NATIONAL SCIENCE FOUNDATION (NSF)

Workshop on Detection, Removal, and Safe Destruction of PFAS from Semiconductor Manufacturing Waste Streams

Workshop Proceedings Report

November 2024

Acknowledgments

Many thanks to everyone who contributed and participated in the National Science Foundation (NSF) Workshop on Detection, Removal, and Safe Destruction of PFAS from Semiconductor Manufacturing Waste Streams. This report was prepared by the workshop planning committee, the members of which incorporated input from 45 attendees to produce a document that represents the synthesis of the discussions held and the results found. Any opinions, conclusions, or recommendations expressed in this material are those of the authors and do not reflect the views of the United States Government.

Special thanks are extended to the invited speakers and to everyone who participated in the facilitated breakout sessions. A complete list is included in Appendix B: Workshop Participants.

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David Speed	GlobalFoundries
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Executive Summary

The National Science Foundation (NSF) Workshop on Detection, Removal, and Safe Destruction of PFAS from Semiconductor Manufacturing Waste Streams, held on August 13-14, 2024, at Intel's Jones Farm Campus in Hillsboro, Oregon, convened 45 experts from academia, government, and industry. This collaborative event addressed the critical challenges posed by per- and polyfluoroalkyl substances (PFAS) in semiconductor manufacturing, focusing on four thematic areas: detection, removal, destruction, and convergence research for remediation.

Workshop Highlights:

1. **PFAS Detection:** Current detection methods face challenges with matrix interferences and sensitivity, especially for short-chain PFAS and low concentrations. Innovations in high-resolution and real-time detection technologies are necessary to address these gaps.
2. **PFAS Removal:** Conventional removal methods are insufficient for short-chain and ultra-short chain PFAS, exacerbated by high salinity and complex wastewater matrices in semiconductor manufacturing. Emerging techniques (e.g. electrochemical separations, new membranes, etc.) offer promise but require further validation and scaleup studies in semiconductor environments. Further understanding of the interfacial chemistry of PFAS during separation steps are also needed, including potential micellization.
3. **PFAS Destruction:** Achieving complete mineralization of PFAS is complex due to their chemical stability. Current technologies often result in harmful byproducts, highlighting the need for integrated approaches that combine separation/concentration and destruction. Available and emerging technologies require further validation and scaleup for semiconductor environments.
4. **Convergence Research:** Interdisciplinary collaboration and standardized frameworks are vital for developing comprehensive PFAS management strategies. Enhanced data sharing, regulatory alignment, and the establishment of testbeds will drive progress.

Key Recommendations:

1. **Advance Detection Methods**: Invest in high-resolution and real-time technologies to improve detection across diverse matrices.
2. **Innovate Removal Techniques**: Develop targeted and scalable removal methods tailored to the variability of PFAS compounds.
3. **Optimize Destruction Technologies**: Focus on energy-efficient processes and robust monitoring protocols to ensure safe PFAS degradation, as well as a comprehensive evaluation of scaleup.
4. **Foster Convergence Research**: Establish cross-sector collaborations and promote standardized models to align industry, academic, government (developmental) and regulatory efforts.

Conclusion

The NSF workshop underscored the urgency of addressing PFAS contamination in semiconductor manufacturing. By fostering innovation and collaboration across sectors, the workshop established a forward-looking research agenda to develop sustainable, efficient, and impactful PFAS management solutions. These efforts align with NSF's broader mission to enhance environmental sustainability, economic competitiveness, and national security.

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Workshop Overview and Purpose

The NSF Workshop on Detection, Removal, and Safe Destruction of PFAS from Semiconductor Manufacturing Waste Streams (NSF Semiconductor Manufacturing PFAS Workshop) took place on August 13 – 14, 2024, and was hosted at the Intel Jones Farm Campus in Portland, Oregon. The in-person workshop brought together 45 individuals representing academia, government, and industry.

Workshop Objective

The NSF Semiconductor Manufacturing PFAS Workshop was organized to engage the semiconductor manufacturing community in discussions exploring the following topics:

- Analytical methods to characterize the PFAS-containing materials used in the industry and detect the releases of PFAS in the waste streams (gaseous emission, wastewater and solid waste).
- Cost-effective and low-energy technologies for PFAS removal, capture and safe destruction from the waste streams.
- Predictive models for physiochemical properties, environmental fate parameters and toxicity endpoints of PFAS.

The overarching goal of the workshop was to offer an integrated overview of the current state of PFAS remediation approaches and to delineate future convergent research agendas for the National Science Foundation (NSF) and other relevant federal agencies.

Workshop Structure

The NSF Semiconductor Manufacturing PFAS Workshop was topically divided into four major themes:

1. PFAS detection
2. PFAS removal
3. PFAS destruction
4. Convergence of science, technology, and policy across multiple stakeholder groups

The workshop began with a plenary discussion, featuring opening addresses from the University of Illinois, Intel, and the Semiconductor PFAS Consortium. Presentations were followed by a combined question and answer (Q&A) session between workshop attendees and presenters. During each topical discussion, invited speakers provided introductory remarks. Copies of the presentations for each speaker can be found on the workshop website.[1] Presentations were followed by facilitated discussions for each topic area. This proceedings report provides a complete description of the facilitated discussions held and conclusions derived from the workshop.

A full agenda for the workshop is included in Appendix A.

[1] https://sites.google.com/vt.edu/nsfworkshop/home

Plenary Session Review

Introduction

The plenary session opened with an introduction by Xiao Su from the University of Illinois Urbana Champaign, followed by opening remarks from David Thompson from Intel. A keynote was jointly presented by Melissa Gresham (Melissa Gresham Consulting), David Speed (GlobalFoundries), and Kevin Wolfe (Intel). Following the presentations, attendees were given the opportunity to ask questions to the presenters.

Summary of Presentations

During the workshop plenary session, invited speakers and workshop organizers provided remarks intended to establish the purpose of the workshop and to contextualize the effort within a broader set of activities being pursued by the research community. The following tables provide summaries from the presentations provided during the plenary session.

Presenter Name	Institution	Role
Xiao Su	University of Illinois	Associate Professor in Chemical and Biomolecular Engineering
Presentation Title: Workshop Welcome and Introduction		
Presentation Summary: Meeting environmental regulations while sustainably manufacturing semiconductors is a significant challenge. While the body of literature on PFAS is growing, the research to date has largely been focused on aqueous film-forming foam (AFFF, also known as firefighting foam). Research specific to PFAS abatement in semiconductor manufacturing is needed, including efficient wastewater treatment and PFAS removal technologies. The goals of the workshop are to explore how PFAS can be used responsibly within the compliance frameworks that apply to semiconductor manufacturing and to foster collaborative knowledge exchange across industry, academia, and government. The discussions held during this workshop will be documented in a workshop summary, and a peer-reviewed publication will be developed.		

Presenter Name	Institution	Role
David Thompson	Intel	Vice President of Technology, Research Process Engineering
Presentation Title: Sustaining Moore's Law Benefits Sustainability Opening Remarks		
Presentation Abstract: With increasing demand for compute power driving up energy consumption, especially in data centers, artificial intelligence (AI) workflows and semiconductor manufacturing advancements are critical to		

sustaining Moore's Law and meeting society's computing needs. This presentation provided an overview of the uses for PFAS in semiconductor manufacturing and described the tradeoffs for potential PFAS alternatives. It reiterated the importance of collaborative efforts with industry, government, and academia to foster solutions for sustainable manufacturing.

Presenter Name	Institution	Role
Melissa Gresham	Melissa Gresham Consulting	Sole Proprietor
Presentation Title: Semiconductor PFAS Consortium Overview		
Presentation Abstract: The Semiconductor PFAS Consortium was established in 2022 under the Semiconductor Industry Association to gather data on the use, impact, and remediation of PFAS in semiconductor manufacturing. It has released over 23 papers, with more papers planned, including a major paper on PFAS characterization in semiconductor wastewater. Computational models for PFAS release are being developed, addressing over 100 chemistries. Funded projects include analytical methods, wastewater treatment evaluations, and PFAS replacement studies, with upcoming reports on wastewater PFAS constituents. This presentation defined PFAS and outlined the Consortium's working groups, activities, and challenges.		

Presenter Name	Institution	Role
David Speed	GlobalFoundries	Distinguished member of the technical staff at GlobalFoundries
Kevin Wolf	Intel	Intel Global Environmental Group, Environmental Engineer
Presentation Title: PFAS Analysis, Detection, Abatement of Semiconductor Activities		
Presentation Abstract: Semiconductors are fabricated at the molecular level, requiring precision with leading-edge features as small as 5 nm. Processes involve multiple additive and subtractive steps like etching, coating, and lithography, with specialized chemicals such as etch and chamber clean gases (e.g., PFCs, CF_4, CHF_3). Other critical PFAS uses include photoacid generators, anti-reflective coatings, and surfactants. This presentation reviewed PFAS analysis, detection, and abatement in wastewater and air emissions, as well as analytical challenges and proposed research directions.		

Summary of the Q&A Session

Q: Besides 100 mg/L of fluoride, what else is present in the background matrix that complicates analytical methods?

A: The waste streams contain a lot of salts, acids, and wet cleans (ethers, TMAH). Co-contaminants make abatement difficult at low PFAS concentrations. Total organic fluorine (TOF) is present in much lower levels than inorganic fluorine, making it difficult to measure PFAS using TOF methods. Fluorine and organic fluorides may be interfering species. There are organic polymers, suspended solids, and quenchers, as well as high levels of sulfuric acid and hydrogen peroxide (though it degrades quickly)—many constituents that can interfere with analysis.

Q: Where does PFAS enter the stream, and at what point in the stream is PFAS treatment appropriate?

A: There are pros and cons to addressing contamination at the point of use versus at end-of-pipe points, where all the sources come together. There are a lot of variables that determine where best to place a treatment method; differences in manufacturing processes and spatial factors related to the piping within the facilities must be considered. While in principle it may sound desirable to treat PFAS at the point of use, it is often more practical to treat at the end of the pipe.

Growing public awareness and litigation are driving regulatory scrutiny, prompting semiconductor manufacturers to seek safer PFAS alternatives and more robust abatement strategies. NSF funds fundamental research to solve these problems and preparing the research enterprise (e.g., PhD students, faculty) to tackle these challenges. Abatement will be challenging and necessary for near-term containment, but does not eliminate PFAS, so NSF is looking for alternatives to PFAS to transform processes with a longer sustainability view. The European Union faces similar challenges; and national security issues need to also be considered.

