Destroying "Forever Chemicals" with Zimpro® Electro-Oxidation (ZEO): Lummus Technology's Solution for PFAS Destruction

Executive Summary

Per- and polyfluoroalkyl substances (PFAS) are increasingly in the spotlight — and for good reason. These persistent synthetic compounds, developed for their unique chemical resilience, have now become a global liability in water systems. For utilities and industrial operators, the escalation of PFAS regulation, detection, and liability risk demands action beyond "treat and store." Crying out for a new paradigm: destruction at the source.

PFAS ARE A HEALTH RISK

Epidemiological and toxicological studies have linked PFAS to serious health outcomes such as:

- Increased risks of kidney and testicular cancers
- Liver and thyroid dysfunction
- Elevated cholesterol levels and immune suppression
- Developmental and fertility impacts

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PFAS In The Spotlight

Per- and polyfluoroalkyl substances (PFAS) have become a defining environmental challenge of this decade. Once valued for their durability and water-resistant properties, PFAS now represent a complex legacy contaminant that resists natural degradation and traditional water treatment methods. Known as "forever chemicals," PFAS persist in soil, water, and air, circulating through ecosystems and reappearing in drinking water, food chains, and even human bloodstreams.

Useful Chemistry with Unintended Consequences

PFAS have been used since the mid-20th century in countless consumer and industrial products: from nonstick cookware and water-resistant fabrics to firefighting foams, semiconductors, and coatings. Their carbon-fluorine bond—among the strongest in organic chemistry—makes them exceptionally stable, resistant to heat, and nearly impervious to natural breakdown processes.

While this stability drove their commercial success, it also underpins their environmental persistence. PFAS compounds bioaccumulate in organisms and magnify up the food chain, leading to long-term exposure risks for both humans and wildlife. Health studies have linked exposure to several PFAS compounds, including PFOS and PFOA, with increased cholesterol, thyroid disease, liver damage, developmental effects in infants, and certain cancers.

A Global Problem

Recent advances in analytical testing have revealed that PFAS contamination is more widespread than once believed. Municipal water utilities, industrial manufacturers, and waste management facilities are now facing the dual pressures of tightening regulations and rising public concern. For many, addressing PFAS is no longer optional—it is a matter of operational, financial, and reputational survival.

The global scope of PFAS pollution underscores the scale of the problem. They have been detected in water sources, soil, and wildlife in nearly every region studied, requiring a coordinated response across industries and jurisdictions.

The Regulatory Landscape

From Awareness to Enforcement

Regulators worldwide are accelerating efforts to limit PFAS exposure. In the United States, the Environmental Protection Agency (EPA) issued its first-ever national drinking water standards for PFAS in 2024, setting enforceable limits for compounds such as PFOA and PFOS at parts-per-trillion (ppt) levels. These limits are based on the agency's evolving understanding of PFAS toxicity and persistence.

Beyond federal action, several U.S. states—including California, Michigan, New Jersey, and Maine—have implemented even stricter standards or have banned certain PFAS-containing products altogether. Many are also enacting cleanup mandates for contaminated industrial sites and landfills. These regulations are continuously tightening as analytical detection capabilities improve and public pressure mounts.

For utilities and industries, this shifting regulatory environment introduces a clear message: PFAS mitigation strategies must not only meet today's limits but anticipate tomorrow's standards.

The Cost of Inaction

For many operators, the financial risks associated with PFAS surpass the cost of proactive mitigation. In the past five years alone, U.S. litigation and remediation expenses tied to PFAS have reached billions of dollars, with significant settlements involving manufacturers, water systems, and downstream users. Beyond direct penalties, utilities face mounting operational expenses from media replacement, waste disposal, and sludge management, particularly as incineration and landfill options come under stricter control.

Industrial facilities that discharge or manage PFAS-containing waste also face reputational and permitting challenges. Noncompliance can halt operations, delay expansions, and expose companies to regulatory and community backlash.

The Challenge

Why PFAS Are Hard to Eliminate

The same chemistry that made PFAS commercially valuable now makes them uniquely difficult to treat. Each molecule is defined by a chain of carbon atoms bonded to fluorine, and this sturdy bond gives PFAS their resistance to heat, water, and oil. But it also prevents them from breaking down naturally in the environment.

