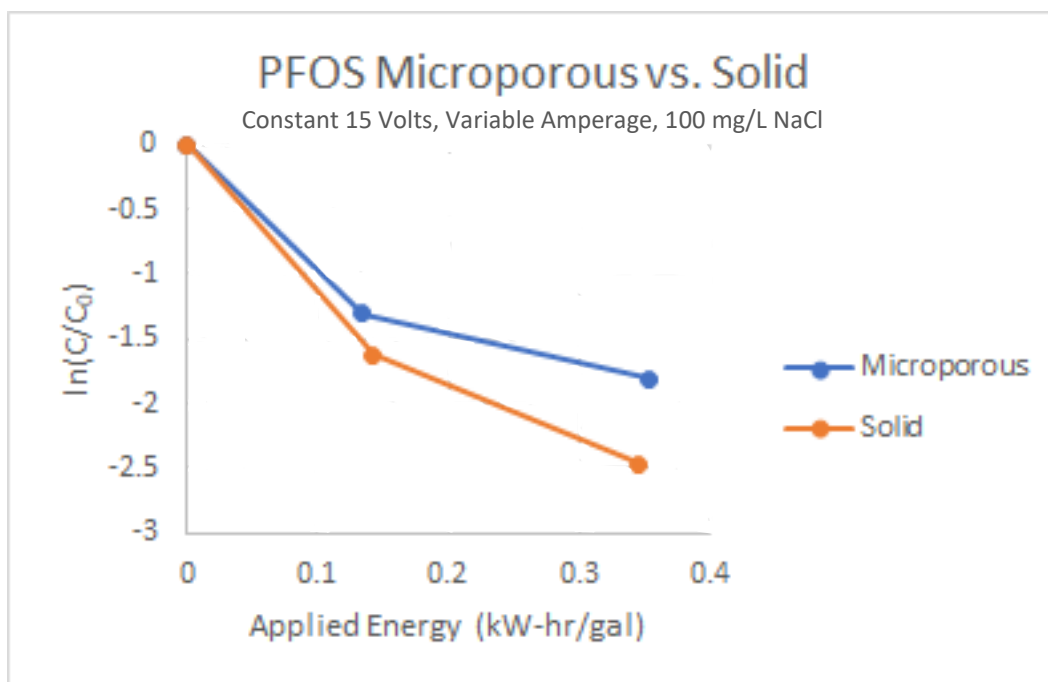


Figure 4: Solid vs. Microporous Reactor PFOS Removal

The effects of two salts, sodium chloride and sodium sulfate, were studied in each reactor. Sodium chloride was added to every test to provide conductivity. The addition of 100 milligrams per liter sodium sulfate was studied at 12 volts. The solid reactor with only sodium chloride, shown in Figure 5, follows the pattern of removal of the longer-chain compounds and little removal of short-chain compounds.