Q: Is there a roadmap for transitioning from PFAS to alternative materials? When will material substitutions likely come into play?

A: The semiconductor's transition from long-chain to short-chain PFAS compounds took 10 years, and each new alternative must be rigorously evaluated to ensure it is truly benign. The cost of developing alternative materials and retrofitting existing facilities is enormous; a Semiconductor PFAS Consortium paper examined the cost of change for 100+ chemistries and concluded that abatement may be a more feasible short-term strategy.

Q: If an abatement technology was available tomorrow, how long would implementation take? What are the relative costs?

A: A relatively simple collection system has taken one year to design and one year to install. A multivariate system would require over 5 years to implement and significant capital investment. PFAS destruction technologies have been rapidly improving.

Q: How much will PFAS abatement impact the cost of microchips?

A: The design of an abatement system costs billions of dollars. The cost of the chip would likely increase significantly with the cost of abatement, with the exact estimates depending on the site and specific factors of the treatment technology. Because semiconductors vary so much, the streams containing PFAS will vary from factory to factory, it is hard to relate an accurate cost of PFAS abatement in a meaningful way across an average cost of a semiconductor.

Q: What metrics drive the cost of PFAS abatement? Can advances in desalination technology drive the cost of PFAS abatement down to that of water treatment?

A: The cost of PFAS abatement depends on the extent to which PFAS needs to be removed, i.e., regulations/concentration limits. The concentration limits determine the technology that can be used and the exact processes needed. Currently, PFAS is not regulated in wastewaters.

Q: Is there a low-hanging fruit for PFAS abatement, i.e., an abatement technology that is more promising than others?

A: Technologies for treatment semiconductor PFAS waste are mostly unproven, and thus there are no low-hanging fruit. It is also cheaper to design new fabs with PFAS treatment factored in than to retrofit or redesign an existing fab.

Q: How many technologies have been explored? Are the new fabs that are being built as a result of the CHIPS Act recovering the PFAS at the point of use or treating the wastewater?

A: For treatment, some factories have begun to implement best-practice for waste collection, including waste collection for aqueous TARCs (top anti-reflective coatings). Treatment technology is advancing rapidly but has not been implemented yet, primarily due to validation of capability within the semiconductor industry. For recovery of PFAS, there has been relatively little exploration due to unknown economics, with a possibility of recovering fluoropolymers.

Q: Is there a vision of where the fluorine will go?

A: Inorganic treatment processes can precipitate the fluoride to CaF_2.

Q: What are the PFAS treatment goals?

A: Goal determination is very dependent on toxicity information which is currently lacking in the literature. With more data we could identify these limits which we need to reach. At the present time, it is uncertain what concentration limits need to be met, both now and in the future: drinking water limits, detection limits, or some other limit. It is also uncertain who will determine these limits.

Q: Are there any frameworks or assessment models to evaluate if PFAS replacements are benign?

A: There is a number of frameworks, but none of them is a great fit for the semiconductor industry. An industry working group is developing a screening process and will soon report on its framework, which is complex. IBM and chemicals suppliers are working to develop frameworks.

Key Takeaways from the Plenary Session

- PFAS compounds are integral to semiconductor fabrication due to their chemical stability and effectiveness in processes like etching and photolithography.
- Despite their utility, PFAS chemicals pose environmental and health risks, driving the need for abatement and, where possible, replacement.
- Abatement technologies are currently a more viable short-term solution, compared to complete replacement of PFAS.

- Alternatives are being explored, but each new chemical requires extensive testing to ensure it will work effectively and is truly benign, which can take over a decade.
- Analytical challenges exist due to co-contaminants in waste streams (e.g., salts, organic compounds), which interfere with PFAS detection at low concentrations.
- Growing public awareness and litigation are driving increasing regulatory scrutiny, prompting semiconductor manufacturers to seek safer PFAS alternatives and more robust abatement strategies.
- Abatement systems, such as zero liquid discharge (ZLD), come with high capital costs and significant implementation timeframes, impacting the overall cost of semiconductor production.
- Retrofitting existing facilities is complex and costly; new fabs offer better opportunities for incorporating PFAS-free and abatement technologies from the ground up.
- Multiple frameworks have been developed to assess the environmental, health, and safety (EHS) profiles of PFAS alternatives, but none is a great fit for the semiconductor industry.
- Transitioning to PFAS-free alternatives or safer substitutes requires a long-term roadmap, often taking 10+ years for full implementation and regulatory approval.

I. PFAS Detection

The first topical discussion within the workshop focused on strategies for detecting PFAS chemicals being used in various stages of semiconductor manufacturing. Expert presenters were invited to provide introductory remarks and to introduce innovations being explored. Subsequent discussions with participants explored related opportunities and challenges. The following summary captures the remarks from invited speakers and summarizes the key discussion points that emerged.

Summary of Presentations

The following table provides a summary of the introductory presentation given on PFAS detection.

Presenter Name	Institution	Role
Jennifer Field	Oregon State University	Professor of Environmental and Molecular Toxicology
Presentation Title: Facilitated Breakout Session for PFAS Detection		

Presentation Abstract:

The detection and analysis of PFAS present significant challenges due to their chemical diversity and varying properties. PFAS range from volatile and semi-volatile substances to high molecular weight fluoropolymers, each with distinct solubility, vapor pressure, and acid-base characteristics (i.e., pKa). These variations necessitate diverse analytical approaches to detect diverse array of PFAS potentially present in semiconductor waste streams, including gases like perfluorocarbons (PFCs), long-chain compounds, and fluoropolymers.

Detection methods currently focus on target PFAS in wastewater including EPA-approved protocols, such as Methods 1633, 3512/8327, and ASTM D7979-20. These methods often incorporate solid-phase extraction combined with liquid chromatography and tandem mass spectrometry (LC-MS/MS). For estimating total fluorine, non-specific techniques like combustion ion chromatography (IC) are employed.

Analytical approaches vary depending on the type of PFAS. Targeted detection uses specific standards and established methods, predominantly for ionogenic PFAS. For suspect and non-targeted PFAS, LC-high resolution mass spectrometry (HRMS) facilitates the identification of novel and emerging compounds, including ultra-short chain PFAS. Fingerprinting techniques, supported by machine learning and multivariate statistical tools, enable the prioritization and potential grouping of PFAS by identifying unique patterns (e.g. fingerprinting).

Specialized analytical techniques are emerging to address specific PFAS challenges. Volatile PFAS are analyzed using gas chromatography-mass spectrometry (GC-MS) and air sampling methods that utilize polyurethane foam, filter, and canisters, or thermal desorption tubes. However, isolating and quantifying ultra-short chain PFAS remains challenging due to their high water solubility and, in some cases, high instrument background. Nuclear magnetic resonance spectroscopy (NMR) is being investigated for total organic fluorine and fluoride analysis and high molecular weight PFAS quantification while GC-HRMS is being explored for neutral PFAS analysis.

Significant challenges persist in achieving a comprehensive analysis of PFAS. The presence of co-contaminants and complex wastewater matrices complicates mass balance calculations for fluorine. Analytical gaps can be addressed through the development of improved and expanded methods and more comprehensive datasets that accommodate organic polymers, salts, and organic solvents.

Additionally, the emergence of replacement PFAS compounds introduces new analytical hurdles due to insufficient analytical standards and toxicological and environmental data, underscoring the need for continued innovation in detection techniques.

Summary of the Facilitated Discussion

The facilitated discussion was organized around a set of key focus questions. Both the questions, and a summary of the responses, as discussed by workshop participants, are included below.

Question 1: What considerations drive your analytical targets for detection, and what methods are you using to meet those targets?

- **Regulatory and Targeting Standards**:
    - EPA regulations (e.g., Method 1633) for main PFAS compounds (e.g., 4-10 ng/L for drinking water) are a baseline, but a more comprehensive set of standards is needed for industrial applications with varying PFAS composition like in semiconductor manufacturing.
    - Consideration for international and regional regulations, such as Registration, Authorization and Restriction of Chemicals (REACH) and Persistent Organic Pollutants (POPs), could support broader compliance.
    - The goal is often total organic fluorine quantification, especially with lower detection limits (ppt/ppb levels).
- **Analytical Techniques and Instrumentation**:
    - Common methods include LC-MS and GC-MS for target PFAS and IC for total organic fluorine.
    - Selection of method depends on the chemical properties (neutral or ionic) and sample matrix.
    - Advanced high-resolution methods (e.g., LC- or GC-HRMS) aid in identifying unknown or trace-level PFAS.
- **Challenges with Background Interference**:
    - Background contributions from reagents (e.g., ammonium acetate), equipment materials (e.g., HDPE or glass), and analytical setup can cause false positives or negatives.
    - Mass balance is essential, but complex wastewater matrices introduce challenges for closing the balance on fluorine.
- **Method Selection Based on Sample Characteristics**:
    - High-flow, low-concentration wastewater samples necessitate sensitive and robust methods.
    - Different waste streams (e.g., air emissions vs. water discharge) require distinctly different analytical approaches.
- **Considerations for Industrial Relevance**:
    - Key concerns include cost and time needed for detection, as well as equipment longevity and reliability in a high-throughput semiconductor fab environment.
    - Reverse engineering can be done to detect and identify PFAS in complex mixtures, though this may impact intellectual property due to disclosure of proprietary formulations.
- **Emerging Techniques and Future Directions**:
    - New technologies are being explored to handle complex mixtures and byproducts, with a focus on process control and real-time analysis.

- Fluorine NMR shows the potential for quantification of total organic fluorine that is distinguished from fluoride ions, along with structural information.

Question 2: What methods are best for detecting PFAS at very low concentrations in different matrices (e.g. water, gases, solvents, etc.)?

