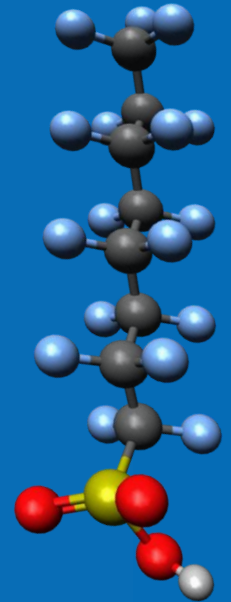
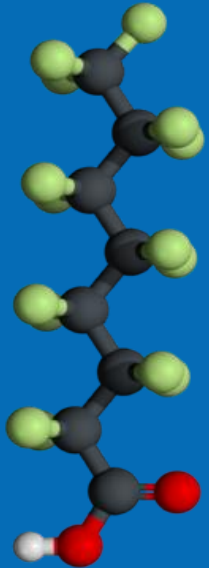


EPA PFAS INNOVATIVE TREATMENT TEAM (PITT) FINDINGS ON PFAS DESTRUCTION TECHNOLOGIES



Tim Watkins

Acting Director, Center for Public Health and Environmental Assessment
US EPA Office of Research and Development

BOSC Executive Committee Meeting

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Outline

- Summary of the PFAS Innovative Treatment Team (PITT)
 - Concept
 - Goals
 - Approach
 - Results
- PITT Experiences Working in Communities

PFAS Innovative Treatment Team (PITT)

- Full-time team of multi-disciplined EPA research staff
- Focused efforts and expertise on a single problem: **how to remove, destroy, and test PFAS-contaminated media and waste**
- For 6 months, the PITT worked to achieve the following goals:
 - Assess current and emerging destruction methods being explored by EPA, universities, other research organizations and industry
 - Explore the efficacy of methods while considering byproducts to avoid creating new environmental hazards
 - Evaluate methods' feasibility, performance and costs to validate potential solutions

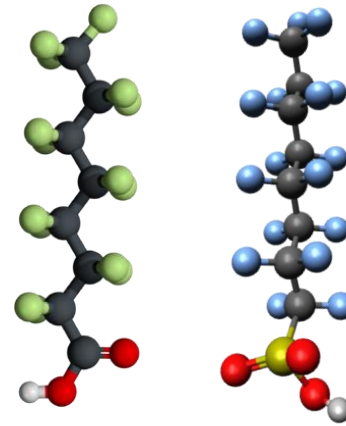
PITT Goals

- Develop a “Toolbox” of reviewed solution(s) for the destruction of PFAS in media and contaminated waste to meet the needs of EPA programs and regions, states and tribes, federal agencies, and industry
 - Traditional (combustion) destruction
 - Temperature and time conditions for C-F bond breakage
 - Performance of flue gas cleaning systems
 - Analysis of byproducts
 - Innovative (high risk), non-traditional approaches
 - Destruction performance
 - Byproducts
- Provide decision makers with state of the science data on incineration effectiveness enabling them to better manage end-of-life disposal of PFAS-containing materials



PFAS Sources Considered

- Biosolids, sludge
- Aqueous film forming foam (AFFF)-contaminated soils
- AFFF concentrate, spent AFFF
- Municipal Waste Combustors (MWCs), landfills, landfill leachate
- Spent granular activated carbon (GAC), anion exchange resins



Non-Combustion Technologies Selected

- Chemical
- Biological
- Plasma
- **Mechanochemical**
- Sonolysis
- Ebeam
- UV
- **Supercritical water oxidation**
- Deep well injection
- Sorption/stabilization
- **Electrochemical**
- Landfill
- Land application
- **Pyrolysis**

Assessment Factors:

- Technology readiness
- Applicability
- Cost
- Required development remaining
- Risk/reward of technology adoption

Assessment Methods:

- Subject matter expert discussions
- Literature reviews
- PITT discussions

Technologies selected for further investigation



PITT Introductory Paper on Four Innovative Technologies Studied

- PFAS problem
- 5 waste characteristics
- 4 innovative technologies
- Crosswalk of wastes and technologies
- **Technology readiness level**

Phase	TRL	Description
Research	1	Basic Principles observed
	2	Technology concept formulated
	3	Experimental proof of concept
Development	4	Technology validated in lab
	5	Technology validated in relevant environment
	6	Technology demonstrated in relevant environment
Deployment	7	System prototype demonstration in operational environment
	8	System complete and qualified
	9	Actual system proven in operational environment