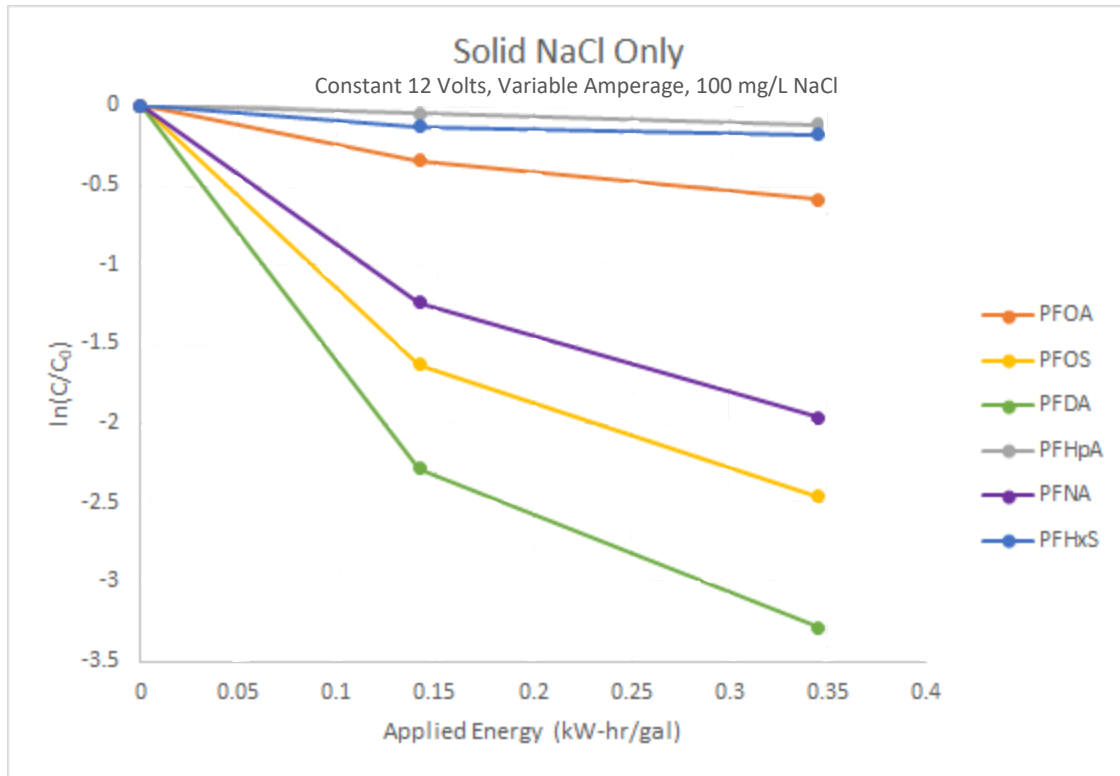


Figure 5: Solid Reactor Removal Using Sodium Chloride Only

With the addition of sodium sulfate, shown in Figure 6, the removal of PFOS and PFNA is hindered by 17% and 20% respectively. The removal of PFOA is also halved with the introduction of sodium sulfate. PFDA only lost 3% removal while PFHpA and PFHxS were no longer removed with sodium sulfate, compared to 2% and 2.5% respectively with only sodium chloride. The sodium sulfate added conductivity to the system that in turn increased the amperage of the system. The greater the amperage of the system allows for more opportunity for reactions which in theory should have helped, but the sodium sulfate may have caused competing reactions in the system and the formation of weaker radicals that were not able to remove PFAS.

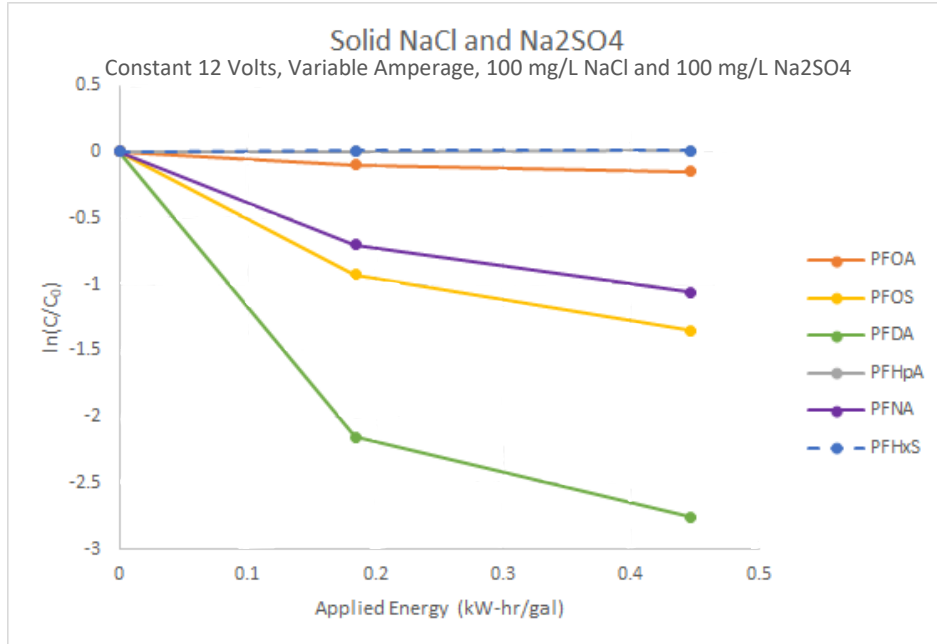


Figure 6: Solid Reactor Removal with Sodium Chloride and Sodium Sulfate

The microporous reactor with only sodium chloride, in Figure 7, is easily able to remove PFDA and there is slight removal of PFOS and PFNA. This follows the same pattern of removal for short and long chain compounds seen in the other tests.

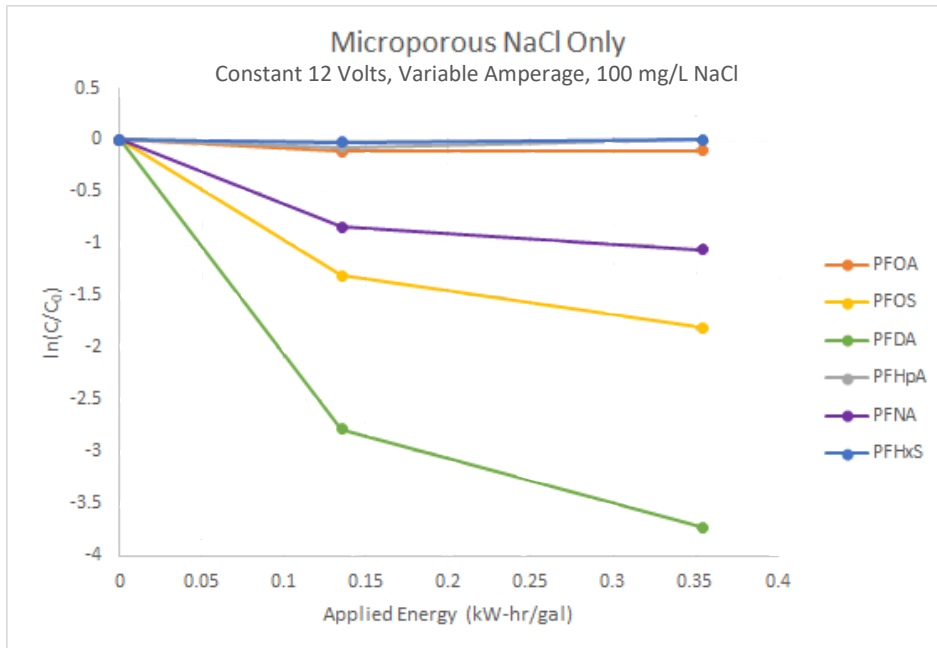


Figure 7: Microporous Reactor Removal Using Sodium Chloride Only

The addition of sodium sulfate, in Figure 8, provides an extreme decrease in removal of all of the PFAS compounds in the microporous reactor. The scale in Figure 8 has decreased

dramatically compared to Figure 7. While it is possible that competing radical formation and reactions caused this decrease in treatment it is unlikely due to how dramatic the change is. There may have been buildup on the reactor that interfered with the removal for this experiment that caused this dramatic change, but there would likely still be a decrease in removal with the addition of sodium sulfate in this reactor.