- **General Detection Methods**:
  - **FT-IR**: Effective for fluorinated gases, quantitative and mobile for end-of-pipe applications.
  - **LC-MS/MS**: Considered the "gold standard" for detecting ionic PFAS in water, highly sensitive and suitable for low-concentrations when combined with solid-phase extraction. Advances are needed for the detection of the ultra-short chain PFAS.
  - **GC-MS**: Utilized for detecting volatile PFAS compounds in various matrices.
- **Sample Preparation and Extraction**:
  - **Solid-Phase Extraction (SPE)**: Key for concentrating PFAS in water, especially for short-chain PFAS, though recovery may be an issue depending on the complexity of the matrix.
  - **Adsorbents and Isotopic Standards**: EPA Method OTM-45 for non-volatile PFAS relies on XAD resins and filters, while OTM-50 for volatile PFAS relies on canisters for sampling. Thermal desorption tubes are an alternative for small-scale air sampling and quantifying semi-volatile PFAS in air samples.
- **Challenges with Low Detection Limits**:
  - Silicon and other background substances in wastewater can increase detection limits.
  - Real samples may contain interferences from treatment processes (e.g., solids in water) that complicate low-level PFAS quantification.
- **Industry Considerations**:
  - In situ sensors and multi-PFAS detection methods are limited and often costly.
  - Monitoring and controlling the effluent is crucial for environmental and public health impacts.
  - Cost-effective and high-frequency sampling methods are under exploration, though proportional sampling can be logistically difficult to perform.
- **Additional Analytical Techniques**:
  - **Total Organic Fluorine (TOF)**: Useful for quantifying the total organic fluorine content as an indirect measure of total PFAS.
  - **Innovative Sensor Technologies**: EPA and industry are exploring new in-situ sensors, though widespread applicability remains limited.

Question 3: What are the most pressing challenges related to PFAS detection in semiconductor manufacturing?

- **Facing the Unknown**
  - Analytical methods, including sampling, sample preparation, and detection approaches are selected and tailored to the structure of target molecules. Without such knowledge of the PFAS structures used by the semiconductor industry, in combination with complex waste streams, analytical methods will likely underestimate the total PFAS in semiconductor waste streams.
- **Sampling and Matrix Variability**:
  - Each fab's processes and waste streams differ, making it hard to standardize sampling and detection methods.

  - Real samples often have high compositional and potentially temporal variability, requiring specialized equipment to detect low concentrations amidst complex matrices.
- **Analytical Limitations and Standards**:
  - Many PFAS lack established analytical standards, especially for ultra-short chains and novel replacements.
  - Matrix complexities, such as co-contaminants (e.g., silicon in wastewater), interfere with detection and limit sensitivity.
  - Reliable real-time detection is needed but currently limited by technology and cost.
- **Abatement System Placement and Design**:
  - Determining where to place abatement systems is critical; decisions affect pollution control effectiveness and cost.
  - Integration with existing infrastructure is challenging due to footprint constraints and compatibility issues.
- **Cost and Resource Constraints**:
  - Analytical equipment and testing are expensive; comprehensive analysis events can cost up to $1M.
  - Turnaround time for testing can be long (6-7 weeks), with costs around $7K for non-targeted analysis.
  - Industry seeks cost-effective methods and scalable solutions for detecting and abating PFAS.
- **Intellectual Property (IP) and Confidentiality Concerns**:
  - Some PFAS analyses (e.g. HRMS to identify PFAS) are restricted due to IP concerns and confidential business information, limiting the ability to share data and best practices.
  - Regulatory challenges arise as companies hesitate to disclose proprietary information regarding PFAS compositions.
- **Regulatory and Compliance Pressures**:
  - The lack of clear regulatory guidelines and standards specific to industrial PFAS emissions complicates compliance.
  - U.S. competitiveness and national security concerns around PFAS management are rising, especially with the CHIPS Act and international regulations (e.g., EU standards).
- **Environmental and Health Data Gaps**:
  - Limited toxicological data for many PFAS compounds hinders risk assessment and regulatory action.
  - Many PFAS alternatives and degradation byproducts lack comprehensive studies on environmental impact and health risks.
- **Future Research and Collaboration Needs**:
  - Encouraging collaboration between industry and academia could accelerate the development of PFAS detection and abatement methods.
  - Industry-driven research on real water samples and practical PFAS limits is necessary to guide future regulations and standards.

Question 4: What pathways exist for addressing the challenges identified?

- **Reference Materials and Testbeds**:
  - Establish a list of actual PFAS used in semiconductor processes, anonymized to protect IP and confidentiality.
  - Establish a standardized reference wastewater matrix for PFAS detection and abatement research.

- Create a dedicated testbed or center, possibly led by CHIPS or NSF, to allow industry-academia collaboration under controlled conditions without IP restrictions.
- **Research and Development Investment**:
  - Increased R&D funding is needed to support innovation in PFAS detection and abatement technologies.
  - Collaboration with academia and institutions like the National Semiconductor Technology Center (NSTC) could drive progress in understanding PFAS impacts and creating effective solutions.
- **Improving Detection and Monitoring**:
  - Develop rapid, in situ detection methods for PFAS to minimize delays from sending samples to external labs.
  - Utilize sensors closer to points of use within fabs, and within abatement systems, to enhance real-time monitoring.
  - Implement data transparency throughout the supply chain to ensure traceability and better management of PFAS sources.
- **Prioritization and Toxicity Assessment**:
  - Toxicity data for various PFAS, especially mixtures, is essential to determine which compounds to prioritize for mitigation.
  - Current metrics like volume and mass may not effectively prioritize PFAS, given the varied toxicity profiles across different PFAS compounds.
- **Analytical and Process Optimization**:
  - Modify sample processing methods to address complex matrices (e.g., semiconductor wastewater).
  - Focus on broad characterization over reverse engineering to identify individual PFAS to assess the effectiveness of abatement processes.
  - Avoid reliance on reverse engineering to identify individual PFAS due to potential IP conflicts and NDAs; instead, focus on characterizing PFAS content in waste streams.
- **Accelerating Industry-Academia Collaboration**:
  - A centralized strategy for PFAS research would streamline efforts and ensure alignment with industry needs.
  - CHIPS and NSF can play roles in facilitating partnerships and advancing technology readiness for industrial applications.

Question 5: What advancements are needed to enable real-time PFAS detection during abatement?

- **Sensor Requirements**:
  - Sensors need to be non-invasive to avoid factory shutdowns during installation.
  - Must be compatible with PFAS-containing streams, considering material durability and calibration needs.
  - Sensors should minimize flow bias to ensure accurate readings in dynamic conditions.
- **Detection Reliability**:
  - Eliminate false positives by enhancing sensor specificity and stability over time.
  - Develop indicators for indirect PFAS measurement, as PFAS is a diverse class and direct detection may be challenging.
- **Separation of Inorganic Fluoride**:
  - Effective separation of inorganic fluoride from PFAS is essential, as total organic fluorine (TOF) may give misleading results if fluoride ions are included in total or6ganic fluorine measurements.

- **Innovation Needs**:
    - New technologies are needed to address the unique challenges of detecting PFAS in real-time, especially in varying matrices beyond water.

Key Takeaways from the Topic #1 Session

The topical discussions on PFAS detection uncovered several insights, which are summarized below.

- **Regulatory and Analytical Standards**:
    - EPA regulations provide baseline standards for PFAS detection, but industrial applications, such as semiconductors, need more comprehensive guidance.
    - Compliance with international standards (REACH, etc.) and total organic fluorine quantification are also priorities.
- **Analytical Techniques and Challenges**:
    - Common methods like LC-MS, GC-MS, and IC are selected based on sample matrix and chemical properties.
    - Advanced techniques, such as LC-HRMS, help detect suspect and nontarget PFAS, but background interferences (e.g., reagents, equipment materials) complicate target, suspect and nontarget measurements.
    - Mass balance and closing fluorine loops in wastewater are significant challenges.
- **Detection Methods for Low Concentrations**:
    - FT-IR is suitable for fluorinated gases; LC-MS/MS is the standard for ionic PFAS in water; GC-MS is used for volatile and semi-volatile PFAS.
    - Solid-phase extraction aids in PFAS concentration but faces recovery and matrix issues, especially for short-chain PFAS.
    - Interferences from silicon and other background substances in wastewater increase detection complexity.
- **Challenges in Semiconductor Manufacturing**:
    - Placing abatement systems and integrating them with existing infrastructure is challenging and costly.
    - Analytical limitations include a lack of established standards for many PFAS, matrix interferences, and high costs for testing.
    - Confidentiality around proprietary formulations limits data sharing, complicating regulatory compliance and industry collaboration.
- **Pathways for Addressing Challenges**:
    - Establish standardized reference materials and testbeds for PFAS research to support industry-academia collaboration.
    - Increase R&D investment from different agencies, focusing on in situ and rapid detection technologies.
    - Enhance data transparency in the supply chain and develop methods that prioritize PFAS based on toxicity rather than just volume.
- **Real-Time Detection Needs**:
    - Non-invasive, accurate, and reliable sensors compatible with PFAS streams are essential.
    - Eliminating false positives and developing indirect PFAS indicators are key for real-time monitoring.
    - Separation of inorganic fluoride is crucial to avoid misleading TOF results in abatement processes.

II. PFAS Removal

The second breakout session of the NSF Workshop focused on exploring techniques for removing PFAS chemicals from semiconductor manufacturing waste streams. This session convened experts from various fields, delving into the complexities, challenges, and emerging strategies for accurate PFAS detection. The following summary captures the guest speaker presentations, primary discussions, key challenges identified, and innovative solutions proposed.

Summary of Presentations

The following table provides a summary of the introductory presentation given on PFAS removal.

Presenter Name	Institution	Role
Xiao Su	University of Illinois	Associate Professor in Chemical and Biomolecular Engineering
Presentation Title: PFAS Removal Introductory Presentation		
Presentation Abstract: The removal of PFAS (per- and polyfluoroalkyl substances) poses significant challenges due to their surfactant nature, variable hydrophobicity depending on PFAS structure, and the strength of their carbon-fluorine (C-F) bonds. Conventional systems like ion exchange (IEX) and granular activated carbon (GAC), which can often address longer-chain PFAS, are less effective for shorter PFAS removal. The high energy required to break C-F bonds means that methods to concentrate PFAS can significantly benefit downstream destruction technologies. Additionally, the interfacial properties of PFAS, especially during separation processes, can affect removal efficiency, necessitating tailored approaches. For example, potential micellization at interfaces may impact separation performance. Separation processes focuses on the removal and concentration of PFAS. Technologies for separation include adsorption-based methods (e.g. activated carbon, ion-exchange), membrane-based techniques (e.g. reverse osmosis, nanofiltration, ultra-filtration) and foam fractionation. Emerging separation methods, including electrochemical separations that leverage field-assisted adsorption (e.g. electrosorption), have shown promise for enhancing PFAS separation and concentration. Evaluating PFAS removal methods requires considering several key metrics, including removal efficiency, cost, energy consumption, scalability, and dependence on PFAS concentration. Additionally, the reusability and regeneration of materials, as well as their potential for up-concentration / volume reduction, are critical factors in determining the suitability of a given method. Research into materials and processes focuses on both commercial solutions and the development of novel chemistries designed specifically for PFAS separation. Efforts aim to improve adsorption and membrane-based separations require a closer molecular understanding of the interfacial properties of PFAS, particularly concerning the dependence on PFAS concentration and ionic strength. Looking ahead, a principal focus for PFAS abatement would be on the scaleup and validation PFAS separation technologies to achieve high throughput and cost reduction for semiconductor wastewater streams. Multi-scale approaches are being explored to tailor methods for diverse industrial applications, ensuring efficient integration within varied operational timelines and scales. These efforts aim to advance the effectiveness, sustainability, and accessibility of PFAS removal technologies for relevant semiconductor applications.		

