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POTENTIAL PFAS DESTRUCTION TECHNOLOGY: ELECTROCHEMICAL OXIDATION

In Spring 2020, the EPA established the PFAS Innovative Treatment Team (PITT). The PITT was a multi-disciplinary research team that worked full-time for 6-months on applying their scientific efforts and expertise to a single problem: disposal and/or destruction of PFAS-contaminated media and waste. While the PITT formally concluded in Fall 2020, the research efforts initiated under the PITT continue.

As part of the PITT's efforts, EPA researchers considered whether existing destruction technologies could be applied to PFAS-contaminated media and waste. This series of Research Briefs provides an overview of four technologies that were identified by the PITT as promising technologies for destroying PFAS and the research underway by the EPA's Office of Research and Development to further explore these technologies. Because research is still needed to evaluate these technologies for PFAS destruction, this Research Brief should not be considered an endorsement or recommendation to use this technology to destroy PFAS.

Background

Various industries have produced and used per- and polyfluoroalkyl substances (PFAS) since the mid-20th century. PFAS are found in consumer and industrial products, including non-stick coatings, waterproofing materials, and manufacturing additives. PFAS are stable and resistant to natural destruction in the environment, leading to their pervasive presence in groundwater, surface waters, drinking water and other environmental media (e.g., soil) in some localities. Certain PFAS are also bioaccumulative, and the blood of most U.S. citizens contains detectable levels of several PFAS (CDC, 2009). The toxicity of PFAS is a subject of current study and enough is known to motivate efforts to limit environmental release and human exposure (EPA, 2020).

To protect human health and the environment, EPA researchers are identifying technologies that can destroy PFAS in liquid and solid waste streams including concentrated and spent (used) fire-fighting foam, biosolids, soils, and landfill leachate. These technologies should be readily available, cost effective, and produce little to no hazardous residuals or byproducts. Electrochemical oxidation (EC) has been identified as a promising technology that may be able to meet these requirements with further development, testing, and demonstrations.

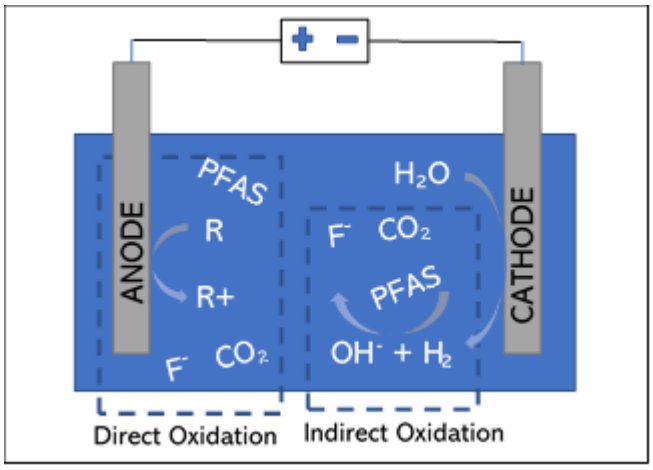

Figure 1. *Mechanisms of electrochemical oxidation.*

Electrochemical Oxidation: Technology Overview

EC is a water treatment technology that uses electrical currents passed through a solution to oxidize pollutants. EC treatment of persistent organic pollutants, such as PFAS, has been demonstrated at the bench and pilot scale (Nzeribe et al., 2019). Advantages of EC include: low energy costs, operation at ambient conditions, ability to be in a mobile unit, and no requirement for chemical oxidants as additives (Garcia-Segura et al. 2018). Limitations of this technology include the potential generation of toxic byproducts, incomplete destruction of some PFAS, efficiency losses due to mineral build up on the anode, high cost of electrodes, and potential volatilization of contaminants (Schaefer et al., 2019; Nzeribe et al., 2019). Despite these potential limitations, EC may be a promising technology for PFAS destruction in certain instances because of its demonstrated ability to destroy PFAS with lower energy demands than thermal incineration.