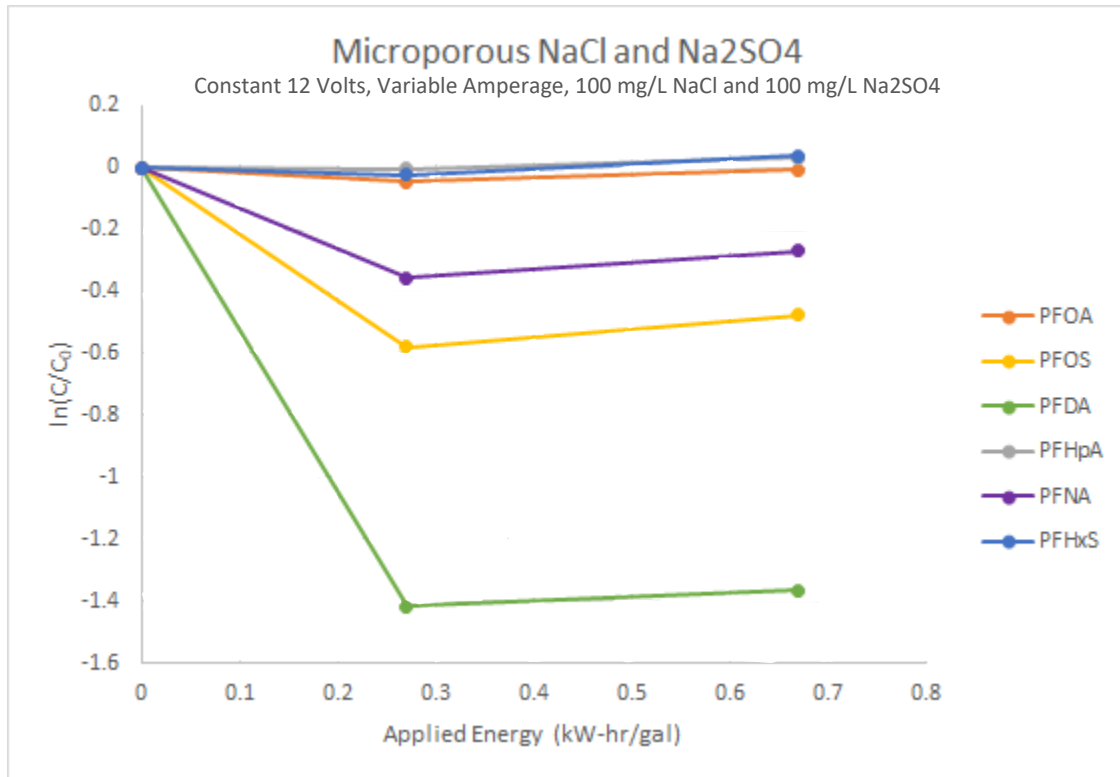


Figure 8: Microporous Reactor Removal with Sodium Chloride and Sodium Sulfate

The effect of removal through voltage is shown through the levels of PFOS removal. As the other long-chain compounds had the same effects from voltage, only PFOS is shown. None of the short-chain compounds were removed significantly in these tests. The results of applying 12 and 15 volts in both types of reactors shown in Figures 9 and 10.