Summary of the Q&A Session

Q: Why is it challenging to find alternatives to fluorine-based chemistries in PFAS separation and abatement?

A: Finding alternatives to fluorine-based chemistries for separation are essential for PFAS separation and abatement. There is interest in finding alternatives that mimic fluorine's unique properties, but achieving comparable effectiveness without using fluorine itself remains difficult.

Q: How could machine learning contribute to the development of alternatives to fluorine-based chemistries?

A: Machine learning was proposed as a tool to help identify species with "fluorine-like" effects that do not actually contain fluorine, potentially offering a pathway to alternative chemistries.

Q: What role do regulatory pressures play in the use of fluorine-based chemistries?

A: Although fluorophilic interactions are promising for the removal of PFAS, and can improve PFAS selectivity, regulatory pressures may limit the use of materials that contain fluorine (e.g. membranes and adsorbents). The balance between regulatory compliance and technical efficacy is a core challenge.

Q: Why is the development of fluorine-free substitutes strategically important?

A: Developing fluorine-free substitutes that retain essential properties could unlock new technologies and reduce dependence on PFAS-related chemistries, which have environmental and health concerns.

Summary of the Facilitated Discussion

Question 1: What chemical properties differentiate PFAS separations from separation for other chemical classes?

- **Broad Chemical Diversity**:
  - PFAS exhibit a wide range of chemical structures and properties, similar to inorganic anions but with significant greater complexity.
  - They have a resistance to degradation due to stable C-F bonds, which makes concentration even more important.
- **Surface Activity and Interfacial Properties**:
  - Many PFAS are surface-active, creating challenges due to their hydrophobic and surfactant-like nature, complicating separation techniques.
  - Low polarizability and weak Van der Waals interactions affect separation efficacy of various adsorbent-type materials.
- **Membrane Selectivity Challenges**:
  - High pressure membranes tend to show lower selectivity to PFAS compared to other classes of compounds.
  - PFAS with different chain lengths and charges behave differently, requiring tailored separation methods.
- **Complex Charge and Functional Group Variability**:
  - PFAS can be neutral or ionic, affecting how they interact with separation materials.

    - Functional groups vary widely, with carboxylic vs. sulfonic acids, fluoropolymers, and fluorophilic interactions, all affecting separation approaches.
- **Challenges in Standardization and Identification**:
    - No standardized mass spectrometry methods exist for cationic PFAS.
    - Existing analytical standards do not fully cover the wide spectrum of PFAS, leading to difficulties in consistent identification and separation.

Question 2: What are the most pressing challenges related to PFAS removal in semiconductor manufacturing?

- **Complex Matrix and Low Concentration**:
    - Semiconductor wastewater has a complex matrix with high salinity, organic content, and low PFAS concentrations, which interfere with treatment effectiveness and increase analytical difficulty.
    - Background elements, such as salts and organic compounds, act as quenchers, complicating PFAS detection and removal.
- **Variation in PFAS Characteristics**:
    - PFAS vary in chain length, charge, and functional groups, making it challenging to identify effective removal methods. Short-chain PFAS, in particular, are hard to remove with conventional adsorbents like activated carbon.
- **Regulatory and Cost Challenges**:
    - Constantly changing regulations on PFAS concentration limits create difficulties in maintaining compliance. The cost of PFAS detection and abatement is high, especially at low concentrations, necessitating expensive analytical tools and specialized materials.
- **Technical Barriers in Treatment**:
    - Current treatment technologies, such as reverse osmosis (RO) and adsorption, struggle with the diverse nature of PFAS. Specific removal methods may work for certain PFAS types but not universally.
    - Regeneration of filter materials and management of residuals is a major issue, especially given concerns about leachate from landfills.
- **Need for Targeted Solutions and Prioritization**:
    - There is a need for industry-specific targets to prioritize PFAS compounds, allowing for tailored treatment strategies. The degree of variability across PFAS compounds makes universal treatment challenging.
- **Operational Disruptions**:
    - Implementing new treatment technologies can disrupt manufacturing processes, so flexibility and adaptability in treatment methods are necessary.

Question 3: What pathways exist for addressing the challenges identified?

- **Selective Separation Approaches**:
    - Development of selective membranes or adsorbents for PFAS can help differentiate between PFAS and other contaminants, reducing the interference of background compounds.
    - Combining adsorption and destruction in a single process (e.g., "trap and zap") could streamline abatement.
- **Focus on Concentrated Streams**:

    - Targeting high-concentration PFAS streams may optimize mass transfer and treatment efficiency. Preconcentration can simplify subsequent treatment stages.
- **Electrochemical Technologies for Separations**:
    - Electrochemical separation methods may offer solutions for a more sustainable PFAS adsorption and regeneration, as they can eliminate need for chemical regeneration. There is a need for scaleup optimization and industrial-level validation of these emerging technologies.
    - Understanding the interfacial PFAS behavior, especially at active materials such as adsorbents and membranes, could improve separation processes. Their structural variability may present complex challenges, e.g. short-chain PFAS may pose different challenges than long-chain due to weaker surfactant properties.
- **Integration of R&D and Validation**:
    - Need for collaboration between academia, industry, and regulatory bodies (e.g., Semiconductor Research Corporation (SRC)) to test and validate emerging technologies in semiconductor-specific wastewater.
    - Establishing a standard wastewater challenge matrix would support R&D consistency and applicability.
- **Layered Treatment and Modular Approaches**:
    - Employing bottom-up methods (process-specific treatment) alongside top-down strategies (mass balance and characterization) may provide comprehensive PFAS management.
    - Modular, scalable solutions are essential to meet varying PFAS concentrations and matrix complexities in different semiconductor fabs.

Question 4: What absorbents and removal techniques are best for short and ultra-short PFAS?

- **Reverse Osmosis (RO)**: Effective for ionic species; may work for ultra-short PFAS if they are neutral. Concentration and cost are key considerations for RO usage.
- **Ion Exchange Resins**: Works for some PFAS but less effective for ultra-short chains, requiring further R&D.
- **Specialized Sorbents**: Includes tailored composite materials, and designer sorbents (e.g., cyclodextrins, selective polymers), focusing on selectivity and uptake for short-chain PFAS. Fluorinated adsorbents have also proven better adsorption for shorter PFAS. However, fluorinated adsorbents are now of concern due to regulatory concerns, with a need for future development of non-fluorinated sorbents.
- **Gas Phase**: Wet scrubbers and plasma may be useful for destroying PFCs and HFCs but face challenges with ultra-short chains. Thermal degradation is the benchmark for CF4 and PFCs.
- **Communication and R&D Needs**: Life cycle analysis is needed to support the use of sorbents, and continued R&D to develop effective sustainable (non-fluorinated) adsorbents, addressing public perception and regulatory acceptance.

Question 5: How can cost-effective, large-volume, low-concentration removal be achieved?

- **Combination of Concentration and Destruction**: Employing both concentration and destruction processes can improve cost-effectiveness and efficiency of PFAS removal.
- **Pre-Concentration and Location Optimization**: Identifying the optimal pH, background conditions, and treatment points in the system helps improve removal efficiency. Multi-state

operations, such as using different adsorbents or membranes at varied pH levels, could enhance effectiveness.

- **Localized Treatment and System Integration**: Treating closer to the point of PFAS generation and redesigning systems for compact, space-efficient treatment can make integration into semiconductor facilities more feasible.
- **Segregation of Waste Streams**: Segregating waste streams in fabs and considering new layouts for future fabs can enable more targeted and efficient PFAS management.
- **Industry-Academia Collaboration**: Engaging equipment designers, tool vendors, and academic institutions to consider PFAS lifecycle and engineering requirements can lead to better treatment technology tailored to fab constraints.
- **Lifecycle Prioritization**: Placing PFAS lifecycle considerations in the design and decision-making for fab equipment can streamline process improvements, potentially reducing the environmental and financial impacts of PFAS treatment.

Key Takeaways from the Topic #2 Session

The breakout session on PFAS removal provided several critical insights, with the following key takeaways highlighting the session's central themes and implications.

- **Chemical Complexity and Resistance**: PFAS compounds are chemically diverse with stable C-F bonds, making them highly resistant to degradation and challenging to remove effectively from wastewater.
- **Surface Activity and Low Polarizability**: PFAS exhibit surfactant-like properties, are hydrophobic, and have low polarizability, complicating separation processes and reducing membrane selectivity, especially for short-chain compounds.
- **Challenges with Detection and Removal**: The semiconductor industry faces issues with low PFAS concentrations in complex matrices containing high salinity and organic content. Background elements (e.g., salts, organics) interfere with PFAS detection and removal, increasing the cost and complexity of treatment.
- **Evolving Regulations and High Costs**: Constantly changing PFAS regulations drive the need for adaptable and compliant solutions, but these solutions are expensive, requiring advanced analytical tools and specialized materials, especially at low concentrations.
- **Targeted and Selective Treatment**: Developing selective membranes and tailored adsorbents could help isolate PFAS from other contaminants. Combining adsorption and destruction (e.g., "trap and zap") offers a promising approach to streamline abatement.
- **R&D and Industry Collaboration**: Cross-sector collaboration among academia, industry, and regulatory bodies is essential for validating new PFAS treatment methods and establishing standardized testing protocols, including a standard semiconductor-specific wastewater matrix.
- **Pre-Concentration and Modular Solutions**: Pre-concentration and treatment closer to PFAS generation points can enhance efficiency. Modular, space-efficient systems could be integrated more easily into semiconductor fabs.
- **Lifecycle and Environmental Considerations**: Emphasizing PFAS lifecycle impacts in fab equipment design and waste stream segregation allows for sustainable management, and address regulatory and public perception concerns.
- **Emerging Techniques**: New separation methods (e.g. electrochemical separations, new membranes, designer adsorbents) show potential for selective PFAS removal and regeneration (e.g. eliminating need for chemical regenerant), though industrial scalability and optimization are needed, particularly for shorter-chain PFAS.