As shown in Figure 1, both direct and indirect oxidation mechanisms are possible, although the mechanisms that

occur vary with the specific PFAS. Direct oxidation can result by electron transfer from the PFAS compound to the anode, while indirect mechanisms involve electrochemically-created, powerful oxidants known as radicals (such as the hydroxyl radical, OH^-, shown in Figure 1). Through a series of reactions, intermediate products are separated from the parent compound and subsequently defluorinated (Schaefer et al., 2019; Zhuo et al., 2012; Nzeribe et al., 2019). The speed of EC treatment of PFAS is dependent on several variables, including: electrode composition and surface area, initial PFAS concentration, desired level of treatment, voltage, and co-contaminants. Treatment duration using two-dimensional electrodes is expected to be on the order of hours; however, recent advances, including development of a reactive EC membrane system, may be able to reduce the treatment time to seconds (Le et al., 2019). It is important to note that most of the testing completed to date has used laboratory control waste streams (i.e. clean waters spiked with PFAS rather than real-world waste streams). Real-world waste streams may require longer treatment times and may see reduced performance and electrode lifetime.

While commercially-available boron-doped diamond (BDD) electrodes are the most common and most widely evaluated in the literature, they are costly (~$7,125/$m^2$) and difficult to produce (Chaplin, 2019). Other mixed metal oxide electrodes, such as Ti_4O_7, are a fraction of the cost of BDD and have demonstrated effectiveness for PFAS destruction but have yet to be commercialized (Le et al., 2019). Very limited work has been done to evaluate long-term EC treatment, and the expected lifespan of these electrodes is unknown (Schaefer et al., 2019). Operational costs are primarily driven by energy consumption (Le et al., 2019). While significant work is being done to overcome these limitations, the initial cost, availability, and lifecycle costs of electrodes remain significant barriers to full-scale use of EC for PFAS destruction.

EC is known to produce perchlorate through oxidation of chloride in solution. Perchlorate generation and treatment should be considered when evaluating overall cost and feasibility of EC for PFAS-laden streams. Several authors have reported destruction of PFAS via EC treatment when evaluating individual compounds, such as PFOS and PFOA, but the fate of the fluorine within the process has not yet been fully assessed in a mass balance, making potential fluorinated byproducts a possibility (Nzeribe et al., 2019). This is especially concerning because some hazardous intermediate degradation compounds, such as trifluoroacetic acid, are volatile (Schaefer et al., 2015; 2017; Nzeribe et al., 2019).

Potential for PFAS Destruction

Researchers report reductions of the parent compounds, but complete PFAS destruction has yet to be confirmed as the potential for formation of products of incomplete destruction has yet to be fully evaluated. Removal here means the effluent contains less of the parent compounds than the influent. Liang et al. (2018) reported total removal of 77.2 and 96.5% of PFOA and PFOS, respectively, from ion-exchange resin regenerate (still bottom) with a Ti4O7 electrode. Xu et al. (2017) reported 97% removal efficiency of PFOA with a Zr-PbO2 film electrode. And Gomez-Ruiz et al. (2017) reported 99.7% removal of 8 PFAS with a BDD electrode. The time required for parent compound removal varied greatly among these studies and the technologies are still under development but the initial results are promising.

Research Gaps

Development of EC into a readily available PFAS destruction technology can be aided by: (i) reduction in cost of electrodes; (ii) coupling the process with a method to treat perchlorate and other byproducts; (iii) evaluation of long-term operation of EC to determine lifecycle electrode costs and evaluate process limitations from impacts of mineral build up; (iv) analysis of potential byproducts to understand that PFAS compounds are being completely degraded; (v) field demonstration of effective scale-up and optimization of process parameters. Currently, EC is assessed to have an intermediate technology readiness level, and further work is needed in multiple areas to maximize technology readiness (Lacasa et al. 2019).

Next Steps

EC is one of the technologies being evaluated by EPA researchers for PFAS destruction. EPA researchers are conducting pilot-scale testing to evaluate PFAS destruction under a variety of conditions. EPA expects to publish the results of this work in 2021.

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Note: This Research Brief is a summary of research conducted by the EPA's Office of Research and Development and does not necessarily reflect EPA policy.