<https://www.twi-global.com/technical-knowledge/faqs/technology-readiness-levels>

TRLs of Technology & PFAS Matrices

	Electrochemical Oxidation	SCWO	Mechanochemical degradation	Pyrolysis
Spent GAC / AEX	TRL 4 ¹ (GAC Only)	N/A ¹¹	TRL 2 ^{9,11}	TRL 1 ¹¹
Soils	TRL 1 ²	N/A ¹¹	TRL 5/6 ⁹	TRL 1 ¹¹
Biosolids / Sludges	N/A ¹¹	TRL 6 ⁵	TRL 1 ¹¹	TRL 7 ¹⁰
Spent and unused AFFF	TRL 4/6 ^{1,3}	TRL 7 ⁵⁻⁸	TRL 3/4 ⁹	N/A ¹¹
Landfill Leachate	TRL 4 ⁴	TRL 4 ⁷	N/A ¹¹	N/A ¹¹

BASIS

- ¹ AECOM
- ² Skinn 2019
- ³ Schaefer et al 2019
- ⁴ Pierpaoli et al 2020
- ⁵ 374Water
- ⁶ General Atomics
- ⁷ Aquarden
- ⁸ Battelle
- ⁹ EDL
- ¹⁰ BioForceTech
- ¹¹ PITT

EPA Research BRIEF
INNOVATIVE RESEARCH FOR A SUSTAINABLE FUTURE

INNOVATIVE PFAS DESTRUCTION TECHNOLOGY: SUPERCRITICAL WATER OXIDATION

Background

Various industries have produced and used PFAS since the mid-20th century. Per- and polyfluoroalkyl substances (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 US citizens contains detectable levels of several PFAS. 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 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. The capability to decompose an array of complex molecular structures simultaneously make **Supercritical Water Oxidation (SCWO)** an ideal candidate for further development.

Supercritical Water Oxidation: Technology Overview

Supercritical water oxidation (SCWO) is a process which can be utilized to destroy hazardous waste compounds. Water above a temperature of 374 °F and pressure of 221.1 bar is considered "supercritical", a special state of water where certain chemical oxidation processes are accelerated. Since the 1980's, SCWO has been used successfully to treat halogenated waste materials (containing fluorine, chlorine, bromine, or iodine) including polychlorinated biphenyls (PCBs) (Liska et al., 2001; Kim et al., 2010). Organic compounds, usually insoluble in liquid water, are highly soluble in supercritical water. In the presence of an oxidizing agent (such as oxygen), supercritical water dissolves and oxidizes various hazardous organic pollutants. Implementation of SCWO at scale has been limited by several technical challenges



Figure 1. SCWO reactions occur above the critical point of water. Image credit: Jonathan Kuyper.

including the buildup of corrosive gases during the oxidation reaction, the precipitation of salts, and the high energy requirements.

Destruction and Removal Efficiency

As an alternative to disposal of PFAS-laden material in a landfill or combustion in an incinerator, SCWO purports to destroy PFAS by breaking the strong carbon-fluorine bonds and decompose the material into a non-toxic waste stream. SCWO's previous applications to destroy chemical warfare agents, PCBs, halogenated compounds, makes it a potential, but currently unproven, alternative for PFAS destruction (Mogge et al. 2004; Milton et al., 2001). Jama et al., (2020) reported greater than 99% destruction of 12 PFAS, from 3.6 µg/L to <0.036 µg/L, from a landfill leachate. These data are preliminary and future experiments analyzing for more PFAS will help to understand if high destruction efficiencies can be expected for complex liquid wastes.

Research Gaps

Technical challenges to implementation of SCWO are presented by the high pressures and temperatures causing potential system degradation and maintenance

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SCWO

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INNOVATIVE PFAS DESTRUCTION TECHNOLOGY: ELECTROCHEMICAL OXIDATION

reduced and used PFAS since the mid-20th century. Per- and polyfluoroalkyl substances (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 US citizens contains detectable levels of several PFAS. 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 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. The capability to decompose an array of complex molecular structures simultaneously make **Supercritical Water Oxidation (SCWO)** an ideal candidate for further development.