III. PFAS Destruction

The third topical discussion within the workshop explored techniques for PFAS destruction. Expert presenters were invited to provide introductory remarks and to introduce innovations being explored. Subsequent discussions with participants explored related opportunities and challenges. The following summary captures the remarks from invited speakers and summarizes the key discussion points that emerged.

Summary of Presentations

The following table provides a summary of the introductory presentation provided during the topical discussion on PFAS destruction.

Presenter Name	Institution	Role
Paul Westerhoff	Arizona State University	Regents Professor, Fulton Chair of Environmental Engineering
Presentation Title: PFAS Destruction Introductory Presentation		
Presentation Abstract: The degradation of PFAS (per- and polyfluoroalkyl substances) involves challenges in achieving complete mineralization into benign products like CO_2 and fluoride. While partial degradation can reduce toxicity, the ultimate goal is to fully mineralize PFAS, eliminating both harmful compounds and associated uncertainties. Destruction pathways often involve shortening the PFAS chains, followed by further degradation to address toxicity. Reactions for PFAS degradation can be categorized into heterogeneous and homogeneous methods. Heterogeneous reactions, such as those utilizing boron-doped diamond electrodes, generally achieve faster destruction rates. Homogeneous approaches, like hydrothermal alkaline treatment using sodium hydroxide, facilitate phase separation and subsequent breakdown of PFAS compounds. The use of additives and catalysts can enhance degradation processes. For example, thermal combustion with calcium hydroxide accelerates mineralization and reduces reaction times. Photocatalysis and hydrogenation using palladium and metal catalysts also show promise, though their effectiveness diminishes with complex PFAS mixtures due to limitations in handling diverse compounds. Real-world PFAS mixtures present additional challenges, as the varied compounds within them can interact and generate new byproducts during degradation. These mixtures complicate analytical detection, as background compounds often interfere with the identification of degradation products, necessitating advanced analytical techniques. Innovative treatment strategies are being developed to address these challenges. The "trap and zap" approach combines adsorption with targeted destruction to improve abatement efficiency. Electrochemical and catalytic methods are being explored for selective treatment, though they require industrial-scale validation before widespread application.		

Further research and optimization are needed to enhance PFAS degradation methods. A better understanding of mechanisms, such as interactions with hydroxyl (OH) radicals, is crucial, but consensus on their roles remains elusive. Scaling up methods like supercritical water oxidation and foam fractionation is essential, particularly for applications in complex environments such as semiconductor wastewater matrices. These efforts aim to advance the effectiveness and scalability of PFAS treatment technologies.

Summary of the Facilitated Discussion

Question 1: What analytical target represents the end-goal for PFAS elimination (e.g. complete elimination vs. permit requirements)?

- **Complete Elimination Goal vs. Practicality**:
    - Complete PFAS elimination is ideal but may not be feasible due to high energy, cost, and technology constraints. Practical goals may target below 10 ppt through preconcentration and partial treatment.
- **Regulatory and Cost Considerations**:
    - Regulations set concentration-based targets, but achieving these can be cost-intensive, especially if complete mineralization to CO_2 and fluoride is pursued. Federal policies and cost-benefit analyses will heavily influence final targets.
- **Lifecycle and Environmental Impact**:
    - Life cycle assessment (LCA) might be required to balance treatment rigor with resource demands. Circular solutions for fluoropolymers and trifluoroacetic acid (TFA) reuse were discussed as sustainable approaches.
- **Treatment Efficiency and Energy Use**:
    - Preconcentration prior to destruction minimizes energy requirements, as destruction processes are energy-intensive. Separation processes are less energy-demanding compared to destruction.
- **Role of Byproducts and Reuse**:
    - Byproducts from PFAS destruction and separation might offer reuse opportunities, e.g., CaF_2 in cement, but require careful evaluation to prevent unintended environmental impacts and release of residual PFAS.

Question 2: What metrics are most useful for comparing the effectiveness of PFAS destruction methods?

- **Energy Efficiency and Cost**: Metrics like Electrical Energy per Order (EEO), which measures the energy cost for removing a unit amount of PFAS, are critical. Both capital and operational costs are significant factors, with energy requirements for complete mineralization being notably high.
- **Life Cycle Analysis (LCA)**: Essential to fully evaluate cost-effectiveness and environmental impact, including greenhouse gas emissions, clean water savings, and waste management.
- **Destruction Effectiveness**: Metrics should focus on mass-based destruction rather than concentration reduction (e.g., percent removal). Total mineralization to CO_2 and HF (for fluorine) is ideal but challenging.
- **Operational and Physical Constraints**: Considerations like residence time, physical footprint, treatment time, and maintenance frequency affect the practicality of various destruction methods.

- **Scalability and Complexity**: Techniques need to be manageable at an industrial scale with minimal operational complexity to facilitate adoption.
- **Regulatory Considerations**: Different sectors (e.g., pharmaceuticals, semiconductors) face varied regulatory demands, affecting which PFAS destruction approaches are permissible.
- **Byproduct Generation and Safety**: Understanding and managing potential toxic byproducts is essential to ensure that destruction methods are both effective and safe.
- **Comparative Metrics for Robustness**: Normalized metrics across various PFAS destruction methods help in selecting robust technologies that can handle diverse wastewater compositions.

Question 3: What advancements are needed to achieve full mineralization of long, short, and ultra-short PFAS chains?

- **Cost and Efficiency**: Full mineralization is possible but requires significant energy and cost. There's a need for less energy-intensive processes, possibly using electrochemical methods to make mineralization feasible.
- **Understanding Mechanisms**: Research is needed to understand destruction mechanisms, especially regarding different PFAS functional groups. This includes studying oxidation-reduction reactions and how PFAS react in various environments.
- **Challenges with Chain Length**: CF_3 groups in PFAS are harder to mineralize than CF_2, particularly in shorter chains. This difference requires specific approaches for different PFAS structures.
- **Modular and Scalable Solutions**: Technologies should be modular and adaptable to different PFAS chain lengths. There is also a need for solutions that handle fluctuations in flow rates and concentrations in real-time.
- **Combination of Technologies**: A single method may not suffice. Combining destructive technologies, such as electrochemical processes, catalytic and advanced oxidation, may be necessary for comprehensive PFAS treatment.
- **Analytical Methods**: Developing methods to analyze and verify PFAS removal is crucial. Understanding what remains in wastewater and confirming removal is necessary for effective treatment.
- **Focus on Bio-based Research**: Exploring bioremediation, including enzyme-based degradation of PFAS, could provide alternative and potentially sustainable degradation pathways.
- **Destruction Byproducts**: Characterizing byproducts from destruction processes is essential to prevent unintended environmental and health impacts from incomplete degradation.

Question 4: What are the most pressing challenges related to PFAS destruction in semiconductor manufacturing?

- **Non-Selective Destruction Methods**: High salinity in wastewater matrices consumes significant energy to destroy PFAS, and current destruction technologies lack selectivity, causing energy to be used on multiple compounds beyond PFAS.
- **Continuous Flow Requirements**: Continuous flow is generally preferred over batch processes to avoid downtime and maintenance, but low PFAS concentration poses difficulties in maintaining efficient continuous flow.
- **Analytical Challenges**: Insufficient analytical techniques hinder the identification of byproducts and the accurate measurement of destruction efficiency, making it challenging to monitor the effectiveness of PFAS destruction.

- **Cost and Resource Constraints**: The cost of PFAS destruction often exceeds the cost of the original material. Additionally, there is no benchmark technology for complete mineralization of all PFAS, with incineration being a costly option.
- **Intellectual Property Concerns**: Ambiguities around intellectual property rights create barriers to adopting new destruction technologies, particularly for smaller companies facing financial constraints.
- **Matrix and Background Effects**: The complex background of semiconductor wastewater (e.g., high salinity and specific chemical compositions) complicates PFAS destruction and may require highly tailored solutions.

Question 5: What pathways exist for addressing the challenges identified?

- **Material and Technology Development**: New materials, such as Pd-based catalysts, and innovative treatment devices are being explored to improve energy efficiency and reduce costs in PFAS destruction.
- **Alternative Approaches to PFAS**: Identifying and using alternative compounds that do not have PFAS-like persistence could mitigate reliance on PFAS, but these alternatives must meet similar performance standards.
- **Use of AI and Machine Learning**: AI and machine learning can assist in in identifying efficient materials for PFAS abatement, and predicting PFAS behavior in complex matrices, aiding in decision-making and prioritization.
- **Enhanced Collaboration and Standards**: Governmental mediation in regulatory, financial, and IP issues can facilitate collaboration between academia and industry, accelerating innovation while protecting proprietary interests.
- **Research Coordination**: Establishing centers of excellence or designated funding from agencies like NSF could enhance research coordination, promote standardization, and focus on practical, scalable solutions.
- **Prioritization Based on Toxicological Data**: Focusing research on the most toxic and abundant PFAS compounds could improve abatement efforts and inform future regulations.
- **AI-Driven Toxicology**: AI can aid in generating toxicological data for PFAS and assist in identifying which compounds to prioritize for destruction.
- **Addressing Long-Term Challenges**: Interdisciplinary approaches are crucial to overcoming scientific and regulatory challenges.

Question 6: What methods are best for achieving total (vs partial) de-fluorination?

- **Advanced Oxidation and Reduction Processes**: These processes use high-energy chemical reactions to break down the stable C-F bonds in PFAS, aiming for full mineralization rather than partial breakdown.
- **Plasma Treatment**: Plasma technology can target C-F bonds with high energy, effectively breaking them down in a controlled environment to achieve de-fluorination
- **Incineration**: Incineration at very high temperatures can break down PFAS compounds entirely, although it requires specialized facilities to control emissions and prevent incomplete destruction.
- **Combination of Methods**: For effective total de-fluorination, combining advanced oxidation/reduction with plasma or incineration may enhance the breakdown of PFAS across various matrices.

Key Takeaways from the Topic #3 Session

Key takeaways from the discussions on PFAS destruction are listed below.