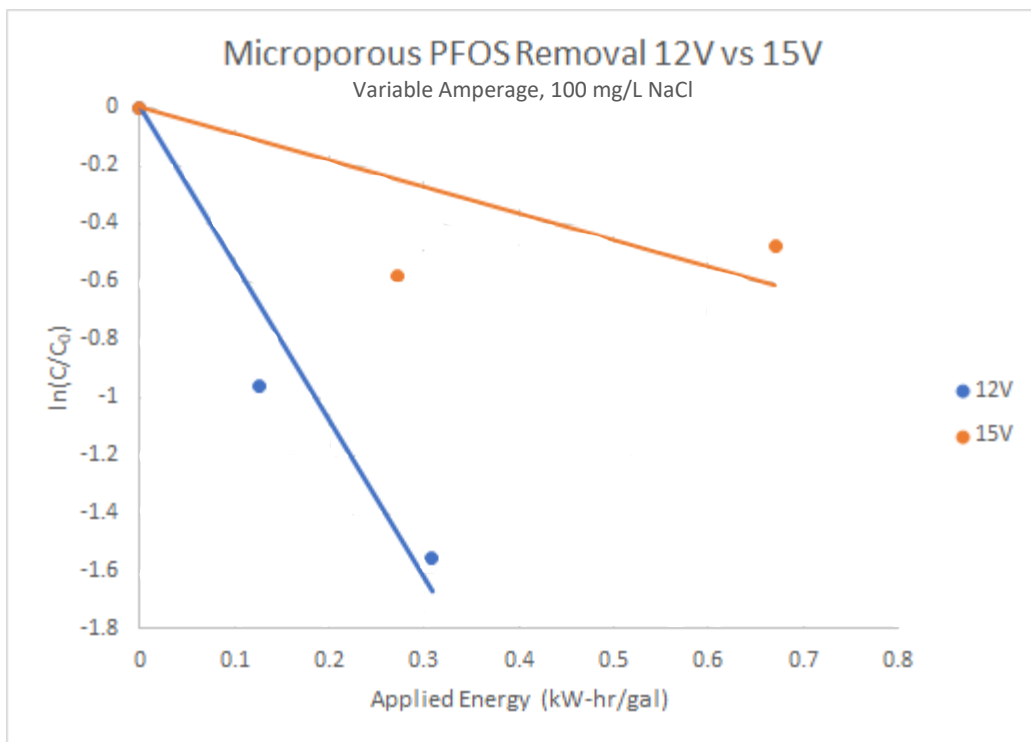


Figure 9: Microporous Reactor PFOS Removal at 12 and 15 Volts

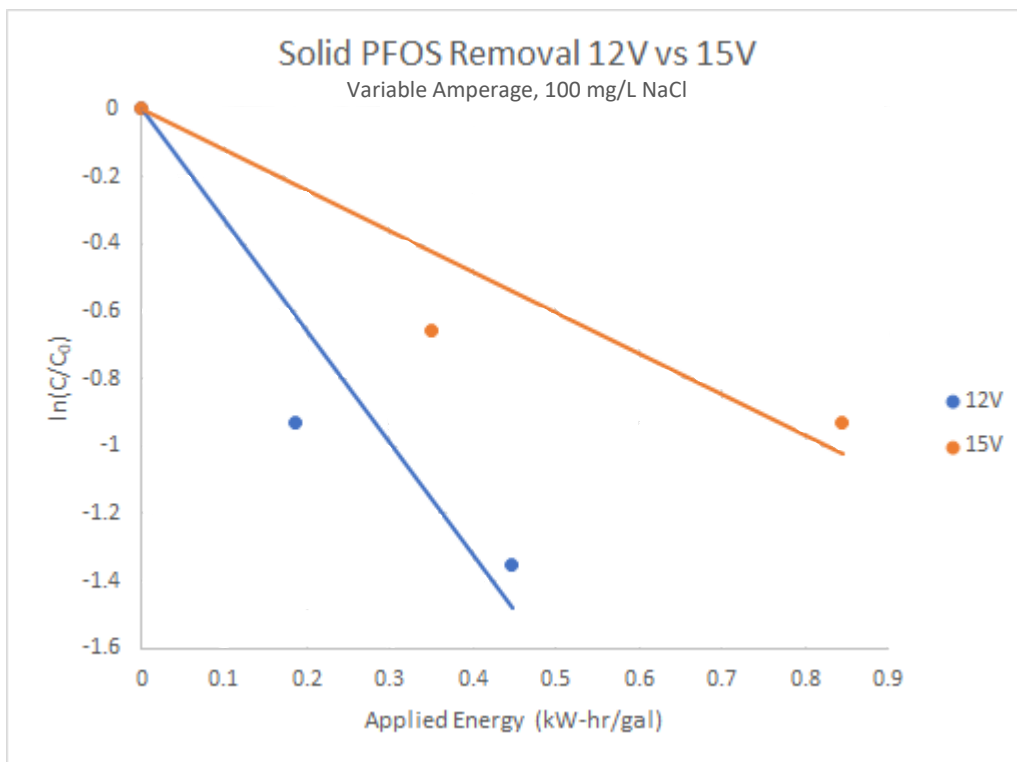


Figure 10: Solid Reactor PFOS Removal at 12 and 15 Volts

In both the solid and microporous reactors, operating at 12 volts removed more PFOS and used significantly less power. The microporous reactor removed 40% more PFOS and used less than half the power than at 15 volts. The solid reactor removed 15% more PFOS at 12 volts and required half the power. While these tests were run at the same amperage, the applied power varies more with voltage which likely accounts for the large difference in power requirement. There was more efficient removal at 12 volts which could be due to parasitic reactions at 15 volts that are not contributing to the destruction of PFAS compounds.

The two amperage settings studied, 60 and 80 amps, were prioritized on the variable switching power supply. Sodium chloride was added to achieve a starting voltage of either 12 or 15 volts. The voltage would drop throughout the duration of the tests as the resistance within the reactor decreases. The difference between 60 and 80 amps paired with 12 volts in both reactors are shown in Figures 11 and 12. Again, only PFOS is shown as representation of the removable short-chain compounds. The long-chain compounds were not affected by the change in amperage.