Traditional biological and chemical treatment systems are unable to cleave this bond. Activated sludge, oxidation, and advanced filtration methods effective for many organic pollutants leave PFAS largely untouched. Instead of being degraded, PFAS persist in the effluent, accumulate in waste media, or simply transfer from one phase to another. The result is containment, not destruction.

Operational and Technical Barriers

PFAS contamination typically occurs at trace levels measured in parts per trillion, requiring exceptionally sensitive analytical and operational approaches. These low concentrations pose a practical challenge: the compounds are widespread but dilute, making treatment volumes large and recovery processes complex.

Moreover, PFAS are not a single substance but a vast family of thousands of related compounds, each with slightly different physical and chemical properties.

Long-chain PFAS tend to bind more easily to solids and can be removed by adsorption, while short-chain PFAS remain highly soluble and pass through conventional media. This chemical diversity means no single treatment method can effectively capture or destroy all PFAS species present in a waste or water stream.

Adding to the challenge, PFAS can interfere with treatment systems by fouling membranes, shortening media life, and producing concentrated waste streams that themselves require safe handling and disposal. The operational costs of managing these systems—particularly when combined with emerging regulatory pressures—are rising sharply for both utilities and industries.

The Limits of Traditional Treatment Methods

For decades, utilities and industries have relied on granular activated carbon (GAC), ion exchange (IX) resins, and membrane filtration to manage contaminants like PFAS. While effective at capturing certain compounds, these technologies do not eliminate PFAS, they merely transfer them into spent media, which must then be incinerated or landfilled.

Activated Carbon (GAC):
GAC can adsorb longer-chain PFAS, but it performs poorly with shorter-chain compounds. Its effectiveness diminishes as the carbon becomes saturated, and disposal or regeneration of used media presents additional cost and environmental challenges.

Ion Exchange (IX):
IX resins are often more selective and efficient for low-concentration PFAS, but the same limitation applies: they capture, not destroy. Single-use resins require frequent replacement and create waste streams that must be managed, while regenerable resins introduce brine solutions that still contain concentrated PFAS.

Membrane Filtration:
Techniques like reverse osmosis and nanofiltration can achieve near-complete removal from water, but they produce PFAS-rich reject streams that still demand final destruction. These systems also involve high energy inputs and substantial capital investment.

In each case, the underlying problem persists: PFAS are isolated, not neutralized. As disposal options tighten—incineration, for instance, faces growing regulatory scrutiny—organizations must look beyond separation technologies toward true chemical destruction solutions.

Regulatory Pressure and the Shrinking Margin for Error

As detection methods improve and toxicological understanding advances, regulatory thresholds for PFAS are tightening across every major jurisdiction. The EPA's enforceable limits now reach single-digit parts per trillion, levels that demand near-total removal to achieve compliance.

This trend will continue. States are already expanding the list of regulated PFAS compounds and lowering allowable concentrations in drinking water, wastewater, biosolids, and landfill leachate. Meanwhile, new reporting and liability frameworks are emerging under the U.S. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), exposing facility operators to cleanup obligations that can span decades.

For engineers and risk managers, these developments signal a pivotal shift: technologies must not only remove PFAS efficiently but also ensure the compounds are permanently destroyed. The era of "capture and contain" is ending. The future of compliance depends on "treat and eliminate."

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Existing and Emerging Destruction Methods

1. Thermal Destruction (Incineration and Pyrolysis)

High-temperature methods such as incineration or pyrolysis can break down PFAS by exposing waste to extreme heat (often exceeding 1,000°C).

Pros:

- Proven for a wide range of organic compounds
- Can process mixed waste streams

Cons:

- Requires substantial energy input and specialized infrastructure
- Incomplete combustion can produce harmful by-products if not tightly controlled
- Increasingly restricted by regulatory agencies due to concerns about secondary emissions

While once the default option for PFAS disposal, incineration is under growing scrutiny, prompting the need for safer, lower-temperature alternatives.