- **Complete Elimination vs. Practicality**: Although complete PFAS elimination is ideal, practical goals often target partial reduction due to high energy, cost, and technological constraints.
- **Energy Efficiency and Cost Metrics**: Energy metrics like Electrical Energy per Order (EEO) are essential to measure destruction efficiency. Life cycle analysis (LCA) is critical to assess the cost-effectiveness and environmental impact of PFAS treatment.
- **Challenges in PFAS Destruction**: Semiconductor manufacturing faces challenges due to high-salinity wastewater, non-selective destruction methods, and the high cost of destruction. Continuous flow processes are preferred but difficult to maintain due to low PFAS concentration.
- **New Material and Technology Development**: Innovations such as Pd-based catalysts and other advanced materials are under development to improve PFAS destruction efficiency and reduce costs.
- **Analytical and Monitoring Needs**: There is a need for robust analytical techniques to accurately measure PFAS destruction, track byproducts, and ensure complete mineralization to safe end products like CO_2 and calcium fluoride.
- **AI and Machine Learning (ML) in PFAS Management**: AI and ML can optimize destruction processes, predict PFAS behavior, and help prioritize compounds based on toxicity data, aiding decision-making.
- **Advanced Oxidation and Plasma Processes**: High-energy oxidation/reduction and plasma treatments are promising for targeting and breaking stable C-F bonds in PFAS, potentially achieving total de-fluorination.
- **Collaborative Efforts and Standards**: Enhanced collaboration between academia, industry, and government, along with standardized regulatory frameworks, can accelerate innovation and ensure protection of proprietary interests.
- **Cost and Scalability Constraints**: Cost, resource requirements, and the need for modular, scalable solutions are pressing concerns, especially for smaller companies with limited financial flexibility.
- **Regulatory and Lifecycle Considerations**: Regulations focus on concentration-based targets, but lifecycle assessments are needed to balance resource use with environmental impact, possibly incorporating circular solutions like fluoropolymer reuse.
- **Combined Destruction Techniques**: Using a combination of advanced oxidation, plasma, and incineration techniques may be necessary for complete de-fluorination and mineralization of various PFAS chain lengths.

IV. Convergence Research for PFAS Remediation

This breakout session brought together experts from diverse fields to discuss convergence research for PFAS remediation. This topic was explored through presentations, Q&A sessions, and open discussions with workshop participants. The discussions provided a comprehensive examination of the current challenges and potential solutions in understanding and improving PFAS remediation approaches.

Summary of Presentations

The following tables provide summaries of the introductory presentations provided during the topical discussion on convergent PFAS remediation research.

<table>
<tr><th>Presenter Name</th><th>Institution</th><th>Role</th></tr>
<tr><td>Linda Molnar</td><td>National Science Foundation</td><td>Program Director</td></tr>
<tr><td colspan="3">Presentation Title:
Be Part of the Solution: The NSF Convergence Accelerator</td></tr>
<tr><td colspan="3">Presentation Notes:

Bridging the gap between proof-of-concept research and scalable, impactful technologies remains a critical challenge, particularly in addressing global issues such as PFAS contamination and sustainable resource management. The NSF Convergence Accelerator program plays a pivotal role in addressing this need by funding transdisciplinary teams to drive innovation through convergence research. Key tracks, such as Track I (sustainable materials) and Track K (equitable water solutions), focus on advancing solutions for pressing challenges, including sustainable materials development, PFAS mitigation, and equitable water resource management.

One prominent initiative, PFACTS (under the Convergence Accelerator), targets accelerated solutions for PFAS, often referred to as “forever chemicals.” By prioritizing information sharing and fostering innovation, PFACTS seeks to tackle the environmental and health impacts of these persistent substances. These efforts align with NSF’s broader mission, which emphasizes the interconnected pillars of environmental sustainability, economic competitiveness, and national security.

The Directorate for Technology, Innovation, and Partnership (TIP), NSF’s first new directorate in 30 years, plays a critical role in translating lab research into societal impact. TIP bridges public and private funding to drive technological innovation and responds to legislative initiatives like the CHIPS Act, fostering economic development in critical industries such as semiconductors. Additionally, TIP advances environmental sustainability and national security through programs like the FUTUR-IC Alliance, which aims to create a sustainable semiconductor supply chain, with lessons applicable to managing PFAS and other industrial challenges.

The Convergence Accelerator operates in phases, providing nine months of funding up to $750,000 in Phase I and up to $5 million over 24 months in Phase II, enabling teams to scale their innovations. Since 2019, Convergence Accelerator tracks (A-M) have evolved to address issues ranging from sustainable materials to water justice, aiming to enhance economic growth and environmental equity.

To further bolster sustainable innovation, NSF supports a circular economy approach, emphasizing the need to manage finite planetary resources effectively. Seventeen cohort teams under NSF</td></tr>
</table>

initiatives are advancing solutions to create sustainable and circular systems across industries. Complementing these efforts, the NSF Engines program, with 10 inaugural engines, fosters sustainable and equitable innovation, reinforcing environmental sustainability as a foundation for national security and economic competitiveness. Together, these initiatives exemplify NSF's commitment to addressing global challenges through innovation, collaboration, and strategic partnerships.

Presenter Name	Institution	Role
Scott Shepard	National Institute of Standards and Technology	Technical Program Manager National Semiconductor Technology Center (NSTC)

Presentation Title:

PFAS R&D Opportunities in CHIPS for America

Presentation Notes:

The CHIPS Act provides a transformative investment in the U.S. semiconductor industry, allocating $39 billion for industry incentives and $11 billion for research and development (R&D). This funding aims to strengthen innovation and economic security in semiconductor manufacturing while addressing environmental and sustainability challenges.

Key programs under the CHIPS Act include the CHIPS Metrology Program, which focuses on advancing measurement science in semiconductor production, and the Manufacturing USA Program, which supports domestic manufacturing capabilities. Additionally, the National Advanced Packaging Manufacturing Program (NAPMP) is dedicated to enhancing advanced packaging technologies, while the National Semiconductor Technology Center (NSTC), operated by the public-private consortium NatCast, defines the industry's R&D strategy. With a projected $5-6 billion in funding, the NSTC involves universities, labor organizations, and industry partners to guide research priorities through advisory committees.

Initial funding for "Jump Start Projects" totals $100 million, targeting initiatives like semiconductor test vehicles and PFAS abatement. The abatement program addresses the immediate environmental impact of PFAS in semiconductor manufacturing, including a prototype demonstration focused on capture and destruction technologies. Long-term solutions prioritize the development of PFAS alternatives, with approximately $100 million allocated to AI-driven research aimed at sustainable replacement chemistries.

The CHIPS for America vision integrates economic and national security with innovation to maintain U.S. leadership in semiconductor technology. Specific funding allocations include approximately $350 million for the CHIPS Metrology Program, $285 million for the Manufacturing USA Program, and $1.6 billion for NAPMP, with the application period for the latter recently extended. Regulatory and R&D priorities are also embedded in the CHIPS Act, ensuring investments address environmental sustainability and drive practical applications.

Artificial intelligence plays a pivotal role in PFAS replacement efforts, supporting the development of sustainable solutions, with formal announcements expected soon. For ongoing updates, stakeholders are encouraged to visit CHIPS.gov or Natcast.org or contact askchips@chips.gov or info@natcast.org for further details and engagement opportunities. As implementation progresses, numerous updates and announcements are anticipated, reflecting the rapid pace and broad scope of the CHIPS program.

Summary of the Q&A Session

Q: How does the NSF aim to prevent duplication of funding across programs?

A: Programs are designed to fund different solutions to tackle the same issues, promoting both collaboration and competition. NSF aims to foster cross-program communication to address gaps and avoid overlap in funding.

Q: How are knowledge sharing and collaboration encouraged across U.S. government programs?

A: The U.S. Government is enhancing cross-program collaboration, with stakeholders encouraged to provide feedback on projects. Learnings from one program may eventually inform others, though this requires strategic coordination beyond initial funding phases.

Q: What infrastructure is being developed to support PFAS research and innovation?

A: A pilot-scale facility for pre-competitive semiconductor research is in development, with site selection underway. This will support testing and prototyping, particularly for PFAS abatement and recycling technologies. This facility aims to support collaborative research across industry and academia, bridging a gap in U.S.-based pilot-scale experimentation.

Q: How can stakeholders engage with programs like the NSTC?

A: The NSTC will soon release a membership model, allowing industry associations and trade groups to participate. NSF and NSTC programs rely on cooperative agreements to foster engagement with industry and ensure alignment on PFAS priorities and strategies.

Q: What metrics are used to measure the success of programs addressing complex issues like PFAS?

A: Metrics are structured as tasks and deliverables rather than specific numerical outcomes, especially for complex issues like PFAS. Proposals are encouraged to suggest measurement strategies. The NSF Convergence Accelerator uses a cooperative agreement approach, with industry engagement setting expectations and priorities.

Q: How is the U.S. government collaborating with industry on PFAS solutions?

A: Various government departments (e.g., DOC, DOD, DOE) are actively involved, with the DOD sitting on the steering committee, emphasizing a whole-of-government approach. The "Greening Government" initiative promotes international cooperation, particularly around technologies like PFAS abatement.

Q: What are the Technology Readiness Level (TRL) goals for PFAS-related programs?

A: Higher TRLs are prioritized for technologies closer to commercialization, while foundational research remains open to lower TRL solutions. Target TRLs vary across programs: TRL 4-8 for PFAS abatement and up to TRL 1-3 for PFAS replacement research.

Q: What role does the EPA play in PFAS-related programs, and what challenges exist?

A: While regulatory agencies like the EPA are engaged with programs like Track I and K, there are existing barriers in collaboration between regulatory and non-regulatory entities. Ongoing efforts aim to bridge this gap, with the possibility of more direct EPA involvement as programs develop.

Q: How do PFAS programs align with economic and national security goals?

A: Programs are positioned not only for environmental impact but also to enhance U.S. economic and national security, aligning with the CHIPS Act's broader vision. PFAS solutions from the semiconductor industry could have cross-industry applications, maximizing impact across sectors.

Summary of the Facilitated Discussion

Question 1: What advancements are needed to create predictive models for PFAS remediation in semiconductor manufacturing?

- **Improved Treatment Train Models**:
  - Development of modular process models for each treatment train stage, allowing for better validation and customization in PFAS remediation.
- **Comprehensive Chemical Data**:
  - Input chemical data, including chemical disclosures, should be accessible to device manufacturers to enhance model accuracy and enable predictive capabilities.
- **Enhanced Understanding of PFAS Properties**:
  - Deepening the knowledge of PFAS physical and chemical properties within water matrices is essential for more effective remediation.
- **Fundamental and Experimental Data Collection**:
  - Increased data availability, including experimental data from real wastewater samples, is necessary to improve ML implementations and ensure models are grounded in realistic conditions.
- **Standardized Data for Cross-Comparison**:
  - Uniform data collection across treatments is needed to facilitate comparisons and standardize terms like "low concentration," which vary across industries.
- **Reference Standards and Benchmarks**:
  - Establishment of benchmarking standards (potentially through NIST) is required to ensure consistency across PFAS treatment data.
- **Leveraging Existing Models and Agency Resources**:
  - Utilizing EPA or similar agency resources can accelerate model development and validation.
- **Pilot and Full-Scale Testing**:
  - Real-world testing at pilot and full scales is critical to validate predictive models and ensure their applicability to various PFAS types.
- **AI and ML Applications**:
  - AI can enhance predictive modeling by using known physiochemical PFAS properties and help predict waste characteristics. AI models can also assist in deconvoluting complex data and support multi-type measurements.
- **Total Cost Prediction**:
  - Predictive models need to include total cost of ownership estimates, enabling industries to assess the economic viability of remediation options.