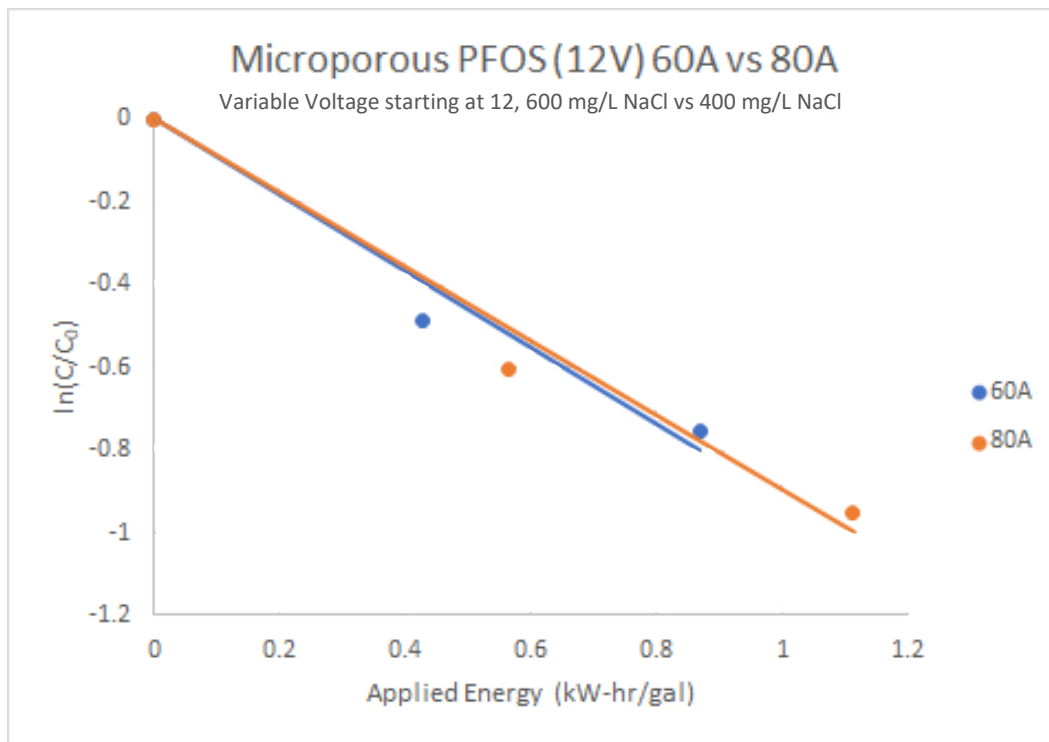


Figure 11: Microporous Reactor PFOS Removal 60 vs 80 Amps at 12 Volts

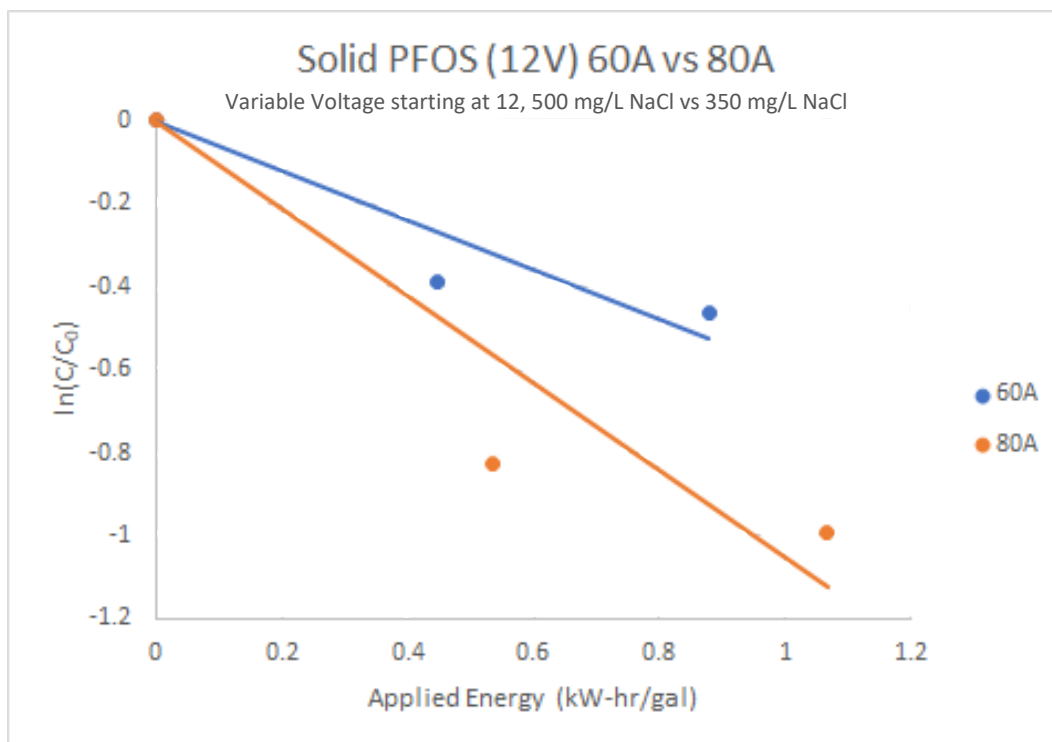


Figure 12: Solid Reactor PFOS Removal 60 vs 80 Amps at 12 Volts

Both reactors apply the same amount of power for 80 amps and remove a similar level of PFOS. The microporous reactor was able to remove almost double the PFOS at 12 volts compared to the solid. The reactors also increased 25% removal efficiency at 80 amps compared to 60 but didn't remove as much PFOS, especially in the solid reactor. These differences are likely due to the different amounts of sodium chloride in the system for each test. More sodium chloride was required to reach 80 amps so there was likely more conductivity available to remove the PFAS.