2. Advanced Oxidation and Reduction Processes (AOPs/ARPs)

Chemical and electrochemical methods that generate highly reactive species (such as hydroxyl radicals or hydrated electrons) are designed to oxidize or reduce PFAS compounds into smaller, benign molecules.

Pros:

- Capable of targeting both long- and short-chain PFAS
- Can be integrated with existing water treatment systems
- Lower temperature and smaller footprint compared to incineration

Cons:

- Energy-intensive for large-scale applications
- Some systems generate intermediate compounds that must be further treated
- Long-term electrode durability and cost remain key design considerations

This class of technologies represents one of the most promising directions for PFAS destruction, with several electrochemical and plasma-based systems now in pilot or early commercial stages.

3. Supercritical Water Oxidation (SCWO)

SCWO leverages water above its critical temperature and pressure (374°C and 221 bar) to create a highly reactive phase that can oxidize PFAS and other refractory contaminants.

Pros:

- Achieves near-complete destruction of organic compounds
- Handles concentrated waste streams effectively

Cons:

- Requires high capital investment and robust materials to withstand corrosive environments
- Complex to operate and maintain
- Limited full-scale installations due to safety and cost concerns

SCWO has demonstrated high efficiency in laboratory settings, but scalability and operational simplicity remain barriers to widespread adoption.

4. Plasma-Based Destruction

Plasma reactors use electrical discharge to generate reactive species that break PFAS bonds in water or air.

Pros:

- Rapid reaction times
- Effective for concentrated PFAS streams
- Minimal chemical inputs

Cons:

- Energy-intensive for dilute water matrices
- Requires pre-concentration for optimal efficiency
- Limited commercial deployment and field data

Although still emerging, plasma-based destruction is an active research frontier and may complement other treatment approaches in hybrid systems.

5. Biological and Catalytic Approaches

Recent studies are exploring enzymatic, microbial, and catalyst-assisted methods to degrade PFAS at lower energy levels.

Pros:

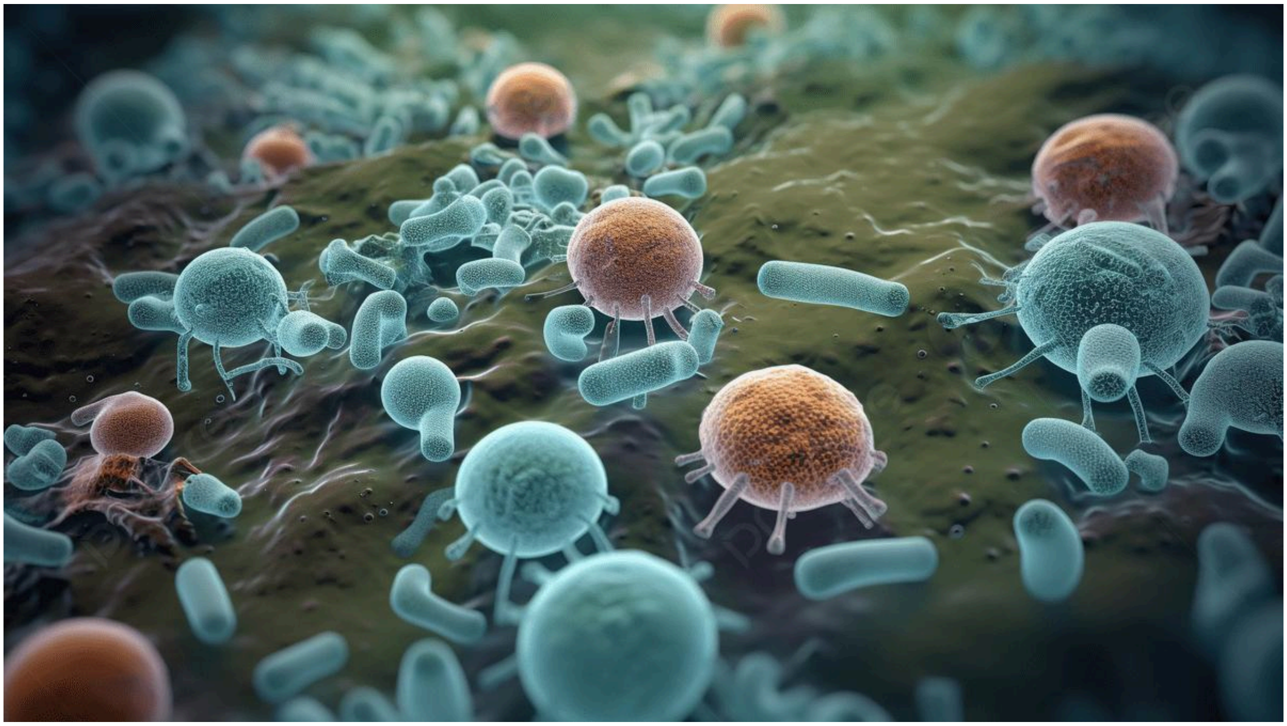
- Potential for cost-effective, environmentally benign treatment
- Could integrate into biological wastewater processes