- **Focus on Byproduct Formation**:
    - Understanding byproduct formation under realistic conditions is key for predicting the full impact of PFAS destruction processes and ensuring safer treatment solutions.
- **AI-Driven Materials Development**:
    - Initiatives like IBM's PFACTS, supported by NSF, are using AI to collect analytical data and design new materials, contributing to open-source advancements in PFAS treatment.
- **Critical Variables for AI Modeling**:
    - Identifying and understanding critical variables in treatment technologies will optimize AI modeling, making it possible to tailor approaches to specific PFAS types, including short and ultra-short chains.

Question 2: What advancements are needed to integrate cost-effective and low-energy technologies for PFAS removal, capture, and safe destruction?

- **Inter-Agency Collaboration**:
    - Bridging NSF, NIH, and EPA to facilitate discussions on PFAS toxicology, addressing the lack of unified toxicological standards and encouraging collaborative efforts across agencies.
- **Challenges in Toxicity Data Collection**:
    - NIH's current focus is on endpoints, which limits interest in intermediate toxicological data for PFAS. Only six PFAS species have EPA-regulated standards, all based on endpoint toxicity, highlighting a need for broader toxicological data.
- **Funding and Grant Support**:
    - CHIPS efforts are working to bridge gaps between agencies, while an EPA grant for next-generation adsorption materials ($1M for a single grant) indicates limited funding availability. Additional NSF grants could help fill this funding gap.
- **Technoeconomic and Life Cycle Assessment Models**:
    - Development of technoeconomic assessment (TEA) models combined with life cycle analysis (LCA) is essential for evaluating and comparing PFAS treatment technologies across industries. Treatment solutions must be tailored to specific company needs.
- **Cost Modeling for the Semiconductor Industry**:
    - Establishing cost models and targets specific to the semiconductor industry is necessary, considering the unique environmental and safety challenges they face with PFAS management.
- **Benchmarking Technology Types**:
    - Comparative benchmarking of various treatment technologies is required to set standards and ensure efficacy. Cost benchmarking should include baseline comparisons, such as against incineration costs.
- **Development of Integrated Separation and Destruction Technologies**:
    - Creating separation and destruction technologies compatible with semiconductor processes is key. Effective process control and integration with existing systems will enhance efficiency.
- **Advancements in Monitoring and Sensor Technology**:
    - Improved sensors are needed for real-time monitoring and integration within semiconductor manufacturing and treatment processes, ensuring that PFAS treatment can be controlled and optimized effectively.
- **Customization Across Industries**:

- Recognizing that the most effective treatment train may vary across companies, standards should be flexible enough to account for industry-specific requirements and variability in PFAS types and concentrations.

Question 3: In what ways can PFAS research benefit from convergent approaches?

- **Reduction of Redundant Research**:
  - Convergent approaches can eliminate duplication of efforts, ensuring resources are used more efficiently and avoiding repetitive studies.
- **Enhanced Collaboration**:
  - Encouraging collaboration between groups working on related projects can lead to faster advancements and the sharing of adjacent insights, improving the quality and efficiency of PFAS research.
- **Interdisciplinary Expertise**:
  - Effective PFAS research requires a multidisciplinary approach, involving fields like environmental engineering, analytical chemistry, chemical engineering, physical chemistry, material science, semiconductor process engineering, toxicology, and modeling.
- **Improved Timelines and Cost Efficiency**:
  - By combining efforts, research timelines can be shortened, and costs can be reduced, making PFAS research more scalable and impactful.
- **Cross-Pollination of Ideas**:
  - Collaborative and interdisciplinary settings promote the exchange of diverse ideas, potentially leading to more innovative and effective PFAS solutions.
- **Efficient Use of Resources**:
  - Convergent approaches allow for optimal allocation of resources, reducing wastage and making the research process more sustainable and outcome focused.
- **Focus on Business Feasibility**:
  - Research initiatives should maintain a business perspective, identifying potential “no-go” areas early to avoid pursuing impractical or non-viable solutions.
- **Development of Life Cycle Assessments (LCA)**:
  - Building LCAs for PFAS would provide valuable insight into environmental impacts. Although current databases may be lacking, a simplified LCA focusing on C-F bonds could be a feasible starting point.
- **Challenges in Sampling and Detection**:
  - Addressing challenges in PFAS sampling, cleanup, and detection requires advanced instrumentation and materials, including innovations in separation column materials, solid-phase NMR, and mass spectrometry (MS).
- **Need for Funding in Analytical Method Development**:
  - There is a significant need for funding, particularly from NSF, to drive innovation in PFAS analytical methods, which are currently limited.
- **Involvement of Instrumentation and Analytical Experts**:
  - Engaging experts in instrumentation and analytical chemistry is crucial to developing the tools needed for accurate PFAS analysis and detection.
- **Advances in Multi-Scale Modeling**:
  - PFAS research can benefit from bringing in experts in multi-scale modeling, such as molecular dynamics (MD) simulation, to deepen understanding. Hosting workshops to bring these experts together would advance the field.

- **Enhanced Communication and Metrics**:
    - Improved communication between disciplines and establishing proper metrics for impact assessment will ensure research stays on track and meets measurable goals.

Question 4: What barriers currently prevent successful convergence approaches from being utilized for PFAS research?

- **Communication Gaps**:
    - Significant communication barriers exist between industry and academia, limiting effective collaboration and knowledge sharing. Improved dialogue is essential to bridge this gap.
- **Divergent Priorities**:
    - Industry, academia, and government entities may have differing perceptions of priority areas, leading to disjointed efforts and lack of cohesive strategy in PFAS research.
- **Intellectual Property and Competition**:
    - Concerns over intellectual property and competition can deter open collaboration, particularly when proprietary information and competitive advantages are at stake.
- **Return on Investment (ROI) and Funding Limitations**:
    - Convergence approaches require substantial funding and ROI considerations. Limited funding and uncertainty in economic returns can hinder the adoption of collaborative models.
- **Logistical Challenges**:
    - Coordinating collaborative research efforts is logistically complex, requiring systems to gather people, resources, and data efficiently. Limited opportunities to convene stakeholders pose a barrier to convergence.
- **Expertise Gaps in Air and Solids Testing**:
    - There is a need to develop expertise in PFAS detection and remediation in air and solids. Incorporating this into a comprehensive solution remains a challenge.
- **Limited Training and Workforce Development**:
    - Lack of awareness and specific training among students and workforce in PFAS-related fields limits the pool of skilled professionals who can contribute to convergence approaches.
- **Lack of Common Standards and Data Integrity**:
    - Variability in test standards, data integrity, and confidence in PFAS research results due to differing stability and persistence metrics creates obstacles for unified efforts.
- **Insufficient Convening Opportunities**:
    - More opportunities for cross-sector meetings and workshops are needed to bring together diverse groups and share knowledge.
- **Need for Expanded Toxicity Testing**:
    - Toxicity tests often lack comprehensiveness, especially in terms of non-standard tests and exposure pathways, limiting the understanding of PFAS risks.
- **Existing Forums and Resources**:
    - SEMI's committees and the Semiconductor Industry Association (SIA) offer platforms for collaboration, but greater exposure and integration of these resources with broader PFAS initiatives are needed.
- **Visibility of Capabilities and Research**:
    - A clearer understanding of available research and technological capabilities across sectors would help identify collaboration opportunities and reduce redundant efforts.

Question 5: What techniques allow for co-optimization of PFAS detection, removal, and destruction?

- **Standardized Wastewater Samples**:
  - Using "challenge" samples that represent real-world conditions can help standardize testing and improve comparability of detection and removal techniques.
- **Cross-Sector Collaboration**:
  - Effective integration of technologies requires collaboration across all stakeholders, including government, funders, consultants, and end users, to ensure solutions are feasible and comprehensive.
- **Pilot Plant for Testing**:
  - A dedicated pilot plant would allow for the integration and testing of detection, removal, and destruction functions, creating a feedback loop to refine these technologies.
- **Feedback Loops and Process Understanding**:
  - Establishing feedback loops and understanding current and future chemical inputs and outputs in the process enables more precise optimization.
- **Nomenclature and Infrastructure Standardization**:
  - Standardizing terms and aligning infrastructure can ensure consistency and clear communication across different PFAS remediation efforts.
- **Detection Standards Development**:
  - Developing standards specifically for PFAS detection is essential to improve accuracy, reliability, and alignment in testing approaches.
- **Mobile and Reconfigurable Test Beds**:
  - Mobile testing setups allow for adaptable, real-world testing of PFAS technologies in various settings, making it easier to adjust processes based on site-specific needs.
- **Early End-User Engagement**:
  - Involving end users early in the development process ensures technologies align with practical requirements and constraints, increasing the chances of successful implementation.
- **Process Simulation Tools**:
  - Process simulators and tools provided by suppliers (e.g., filtration models) can assist in testing and predicting performance, making co-optimization more efficient.
- **Space and Implementation Constraints**:
  - Semiconductor fabs are densely packed, and retrofitting or adding abatement systems is challenging. Solutions must be compact, with minimal footprint to be feasible at the point of use.
- **Sampling and Infrastructure Limitations**:
  - Adding sampling ports and conducting sampling within existing fab infrastructure can be difficult. Controlled design in sampling protocols is necessary for accurate and safe monitoring.