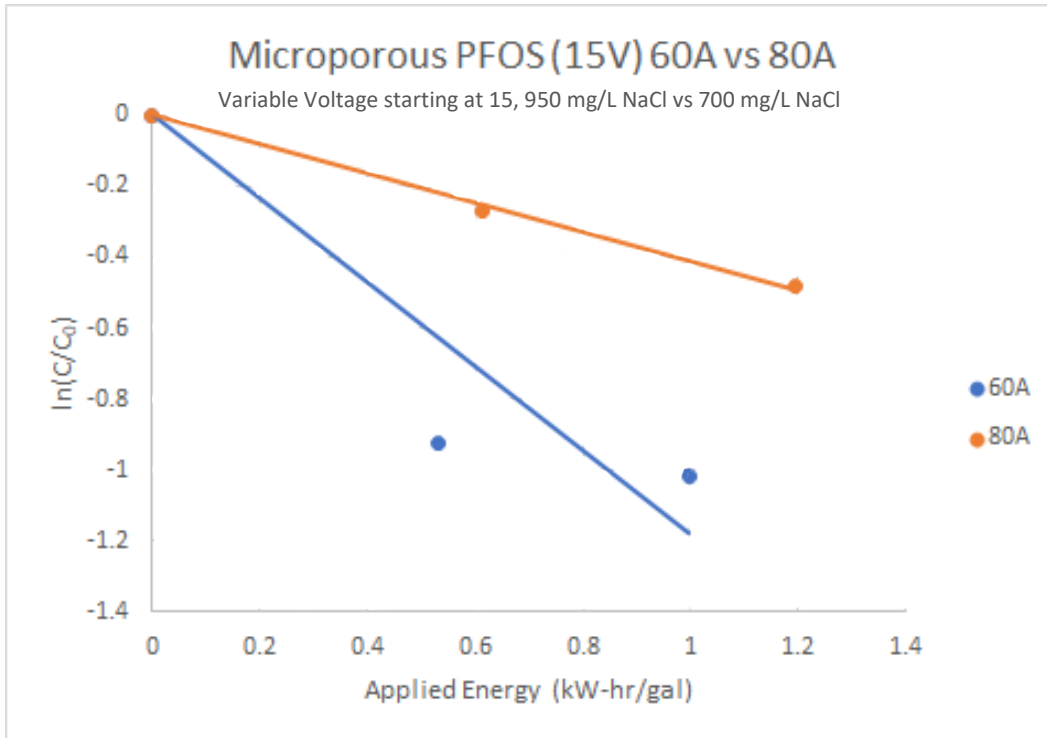


Figure 13: Microporous Reactor PFOS Removal 60 vs 80 Amps at 15 Volts

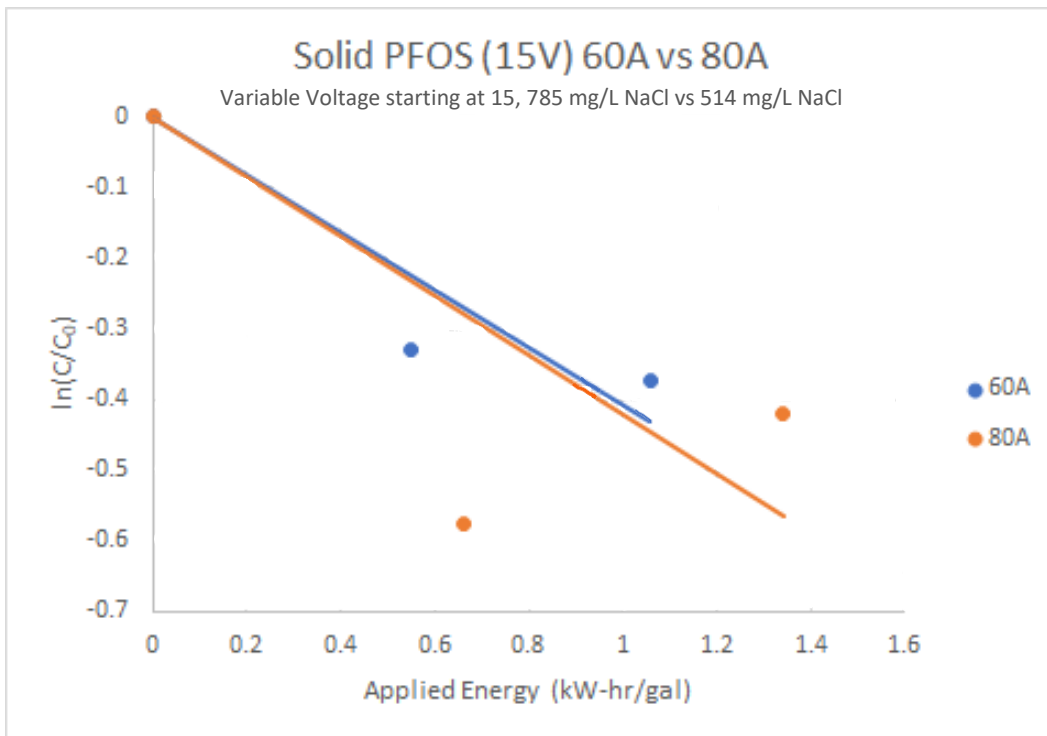


Figure 14: Solid Reactor PFOS Removal 60 vs 80 Amps at 15 Volts

At 15 volts, in Figure 13, the microporous reactor experiences a greater effect on the percent removal of PFOS while the solid reactor, in Figure 14, is not affected greatly. It is interesting to note that this is the opposite of the results at 12 volts. The more amperage applied to the system always achieves slightly better removal in both reactors but uses more power. It may be possible to remove PFOS to the same levels at 60 amps but would require more treatment time. Increasing the amperage of the system allows for more reactions, and therefore more removal of PFAS, to take place which is clearly seen from these experiments. The higher amperage enables the reactors to remove more PFOS while only using 0.3 kW-hr/gal more. The microporous reactor at 15 volts in Figure 13 was the only testing scenario that did not follow this trend. This could be due to fouling of the reactor or the flow pattern of the water going through the anode that could create bubbles that keep the PFAS compounds from being treated at the anode.