Cons:

- Still at early research stages with limited demonstration data
- Slow kinetics and incomplete breakdown of complex PFAS structures

While promising for the long term, these approaches are not yet viable for near-term industrial or municipal deployment.

As regulatory thresholds continue to decline, the balance is shifting toward destruction-first strategies that can meet future compliance standards without creating new environmental liabilities.



A close up of bacteria used in water treatment

Zimpro

A Proven Pathway to Complete PFAS Destruction

Lummus Technology's Zimpro® Electro-Oxidation (ZEO) system represents a decisive shift from containment to true destruction. Unlike adsorption or separation processes that merely transfer PFAS into waste streams, ZEO permanently breaks the carbon–fluorine bond, the defining feature that makes PFAS so persistent. The result is complete mineralization of PFAS compounds into carbon dioxide, water, and fluoride ions.

ZEO is built on more than a century of process engineering excellence and decades of experience scaling chemical and environmental technologies. The system combines electro-oxidation chemistry with Element Six's proprietary boron-doped diamond (BDD) electrode materials to deliver a robust, scalable, and verifiable solution for the most recalcitrant contaminants in wastewater.

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The Science Behind the Solution

In 2024, Lummus and Element Six established a partnership to introduce scalable and viable solutions to treat, destroy and eliminate PFAS from water. This partnership combines Element Six's leading patented BDD electrochemical oxidation technology with Lummus' patented electro-oxidation technology and system integration for water and wastewater treatment.

At its core, electro-oxidation is a process that uses electrical energy to generate highly reactive hydroxyl radicals (•OH) directly within the contaminated water stream. These radicals rapidly attack organic molecules, including the strong C–F bonds in PFAS, converting them into benign end products. In addition, the boron-doped diamond (BDD) electrode surfaces are capable of direct oxidation of PFAS.

The ZEO process uses Element Six's pure BDD electrodes, engineered for exceptional conductivity, chemical stability, and corrosion resistance. These electrodes can sustain current densities up to 100 times greater than those of conventional electrochemical systems, enabling the oxidation of even the most stable PFAS molecules.