Key Takeaways from the Topic #4 Session

The breakout session on convergence research in PFAS remediation yielded several crucial insights, summarized in the following key takeaways:

- **Predictive Modeling for PFAS Remediation**:

    - Enhanced treatment train models and comprehensive data collection, including real wastewater samples, are essential for accurate predictive models.
    - AI and machine learning tools can improve model accuracy by processing chemical data and physiochemical properties, enabling better predictions and cost estimation.
    - Standardized benchmarks and pilot testing are crucial to validate models across varied PFAS compounds.
- **Cost-Effective and Low-Energy PFAS Treatment**:
    - Cross-agency collaboration (e.g., NSF, EPA) is needed to bridge funding gaps and set toxicity standards, supporting more cohesive and informed research.
    - Technoeconomic assessments (TEA) and life cycle analyses (LCA) specific to semiconductor industry needs are key for evaluating different PFAS technologies.
    - Development of integrated monitoring and sensor technologies will help optimize PFAS treatment within existing manufacturing setups.
- **Convergent Approaches in PFAS Research**:
    - Convergence can eliminate redundant research and facilitate faster innovation by pooling interdisciplinary expertise in environmental engineering, toxicology, and process engineering.
    - Resource efficiency and cross-pollination of ideas enhance both business feasibility and the potential for innovative solutions.
    - Building a PFAS life cycle assessment (LCA) with standardized data can drive impactful environmental and economic insights.
- **Barriers to Successful Convergence**:
    - Communication gaps, differing priorities, and IP concerns hinder collaboration across industry, academia, and government.
    - A lack of unified standards, limited training, and logistical challenges in coordinating efforts also pose obstacles.
    - More convening opportunities and clarity on research capabilities can help bridge these gaps, particularly in specialized areas like air and solids testing.
- **Co-Optimization of PFAS Detection, Removal, and Destruction**:
    - Standardized “challenge” samples, mobile test beds, and early end-user engagement are vital for refining PFAS technologies.
    - Pilot plants provide valuable feedback loops, allowing for real-world testing and adjustments in treatment approaches.
    - Solutions must account for the constraints of semiconductor fabs, including limited space and infrastructure integration challenges, requiring compact, efficient setups.

Findings and Recommendations

The workshop on PFAS detection, removal, and destruction in semiconductor manufacturing waste streams identified key insights and actionable steps to address challenges associated with managing PFAS contamination. This section summarizes the findings and presents recommendations under the thematic areas discussed.

Findings:

- **PFAS Detection**
  - Current detection technologies (e.g., LC-MS, GC-MS) face challenges with matrix interferences and sensitivity, particularly at low PFAS concentrations.
  - Ultra-short chain PFAS compounds and their replacements remain difficult to detect due, in part, to limited analytical standards.
  - Real-time and in-situ detection technologies are underdeveloped and require significant innovation to be viable for industrial application.
- **PFAS Removal**
  - Conventional removal methods like activated carbon and ion exchange are less effective for short-chain PFAS, necessitating novel approaches.
  - High salinity and organic content in semiconductor wastewater complicate PFAS removal and increase treatment costs.
  - Emerging techniques, such as electrochemical separations and functional adsorbents/membranes, show promise but require scalability and validation.
- **PFAS Destruction**
  - Complete mineralization of PFAS to benign end products remains challenging due to high energy requirements and the complexity of wastewater matrices.
  - Current destruction technologies often generate toxic byproducts, necessitating advanced analytical methods to monitor and mitigate these outputs.
  - Combining separation and destruction technologies ("trap and zap") offers a promising pathway for efficient PFAS management.
- **Convergence Research**
  - Collaborative, interdisciplinary approaches are essential to integrate detection, removal, and destruction technologies effectively.
  - Gaps in data sharing, communication, and regulatory alignment hinder progress in research and implementation.

- There is a critical need for standardized testbeds and reference materials to validate technologies across different applications.

Recommendations:

For Detection

- **Advance Analytical Capabilities:**
  - Invest in high-resolution methods (e.g., LC-HRMS) and real-time sensors to improve PFAS detection across diverse matrices.
  - Develop standardized reference matrices for PFAS testing to ensure consistency and comparability of results.
- **Enhance Method Sensitivity:**
  - Prioritize techniques capable of detecting short-chain and ultra-short-chain PFAS at trace levels.

For Removal

- **Innovate Targeted Separation Methods:**
  - Promote R&D on selective adsorbents and membranes tailored for PFAS variability (e.g., chain length, charge).
- **Scale Novel Technologies:**
  - Focus on scalability of emerging methods such as electrochemical separations and functional adsorbents/membranes for industrial use.
- **Optimize Treatment Locations:**
  - Implement localized treatment systems near PFAS sources within semiconductor fabs to enhance efficiency.

For Destruction

- **Develop Energy-Efficient Techniques:**
  - Explore energy-efficient processes like supercritical water oxidation and advanced oxidation-reduction systems for PFAS degradation.
- **Monitor Byproduct Formation:**
  - Establish robust analytical protocols to detect and mitigate toxic byproducts resulting from PFAS destruction.
- **Adopt Integrated Approaches:**
  - Encourage the combination of separation and destruction technologies to optimize overall treatment efficiency.

For Convergence Research

- **Facilitate Cross-Sector Collaboration:**
  - Establish government-funded centers to bridge academia, industry, and regulatory bodies for PFAS remediation.
- **Standardize Data and Models:**
  - Develop and share predictive models for PFAS behavior in wastewater to inform treatment strategies.
  - Create standardized testbeds and reference materials to validate technologies across different PFAS applications
- **Promote Life Cycle Analysis (LCA):**
  - Prioritize LCAs for new PFAS treatment technologies to assess environmental and economic impacts comprehensively.

Policy and Industry Alignment

- **Strengthen Regulatory Frameworks:**
  - Align international and domestic regulations to provide clear guidelines for PFAS limits and acceptable technologies.
- **Incentivize Sustainable Practices:**
  - Provide financial incentives for industries adopting innovative, low-energy, and cost-effective PFAS management solutions.
- **Enhance Workforce Training:**
  - Develop specialized training programs to equip professionals with skills in PFAS analysis and treatment technologies.

These findings and recommendations lay the groundwork for advancing PFAS management strategies in semiconductor manufacturing, emphasizing innovation, collaboration, and sustainability.

Appendix A: Workshop Agenda

Day one	Tuesday, August 13th
7:00 AM	Pre-Meeting Networking with Coffee/Tea
8:00 AM	**Welcome, Introduction, Opening Remarks** *Emmanuel Taylor, Energetics* *Xiao Su, University of Illinois Urbana Champaign* *David Thompson, Vice President of Technology Research Process Engineering, Intel*
8:40 AM	**Plenary Presentations: PFAS Analysis, Characterization and Abatement – Industry Activities** *Melissa Gresham, Melissa Gresham Consulting* *David Speed, GlobalFoundries* *Kevin Wolfe, Intel*
9:40 AM	**Industry & Academic Experts Q&A**
10:10 AM	Break
10:25 AM	**Instructions for Facilitated Sessions** *Emmanuel Taylor, Energetics*
10:35 AM	**PFAS Detection Introductory Presentation and Q&A** *Jennifer Field, Oregon State University*
10:50 AM	**Breakout #1 (parallel sessions)** PFAS detection
12:05 PM	**Lunch Break and Virtual Tour of Intel Wastewater Treatment Facilities** *John Longley, Intel*
1:05 PM	**PFAS Removal Introductory Presentation and Q&A** *Xiao Su, University of Illinois Urbana Champaign*
1:20 PM	**Breakout #2 (parallel sessions)** PFAS Separation/Removal
2:35 PM	Break
2:50 PM	**PFAS Destruction Introductory Presentation and Q&A** *Paul Westerhoff, Arizona State University*
3:05 PM	**Breakout #3 (parallel sessions)** PFAS Destruction
4:20	**Next Steps and Closing Remarks** *Xiao Su, University of Illinois Urbana Champaign*
4:30	Adjourn
Day two	**Wednesday, August 14th**
8:00 AM	Pre-Meeting Networking with Coffee/Tea
9:00 AM	**Day 2 Welcome and Overview** *Emmanuel Taylor, Energetics*
9:05 AM	**Plenary Presentations from Invited Speakers for Convergence Topics** Linda Molnar, Program Director, National Science Foundation Scott Shepard, Technical Program Manager, NIST CHIPS R&D Office
9:35 AM	**Government Program Experts Q&A**
9:50 AM	**Report Outs from Day 1 Discussions and Breakout Sessions**

10:50 AM	**Instructions for Breakout Sessions** *Emmanuel Taylor, Energetics*
11:00 AM	Break
11:15AM	**Breakout #4 (parallel sessions)** Facilitated Convergence Discussion
12:30 PM	Review of Findings
12:45 PM	Workshop Summary & Closing Remarks
1:00 PM	Workshop Conclusion and Networking Lunch

Appendix B: Workshop Participants

First	Last	Affiliation
Diana	Aga	University at Buffalo
Nirupam	Aich	University of Nebraska-Lincoln
Pedro	Arrechea	IBM
Gautam	Banerjee	IBM
Gabriel	Cerron Cale	Arizona State University
David	Darwin	National Science Foundation
Mamadou	Diallo	Caltech
Kyle	Doudrick	University of Notre Dame
Jennifer	Field	Oregon State University
Kenneth	Flores	Arizona State University
Devashish	Gokhale	University of Illinois Urbana Champaign
Michael	Gordon	Edwards
Melissa	Gresham	Melissa Gresham Consulting, SIA PFAS Consortium
David	Hanigan	University of Nevada Reno
Raul	Hernández Sanchez	Rice University
Matt	Hicks	Intel
John	Howarter	Purdue University
Jianbing	Jiang	University of Cincinnati
Gerrard	Jones	Oregon State University
Mitchell	Kim-Fu	Oregon State University
Detlef	Knappe	North Carolina State University
Melissa	Laffen	Energetics
Linda	Lee	Purdue University
Bob	Leet	Intel
Haizhou	Liu	University of California Riverside
Jonathan	Longley	Intel
Katherine	Manz	University of Michigan
Erica	McKenzie	Temple University
Dave	Medeiros	Entegris
Linda	Molnar	NSF
Carl	Naylor	Intel
Sarah	Propp	Ingersoll Rand
Rich	Riley	Intel
Anaira	Román Santiago	University of Illinois Urbana Champaign
Robert	Sandoval	TSMC

Scott	Shepard	National Institutes of Standards and Technology
Dave	Speed	GlobalFoundries
Timothy	Strathmann	Colorado School of Mines
Xiao	Su	University of Illinois Urbana Champaign
Emmanuel	Taylor	Energetics
David	Thompson	Intel
Shao-Wei	Tsai	University of Illinois Urbana Champaign
Arjun	Venkatesan	New Jersey Institute of Technology
Paul	Westerhoff	Arizona State University
Kevin	Wolf	Intel
Dongye	Zhao	San Diego State University

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