Table 1: Compilation of Rate Constants (min^{-1}) for Individual PFAS Compounds in each Testing Condition

Testing Conditions	PFDA	PFNA	PFOS	PFOA	PFHpA	PFHxS
Microporous 15V NaCl Only Variable Amperage	0.016	0.004	0.008	0.0004	-0.000004	-0.00002
Solid 15V NaCl Only Variable Amperage	0.01	0.008	0.01	0.003	0.0005	0.0008
Microporous 12V NaCl & Na ₂ SO ₄ Variable Amperage	0.016	0.003	0.007	0.0001	-0.0002	-0.0001
Solid 12V NaCl & Na ₂ SO ₄ Variable Amperage	0.01	0.004	0.006	0.0006	-0.00004	-0.0001
Microporous 15V NaCl & Na ₂ SO ₄ Variable Amperage	0.0057	0.0011	0.002	0.00003	-0.0001	-0.0002
Solid 15V NaCl & Na ₂ SO ₄ Variable Amperage	0.01	0.004	0.004	0.0007	0.0001	-0.0003
Microporous 12V 60A	1.49	0.82	0.92	0.21	0.10	0.11
Solid 12V 60A	1.28	0.40	0.53	-0.03	-0.07	-0.06
Microporous 12V 80A	1.36	0.56	0.85	0.22	0.012	0.0004
Solid 12V 80A	1.29	0.92	1.05	0.24	0.02	0.08
Microporous 15V 60A	2.19	0.81	1.18	0.21	-0.08	-0.03
Solid 15V 60A	1.04	0.26	0.36	-0.01	-0.03	0.0006
Microporous 15V 80A	0.84	0.32	0.40	0.05	-0.09	-0.11
Solid 15V 80A	0.82	0.31	0.31	0.03	-0.03	0.0346
<i>Average</i>	0.743	0.317	0.403	0.066	-0.013	0.001

Table 1 details the various testing conditions reported and the first order rate constants for each of the six PFAS compounds discussed. The long-chain compounds, PFDA, PFNA, and PFOS were removed significantly better during tests that controlled for amperage. This is not the case for PFOA, PFHpA, and PFHxS which usually are not removed and appear to reform, although this is likely due to error in measurement rather than formation.