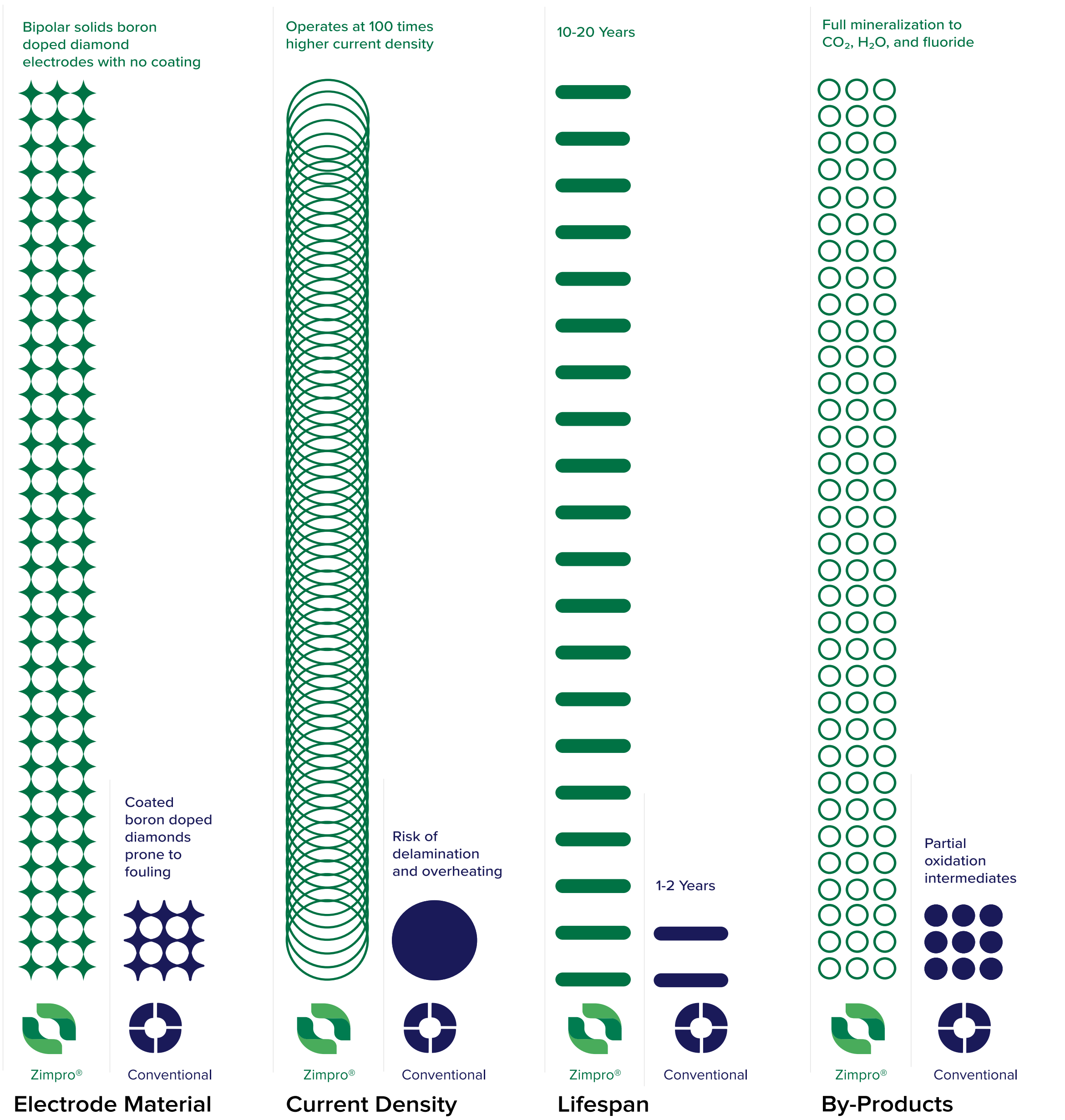
Key Differentiators

The ZEO system's bi-polar reactor design also prevents deposit buildup, ensuring consistent performance over extended operation. This reliability, combined with the chemical inertness of Element Six's BDD, makes ZEO uniquely suited for high-strength industrial waste streams and concentrated PFAS solutions.

How Lummus Zimpro® (ZEO) Compares to Conventional Electro-Oxidation

Lummus Zimpro® Electro-Oxidation
Full integration with
all concentration methods

Conventional Electro-Oxidiation
Fragmented compatibility



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Lab and Pilot Testing Results