Electrochemical Oxidation: Technology Overview

Electrochemical oxidation (EC) is a water treatment technology that currently passes through a series of stages. EC treatment of persistent PFAS, has been demonstrated at pilot scale (Nzeribe et al. 2019). Advantages of EC include: operation at ambient temperature and pressure; no need for hazardous oxidants as additives (Garcia et al. 2018). Limitations of this technology include: the potential generation of toxic byproducts from the destruction of some PFAS, such as mineral build-up on the anode, high energy requirements, and the potential volatilization of PFAS (Nzeribe et al. 2019). EC may be a promising technology for certain industries.

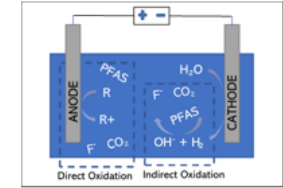


Figure 1. Mechanisms of EC.

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-generated, 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; Zhou 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 (Lo 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

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Electrochemical Oxidation

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INNOVATIVE PFAS DESTRUCTION TECHNOLOGY: MECHANOCHEMICAL DEGRADATION

Background

Various industries have produced and used PFAS since the mid-20th century. Per- and polyfluoroalkyl substances (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 US citizens contains detectable levels of several PFAS. 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 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. One potential technology to destroy PFAS-contaminated solid or semi-solid matrices is **mechanochemical degradation (MCD)**.

Mechanochemical Degradation: Technology Overview

MCD describes the mechanism of destruction that persistent organic pollutants undertake in a high-energy ball-milling device (Cagnetta, Huang et al. 2016). Mechanochemical degradation (MCD) does not require reagents or high temperatures to remediate solids and can be considered a "greener" method compared to traditional incineration (Bolan et al. 2020). Co-milling reagents like a, potassium hydroxide, or calcium oxide are added to react with the fluorine and to produce highly reactive species. The crystalline structures of the co-milling reagents are crushed and sheared by the high energy jets from the stainless-steel milling balls in the rotating vessel (Figure 1). Research has found that these collisions produce radicals, electrons, heat, and even plasma (Kiyama 2010) that react with PFAS to produce




Figure 1. Ball impacts create radicals from co-milling materials and localized high temperatures that mineralize PFAS.

Destruction and Removal Efficiency

MCD has shown promise at the benchtop and pilot scale and has the potential to be an alternative to incinerating solids containing persistent organic pollutants. A recent study by one commercial company showed destruction of greater than 99 percent of persistent organic pollutants in about six tons of soil in an hour with a transportable MCD setup (Bolan et al., 2020), but their work with PFAS is still in its preliminary stages. MCD also has the potential to produce gaseous PFAS emissions but these products of incomplete destruction (PIOs) have not yet been assessed. MCD could also be a unit operation in series with other treatment technologies, processing ash from an incineration unit or treated biosolids from a pyrolysis/gasification unit.

Research Gaps

Further research into the destruction of PFAS with MCD is needed to understand the effects of various matrices, the function of different co-milling reagents, the potential for loss of volatile PFAS, and performance at field application scales. MCD methods for destruction of persistent organic pollutants perform best with dry, sandy soil and the efficiency decreases as the soil becomes more clay-like. Co-milling reagents and other conditions can be modified to provide high efficiencies, but the destruction of PFAS in a variety of soils has not been fully studied yet. A large scale PFAS remediation project has not yet been undertaken, so design

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Ball Milling

EPA Research BRIEF
INNOVATIVE RESEARCH FOR A SUSTAINABLE FUTURE

INNOVATIVE PFAS DESTRUCTION TECHNOLOGY: PYROLYSIS AND GASIFICATION

Background

Various industries have produced and used PFAS since the mid-20th century. Per- and polyfluoroalkyl substances (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 US citizens contains detectable levels of several PFAS. 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 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. Pyrolysis and gasification have been identified as promising technologies that may be able to meet these requirements with further development, testing, and demonstrations.