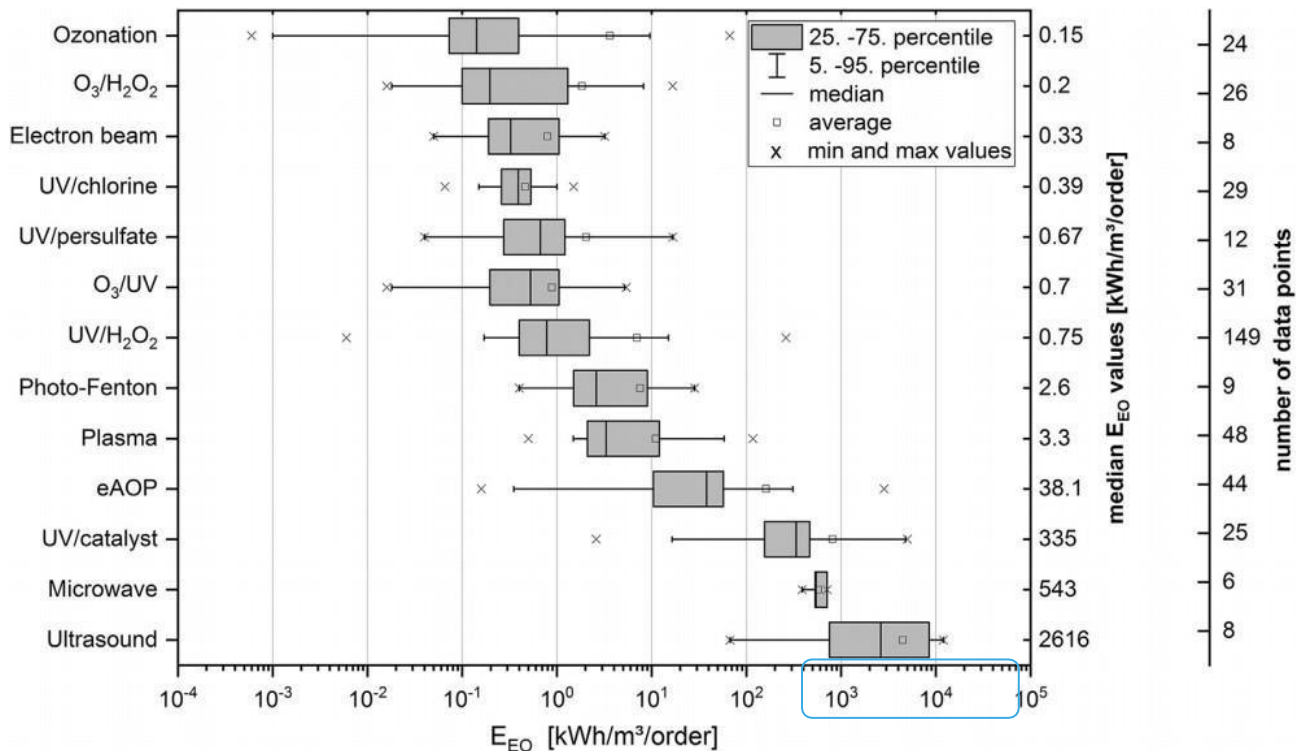


Figure 15: Electrical Energy Use Per Order Comparisons of AOPs From Miklos, D. B., Remy, C., Jekel, M., Linden, K. G., Drewes, J. E., & Hübner, U. (2018). Evaluation of advanced oxidation processes for water and wastewater treatment – A critical review. *Water Research*, 139, 118–131

Figure 15 describes the average electrical energy use per order (E_{EO}) of multiple advanced oxidation processes (AOPs) from Miklos et. al. 2018. Miklos' definition of feasibility in terms of E_{EO} is that technologies with a median of <1 kWh/m³/order and are technologies that can be used in full-scale applications with realistic operating costs. Medians of 1 - 100 kWh/m³/order are likely too energy intensive for most applications, but they may still be applicable solutions for certain contaminants. Any technology with greater than 100 kWh/m³/order was considered to not be an energy efficient technology. It is important to note that these E_{EO} values are dependent on many factors such as water matrix, molecular structure of the contaminant, and many physio-chemical characteristics of the particular AOP. The interdependencies makes the comparison of AOPs arduous, particularly for energy intensive contaminants like PFAS. While Figure 15 does include minimum and maximum values for each technology, these "energy intensive" points may not even be able to remove PFAS for many technologies, particularly the upper half of the figure. In such, large E_{EO} for PFAS treatment may be more energy efficient than is deemed by Figure 15. The E_{EO} is also dependent on the PFAS

compounds being removed. Short-chain compounds are much more energy intensive than long-chain compounds which broadens the range of E_{EO} considerably which also makes it difficult to compare to the values in Figure 15.

Both reactors that were studied fall into the last category with E_{EO} values of 1,300 kWh/m³/order and 800 kWh/m³/order for the removal of PFOS, in the microporous and solid reactor, respectively. The reactors, which cannot remove more than 40% of PFOA, one of the short-chain compounds, with E_{EO} values of 77,000 kWh/m³/order and 6,000 kWh/m³/order, in the microporous and solid reactor, respectively. The range of these values are marked by the blue box on Figure 15. These values were obtained by averaging all of the E_{EO} values for PFOS and PFOA from the testing conditions listed in Table 1. Although these large-scale electrochemical reactors do not fit into Miklos' definitions of energy efficient technology, the economics of these reactors may not be in the realm of impossibility. These tests operated with a high starting concentration of PFAS compounds in order to see the curve of removal more clearly. With more realistic concentrations this technology is not that expensive for destruction technology.

For example, using a contaminant level of 300 ng/L, which is common in a PFAS contaminated groundwater, to a treatment goal of Massachusetts' maximum contaminant level of 20 ng/L would be a feasible application for these reactors. With the average removal rate for PFOS and assuming an electrical rate of 0.1 \$/kWh, the reactor would use \$6,500 per year of electricity for treating 5,000 GPD to meet that contaminant goal. With the possibility of firm regulations of PFAS, these economics are rather favorable for this type of destruction technology. Treatment technologies like granulated activated carbon (GAC) for removal of PFOS and PFOA would be around \$25,000 per year to treat 5,000 GPD (Speth, slide 14). An ion exchange system would also be approximately \$24,000 per year to treat the same conditions (Speth, slide 15). These estimates from the EPA do not take into account the starting concentration though but these systems would be more expensive than Aclarity's destruction technology.

4. Conclusions

This study explored the degradation of six of the most commonly regulated PFAS compounds on a scale that could be used in industrial applications. Two designs of Magnéli phase Ti_4O_7 anodes, solid and microporous which differ in flow pattern, were tested. These reactors were evaluated for the ability to destroy individual PFAS compounds at two voltages, two amperages, and with the addition of sodium sulfate to the base conductivity of sodium chloride. The reactors could not remove more than 40% of the shorter-chain PFAS compounds like PFOA, PFHpA, and PFHxS but were easily able to achieve over 90% removal of PFOS, PFDA, and PFNA. The flow pattern in the solid reactor allowed for more contact time with the anode which was able to remove the long-chain compounds more effectively than the microporous at the same power settings and conductivity. The addition of sodium sulfate in the system along with sodium chloride hindered removal, likely due to other reactions taking place on the anode surface. Both reactors were able to remove PFOS more effectively at 12 volts than 15 volts. This could be due to parasitic reactions at 15 volts that are not contributing to the destruction of PFAS compounds. Higher amperage, 80 amps, is able to remove more PFAS compounds in both reactors than at 60 amps but also applies more power. When removing the longer-chained compounds, these systems can be economical for their destruction of PFAS rather than transfer to another media, but further investigation is required to remove short-chain compounds such as PFOA, PFHpA, and PFHxS with this large-scale reactor and to make the system more energy efficient.

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