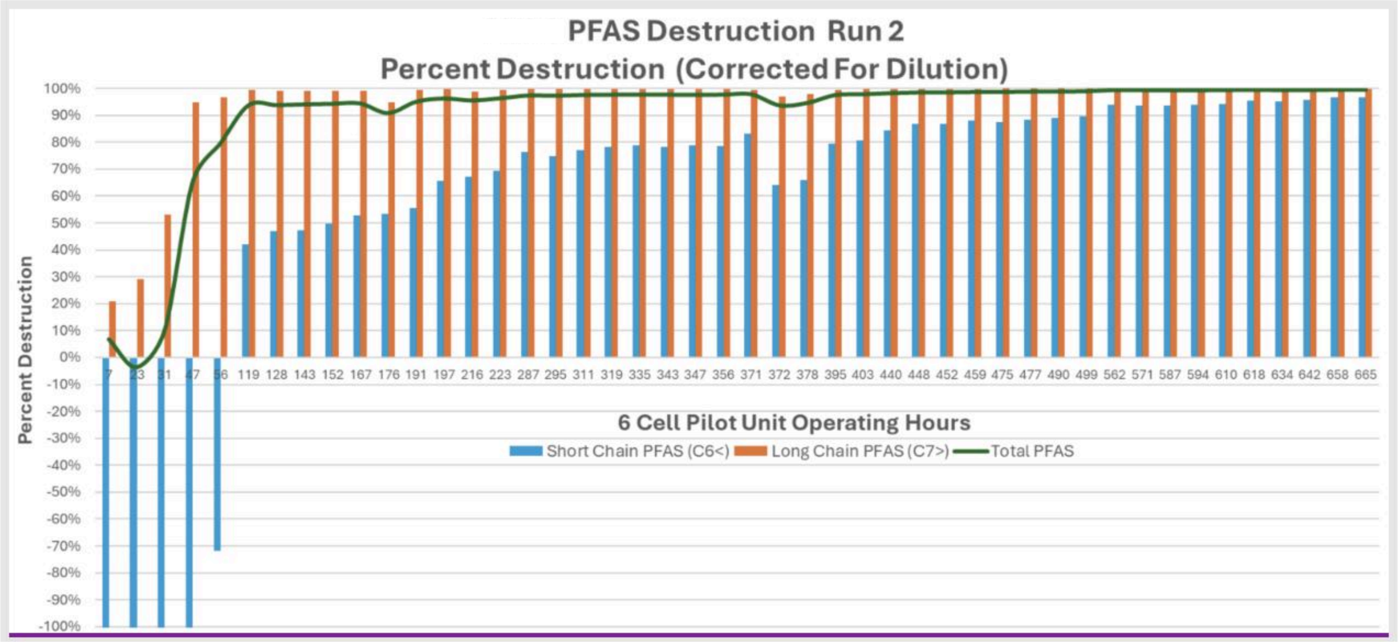
ZEO has been validated through controlled laboratory testing and real-world pilot operations at Lummus's Water Laboratory in Houston, Texas. Analytical procedures follow in-house EPA Method 1633, confirming both the breakdown of PFAS molecules and the stoichiometric recovery of fluoride ions, direct evidence that C–F bonds are being fully cleaved.

KEY PERFORMANCE HIGHLIGHTS

- >99.99% destruction efficiency across short- and long-chain PFAS compounds
- Confirmed mineralization: total organic fluoride converted to inorganic fluoride. Mass balances comparing organic fluoride to inorganic fluoride substantiate this.
- Validated with landfill leachate: 99.996% total PFAS reduction after foam fractionation pre-treatment

Safety, Scalability, and Commercial Readiness

Unlike high-temperature or chemically intensive methods, ZEO operates under ambient conditions with no additional reagents or combustion steps. The process is electrically driven, providing precise control and on-off responsiveness that align with modern water treatment automation systems.