Pyrolysis/Gasification: Technology Overview

Pyrolysis is a process that decomposes materials at elevated temperatures in an oxygen-free environment. Gasification is similar to pyrolysis but uses quantities of oxygen, taking advantage of the partial combustion process to provide the heat to operate the process. The oxygen-free environment in pyrolysis and the oxygen environment of gasification distinguish these processes from incineration. Pyrolysis, and certain forms of gasification, can transform input materials, like biosolids, into a biochar while generating a hydrogen-rich synthetic gas (syngas). Biochar and syngas can be valuable products. Biochar has many potential applications and is currently used as an amendment that increases the soil's capacity to hold water and nutrients, requiring less irrigation and fertilizer



Figure 1. Biosolids, from wastewater to beneficial use on crops. Syngas can be used on-site as a supplemental fuel for biosolids drying operations, significantly lowering energy needs. As an additional advantage, pyrolysis and gasification require much lower air flows than incineration, which reduces the size and capital expense of air pollution control equipment. PFAS have been found in effluent and solid residual (sewage sludge) streams in wastewater treatment plants (WWTPs), prompting increasing concern over management of these materials. In the U.S., WWTP solids have typically been managed in one of three ways: (1) treatment to biosolids followed by land-application; (2) disposal at a lined landfill; or (3) destruction (burning) in a sewage sludge incinerator. WWTP solids are rich in nutrients and the most common U.S. practice is to aerobically or anaerobically digest it to produce a stabilized biosolid product that can be land-applied as fertilizer. This is done because the nutrients in biosolids deliver nitrogen, phosphorus, and other trace metals that are beneficial for crops and soil (Figure 1).

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Pyrolysis & Gasification

Summary of PITT Findings and Accomplishments

- The PITT was successful in significantly accelerating research to evaluate “traditional” thermal treatment of PFAS waste and catalyzing research to identify and evaluate potential innovative approaches for PFAS waste treatment.
- Preliminary results in laboratory and pilot-scale treatment systems demonstrate up to 99% loss of the initial PFAS compounds in the contaminated waste.
 - Still unknown, however, is what PFAS byproducts, if any, are formed.
- PITT efforts also drove the development of new PFAS measurement methods to be used to characterize air emissions sources and evaluate efficacy of PFAS destruction/removal technologies
 - Stationary source air emissions test method - [Other Test Method 45 \(OTM 45\)](#)
- PITT scientists contributed to recently released EPA “Interim Guidance on Destroying and Disposing of Certain PFAS and PFAS-Containing Materials That Are Not Consumer Products”
 - <https://www.epa.gov/pfas/interim-guidance-destroying-and-disposing-certain-pfas-and-pfas-containing-materials-are-not>

Building Upon the PITT

- Continue laboratory and pilot-scale research and development efforts on:
 - Non-combustion, innovative technologies
 - Thermal/combustion technologies
- Identify potential fluorinated byproducts formed during the application of these treatment approaches (non-target compound analyses)
- Exploring opportunities for field sampling at industrial and utility facilities
 - Wastewater Treatment/Sewage Sludge Incineration
 - Municipal Waste Combustion
 - Hazardous Waste Incineration

PITT Experience with Working in Communities

PITT Experiences with Working in Communities

- The PITT attempted two field studies to evaluate PFAS treatment/destruction technologies
 - Municipal Waste Combustor facility in Rahway NJ – cancelled due to community concerns
 - Pyrolysis Biosolids Treatment facility in Redwood City CA – completed but with reduced scope
- Communications and Community Engagement
 - Develop communications materials (Desk Statement, Background, Q&As) which were reviewed, edited and approved by ORD, EPA Regions, and Office of Public Affairs.
 - Focused communication on a few key stakeholders, but decision to not communicate widely in advance of testing
- Challenges
 - PITT initiated in April with a 6-month timeline – limited time for community engagement
 - Inaccurate or misinformed coverage from the press

PITT Experiences with Working in Communities

Lessons Learned

- Greater recognition to cumulative impacts in community
- Ensure sufficient time for community engagement and communications
- Consider proactive communications to control key messages
 - Purpose of the study
 - Post study plans and actions
- Strong partnerships are critical
 - EPA Region
 - State
 - Facility

Lessons Learned from PITT experience applied as ORD completed a field study in August at a wastewater treatment plant in Cedar Rapids, IA

Contacts

Brian Gullett

Lead, PITT Team

Center for Environmental Measurement
and Modeling

US EPA Office of Research and Development

919-541-1534

Gullett.Brian@epa.gov

Tim Watkins

Acting Director

Center for Public Health and Environmental
Assessment

US EPA Office of Research and Development

919-541-5114

Watkins.Tim@epa.gov

<https://www.epa.gov/chemical-research/pfas-innovative-treatment-team-pitt>

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