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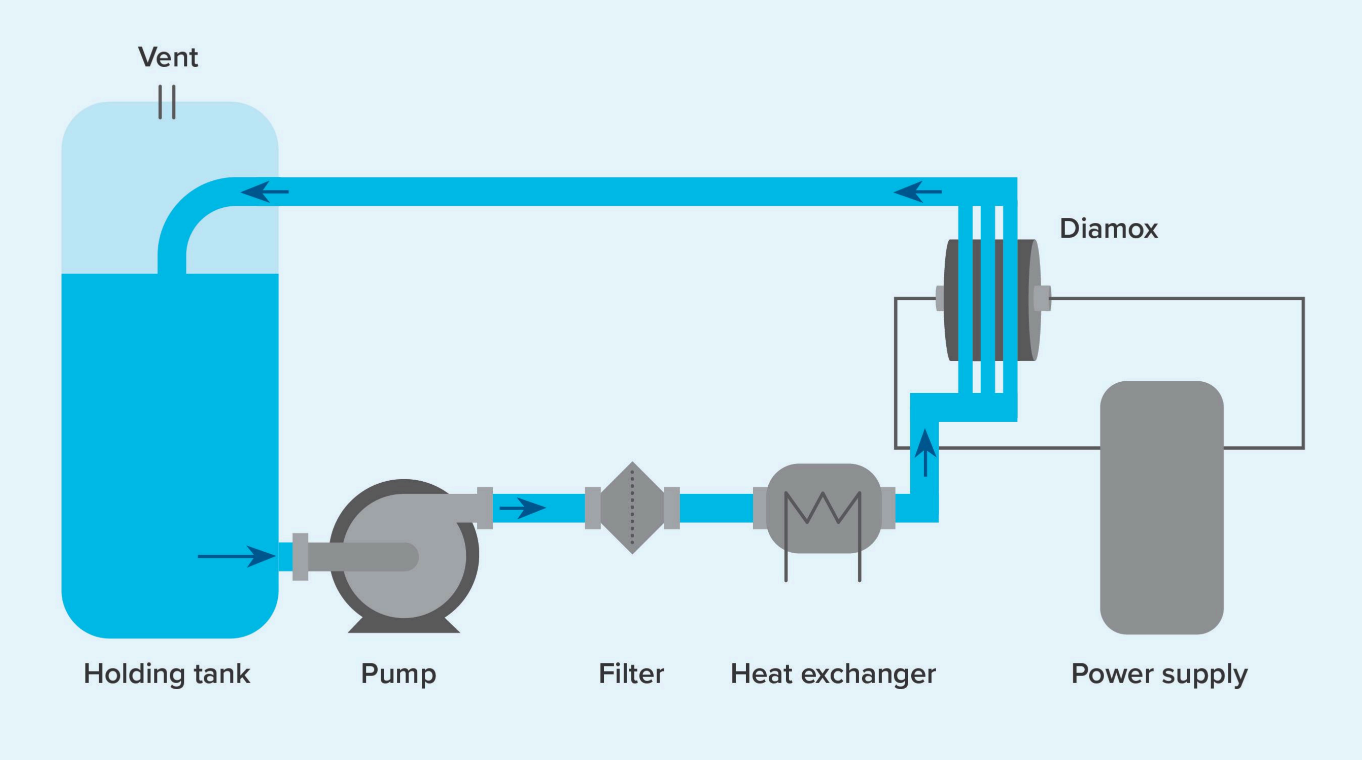
ZEO's modular design allows for easy integration into existing treatment frameworks—either as a polishing step following PFAS concentration (e.g., ion exchange, reverse osmosis, or foam fractionation) or as a stand-alone destruction unit for brine and leachate streams.

With a commercial-scale reactor already operational and pilot units available for demonstration, Lummus offers utilities and industries a proven, low-risk pathway to full PFAS compliance.

Typical System Design and Operational Footprint

ZEO units are modular and compact, designed to fit within standard industrial footprints. A single skid-mounted unit can treat thousands of gallons per day depending on concentration and flow requirements, and systems can be scaled in parallel to accommodate higher volumes.

The process is fully automated, energy-efficient, and adaptable to intermittent or continuous flow operation. Because no chemical reagents are required, on-site handling risks are minimal, and maintenance primarily involves electrode inspection and occasional cleaning.



Case Study: Landfill Leachate Treatment

A full-scale pilot conducted at Lummus Water Lab in Houston demonstrated the system's robustness in treating landfill leachate, a notoriously difficult matrix due to its high solids content and ionic strength.

After a 1:1000 concentration step using foam fractionation, the ZEO system achieved near-total PFAS destruction.

Outlet From ZEO

PFAS Component	Units	% Destruction
PFBA	ng/L	99.086%
PFPeA	ng/L	99.968%
PFHxA	ng/L	99.992%
PFHpA	ng/L	99.993%
PFOA	ng/L	99.961%
PFNA	ng/L	99.994%
PFBS	ng/L	99.193%
PFPeS	ng/L	99.992%
T-PFHxS	ng/L	99.999%
PFHpS	ng/L	99.994%
T-PFOS	ng/L	99.988%
6:2 FTS	ng/L	100.000%
5:3 FTCA	ng/L	99.999%
7:3 FTCA	ng/L	99.986%
Total PFAS	ng/L	99.996%

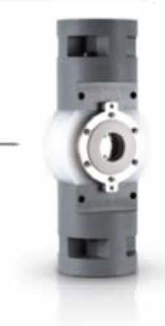
The process also demonstrated stoichiometric fluoride recovery—confirming full C–F bond cleavage—and maintained stable operation despite the presence of organic matter and cations that often foul conventional systems

Integration Within Existing Workflows

ZEO's design allows for integration at multiple points in a treatment process. Optimally the ZEO process will be used in synergy with the collection and concentrating step. This allows for a high degree of destruction to occur at a lower energy consumption. Conversely it can also be used as a end of pipe solution which can achieve the most stringent treatment and discharge requirements.

Each commercial reactor is capable of oxidizing approximately 2.0 kg/hr of chemical oxygen demand. These reactors can be placed into a system (pre engineered and standardized systems available to contain up to 4 reactors) to increase capacity. These systems can then be run in parallel or series to increase capacity further.

This modular flexibility ensures that utilities and industries can scale adoption incrementally, without overhauling existing infrastructure. For organizations facing increasing regulatory and community pressure, ZEO provides a practical, near-term path to compliance and environmental stewardship.

Product	Application	# of BDD Elec.	Power Requirements	Oxidation Capacity (COD)	
Microcell 5C-016	PFAS development	5	<50 W	< 0.6 mg hr^{-1}	
Diapod™ 4C-02	Laboratory cell for efficacy and efficiency measurement	4	~1.5kW	<30 g hr^{-1}	
Diamox™ 6C-016	Pilot Plant cell for process development	6	<15 kW	<0.5 kg hr^{-1}	
Diamox™ 20C-016	Modular unit for industrial water treatment technology	21	< 50 kW	< 2.0 kg hr^{-1}	

Diapod™ and Diamox™ images courtesy of Element Six

The Path Forward: Steps to Get Started

Partnering for Progress

The path to eliminating PFAS is not just about adopting a new technology, it's about building the right partnership. Lummus Technology brings more than a century of process-engineering expertise and a proven record of commercializing complex treatment systems at industrial scale. Lummus supports clients from initial feasibility to full implementation, ensuring every project achieves both technical success and regulatory compliance.

For utilities and industrial operators facing PFAS challenges, the next step is understanding how destruction technologies like Zimpro® Electro-Oxidation (ZEO) fit into their existing treatment infrastructure.

Pilot Testing Opportunities

Lummus offers pilot and demonstration units that allow clients to evaluate performance on their specific waste streams before full-scale deployment. These trials help validate:

- PFAS destruction efficiency across various chain lengths and concentrations
- Energy and operating requirements
- Integration compatibility with pre-treatment systems such as IX, RO, or foam fractionation
- Analytical verification of fluoride recovery and PFAS elimination

Each pilot test is supported by Lummus's applications engineering team, who guide sampling protocols, data interpretation, and regulatory documentation.

Engage with Lummus

Lummus provides multiple avenues for engagement, depending on where an organization is in its PFAS management journey:

Schedule a Consultation: Meet with a Lummus PFAS specialist to review the specifics of current challenges and discuss system options

Request a Pilot Evaluation: Utilize the pilot unit to validate destruction performance under real-world conditions.

Access Technical Reports and Data: Receive detailed technical literature and case results to support internal assessments or regulatory filings.

Collaborate on Regulatory Guidance: Work with Lummus experts to align treatment strategies with EPA and state-specific compliance frameworks.

Whether through early-stage feasibility or full-scale deployment, Lummus acts as a long-term technology partner, bridging innovation with practical application to deliver sustainable water treatment solutions.

Let's work together

PFAS contamination represents one of the most pressing technical and environmental challenges of our time—but it is solvable.

Organizations ready to move beyond capture and containment can take the first step today:

Email our team

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